A METHODOLOGY FOR IDENTIFYING FLEXIBLE DESIGN OPPORTUNITIES

by

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Bachelor of Science Aerospace Engineering – Texas A&M University, 2002

Submitted to the Department Engineering Systems Division and the of Aeronautics and Astronautics in Partial Fulfillment of the Requirements for the degrees of Master of Science in

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Abstract

Technical and operational uncertainties dynamically change environments for engineering systems. Flexibility allows systems to continue delivering value as the uncertainty unfolds. Uncertainty can better be managed by embedding flexibility into the system. However, system designers do not have a tool or metric that identifies which components within the system to focus embedded flexibility efforts. They rely on intuition developed through experience and expertise to build in system flexibility, often leading to disagreement between system stakeholders (both designers and customers) about where to focus efforts due to the differing perspectives and inability to assess knock-on effects. Therefore, providing a tool to help designers screen the system for opportunities for embedded flexibility will also establish reasoning supporting their claims.

This thesis proposes a general screening methodology for identifying potential Flexible Design Opportunities (FDOs) in systems; demonstrates the methodology using a Micro Air Vehicle (MAV) platform developed for Department of Defense (DoD); evaluates the ability to exploit FDOs within DoD Acquisitions; and makes recommendations to system designers using the presented case, where the question of where and how to embed flexibility is complicated by multiple system uncertainties. The case study provides useful results, identifying FDOs that were validated by the author's experience as a system engineer and program manager.

The development of the methodology yielded two characteristics to screen system components for FDOs: the component's ability to propagate or absorb change and its switch cost associated with making the desired change. Change Propagation Analysis coupled with filtering techniques to reduce the complexity of the data and rank system components with respect a newly proposed metric, Desired Flexibility Score (DFS), that represents the attractiveness of the component for embedded flexibility.

The analysis concludes that the DoD acquisitions guidelines do provide opportunities to implement FDOs for longer term programs (> five years). However, process requirements may hinder the ability to react quickly to rapidly changing or emerging technical and operational uncertainties to maximize the upside potential of systems, while minimizing the downside risk.

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Disclaimer -- The views expressed in this thesis are those of the author and do not reflect the official policy or position of the U.S. government or the Department of Defense.

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Acronyms

AFRL	Air Force Research Laboratory
AT&L	Acquisition, Technology & Logistics
AV	Air Vehicle
BDI	Bomb Damage Information
CAIV	Cost As an Independent Variable
CDD	Capability Development Document
CEE	Component Expected Expense
CI	Coupling Index
CIRT	Change Initiator-Relationship Type
COCOM	Combatant Command
CPD	Capability Production Document
CPI	Change Propagation Index
CS	Change Scenario
DAS	Defense Acquisition System
DFARS	Defense Federal Acquisition Regulations Supplement
DFS	Desired Flexibility Score
DMM	Domain Mapping Matrix
DoD	Department of Defense
DSM	Design Structure Matrix
ESM	Engineering Systems Matrix
EA	Evolutionary Acquisition
ECP	Engineering Change Proposal
ESC	Electronic Speed Controller
EV	Expected Value
FDO	Flexible Design Opportunity
f-OD	filtered Outdegree
FRDP	Functional Requirement-Design Parameter
GAO	Government Accountability Office
GCS	Ground Control Station
GPS	Global Positioning System
GVI	Generational Variety Index
HPT	High Performance Team
ICD	Initial Capabilities Document
IDIQ	Indefinite Delivery, Indefinite Quantity
IEDs	Improvised Explosive Devices
IPR	Intellectual Property Rights
ISR	Intelligence, Surveillance, and Reconnaissance
IWN	Immediate Warfighter Needs
JCIDS	Joint Capabilities Integration & Development System
JRAC	Joint Rapid Acquisition Cell
JUONs	Joint Urgent Operational Needs
MAV	Micro Air Vehicle
MAJCOM	Major Command
MIT	Massachusetts Institute of Technology

OCU	Operator Control Unit
OEF	Operation Enduring Freedom
OIF	Operation Iraqi Freedom
O&M	Operations & Maintenance
PC	Personal Computer
P&D	Product & Development
POM	Program Objectives Memorandum
PPB&E	Planning, Programming, Budgeting & Execution
QFD	Quality Function Deployment
RDT&E	Research, Development, Test & Evaluation
ROA	Real Options Analysis
SC	Switch Cost
SD	Spiral Development
SDD	System Development & Demonstration
sDSM	Sensitivity DSM
SMaRT	System Modeling and Representation Tool
SME	Subject Matter Expert
SOPs	Standard Operating Procedures
SPO	System Program Office
TDN	Time-expanded Decision Networks
T&E	Test & Evaluation
UAV	Unmanned Air Vehicle
UCAs	Undefinitized Contract Actions

Chapter 1: Motivation and Introduction

The new threat environment facing the US military presents environmental, operational, and technical challenges. The ability to project military power "anywhere, anytime" is possible given the vast mobility resources available. Maintaining global presence demands that military systems be versatile and efficient in many different environments, including transitioning from forests or jungles to deserts. The threats encountered within these environments also change drastically, and thus defensive and/or offensive operational tactics are altered in response. Furthermore, the enemy is able to adapt to new technologies very quickly to defeat the advantage of high-tech resources and weapon systems. This fact has proven detrimental in the current conflicts of Operation Enduring Freedom (OEF) and Operation Iraqi Freedom (OIF), where low-tech Improvised Explosive Devices (IEDs) are able to slow and disable state-of-the-art US military equipment. Therefore, Department of Defense (DoD) must rapidly develop and procure weapon systems to keep pace with the changing threats.

There is a growing emphasis within DoD to develop and acquire flexible systems. However, tension exists between this need for flexible systems, rapid development and procurements to meet immediate capability deficiencies, and the DoD acquisitions process and funding decisions.

Designing a flexible system requires planning and investment to first recognize the uncertainties affecting the systems. Then, system designers must identify how to embed flexibility in the initial design such that the system is capable of easily adapting to the possible future states. Finally, stakeholders must understand when to exploit the embedded flexibility to create added value, or minimize losses, as the future unfolds.

DoD's need for rapid development and procurement challenges the ability to design flexible systems. System designers and stakeholders neglect early planning processes for rapid development and procurements. Instead they focus on producing an immediate "fix" or "band-aid." These solutions do not consider the uncertainties that will affect the system, nor does the development pause to consider how or if the system will be able to respond to different environments. Furthermore, the rapidly developed solution is short-term and often does not have the necessary lifecycle development required to sustain fielded solutions. Giving little thought to potential future long-term needs, the system also will lack the ability to be easily modified to accommodate new environments and operational tactics. Thus, the DoD must continue to create "fixes" as the future unfolds, which will inevitably lead to less efficiency and higher long run costs. Therefore, flexibility becomes even more important!

Two sources of DoD policy also conflict with the goal of acquiring flexible systems: funding allocation and acquisitions processes.

DoD's policy to select the lowest-cost bid for product development may be contrary to the desire to obtain flexible systems. In some cases, embedding flexibility increases initial costs. These costs are offset by the benefits of future value, which is why recognizing the uncertainty must be accompanied by resources to assess when the flexibility is valuable. Therefore, emphasis on near-term costs prohibits the DoD from realizing the long-term benefits, such as reducing longer-term lifecycle costs, possible through acquiring flexible systems. Additionally, DoD fails to understand the short-term cost advantages of flexible systems. Flexibility does not necessarily require larger initial costs. On the contrary, designing a flexible system may allow stakeholders to delay costly capital investments. To recognize the cost savings, funding resources must be allocated to analyzing the system uncertainties, where to focus efforts to design for flexibility, and modeling the future such that stakeholders understand how to exploit the flexibility to reap the rewards.

Furthermore, DoD acquisition process policies restrict the ability to develop or procure flexible systems capable of adapting to the new dynamically changing threats. The DoD acquisitions process has been in a state of reform since 1994 after the 1987 budget reductions for defense procurements.[1] (Grasso 2003) The latest version brings the solution known as Evolutionary Acquisitions (EA) using Spiral Development (SD). Now the "preferred method of acquisitions" for all programs entering the development cycle, the goal of EA is to focus on delivering minimally acceptable capability in the short-term and then building upon that basis as risks and uncertainty are resolved over time. (Shah 2004) In 2003, the OIF and OEF operations spurred the need for rapid reaction programs to deliver and field immediate urgent needs, providing a perfect opportunity to test the potential of this new acquisitions policy. However, since that time DoD has proven capable of generating the short term solution, yet has difficulty maturing the design for expanding requirements and needs in the long term. Recognition of operational and technical uncertainties has been under-emphasized, and understanding how to leverage embedded flexibility to respond to the uncertain future has been neglected in military system design.

Air Force Research Laboratory (AFRL) developed a Micro Air Vehicle (MAV) in 2003 to respond to an urgent need for a supplementary Unmanned Air Vehicle (UAV) to augment the growing demand for small UAV operations. An 80% solution was developed within nine months of conceptualization using spiral development and rapid transition strategies. (Snyder and Wilds 2004) Five years later, this initial solution is unable to adapt to the growing requirements demanded by the warfighter as a result to

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[1] Congress has passed several important reforms, among them the Federal Acquisition Streamlining Act of 1994, Federal Acquisition Reform Act of 1996, Defense Reform Act of 1997, and the Federal Activities Inventory Reform Act of 1998. The FY2002 National Defense Authorization Act called for a overhaul of the DoD Acquisition, Technology and Logistics organization; revisions to the Defense Federal Acquisition Regulations for procurements; and temporary emergency procurement authority to raise the simplified acquisition threshold in response to the events of 2001. DoD issued the revised acquisitions policy in the form of two directives: DoD 5000.1 and DoD 5000.2 which define the policy of acquisitions and description of the operations, respectively. (Grasso 2003)

changing operational environments and new technology developments. As such, new platforms are currently in development. While one can argue that the lessons learned and enabling technologies developed for the initial design are beneficial to the new programs, the decision to discard the original platform design for new initiatives leaves an unresolved question: why was the 80% solution unable to adapt as the EA strategy suggests?

One potential answer is that the system was not designed for flexibility. This research examines how the MAV and similar systems, in both the defense and commercial sectors, can be screened to inform systems designers where in the system to look for opportunities to embed flexibility.

Motivation for Designing Flexible Systems

This section defines the term flexibility as used in this research and provides motivation for designing flexible systems. Additionally, it addresses the relationship between uncertainty and system flexibility.

Definition of Flexibility

Flexibility is the ability of a system to respond to change.[2] Program managers and system designers use flexibility as a tool to create systems that continue delivering value by *altering their performance* given contextual changes. Change is broadly defined as a transformation or modification; a variation or deviation; or the substitution of one thing for another. More specifically, a change is an event that occurs when something passes from one state or phase to another. A contextual change is a change to the system's environment or inputs that provides the motivation for flexibility. These contextual changes include technical, economic, political, industrial and regulatory conditions influencing the system.

Contextual changes are uncertain over time, which can disrupt the initial forecasts and even change value delivery. Therefore, designing for flexibility implies some recognition these system uncertainties. Flexibility is a system attribute. Components within the system are designed such that the collective system is capable of changing in response to the contextual change, and is thus a flexible system. Careful attention must be given to defining the system boundary, since systems can often be decomposed where components may be considered systems within the system.

There are two types of flexibility: flexibility "in" a system and flexibility "on" a system. (de Neufville 2002) Flexibility "in" a system uses the technical components within the

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[2] Flexibility is a generally used term throughout engineering systems and design literature with many different connotations. For example, Ross (2006) defines changeability as the system's ability to respond to change. He further decomposes changeability into flexibility and adaptability, differentiating between external and internal changes respectively. The definition of flexibility stated here corresponds to Ross' changeability. However, the distinction of internally/externally initiation of the change is not necessary for this research, and thus the definition reflects the more commonly used connotation of the term. For other definitions and uses of the term flexibility, see Cardin (2008), Rajan et al (2004), Saleh (2002), Silver and de Weck (2007), and Suh (2005).

system as the source to create flexibility. The design of the technical components allows the system to be easily altered at a later time such that the performance can be altered to continue delivering value in response to the unfolding uncertainty. The second type of flexibility, flexibility "on" a system, maps uncertainties to levers which are external to the system boundary. These levers, which most frequently are operational decisions to abort, delay, or accelerate deployment, may involve physical components outside the system, processes, or stakeholder networks and are often related to management decisions. (Cardin 2008)

Importance of Flexibility

Flexibility has long been cited as a key goal for dealing with uncertainty in the design and the future use of complex systems. The existence of uncertainty is what makes flexibility valuable. Real Options Analysis (ROA)[3] techniques have proven useful to value flexibility in design for systems in a diverse sample of industries. Cardin (2008) provides a thorough review of ROA techniques and cites several example case studies that demonstrate their application to real-world projects.[4]

To appreciate the full value of incorporating flexibility, this literature emphasizes that uncertainty has both an upside and a downside. The upside to uncertainty is known as opportunity, while the downside is often referred to as risk. Risk is defined as a measure of the downside of uncertainty in attaining a goal, objective, or requirement pertaining to technical performance, cost, and schedule. Risk level is categorized by the probability of occurrence and its consequences (Thunnissen 2004). Opportunity likewise has a probability of occurrence and rewards. Therefore, flexibility can enable rewards and/or reduce consequences if system designers can figure out where to embed the flexibility in the system such that it can adapt to exogenous factors that are likely to change over time.

In the case of a commercial market, Fricke and Schultz (2005) contend that staying ahead in a dynamic environment requires a state-of-the-art system throughout the system lifetime. To achieve that capability level, systems need to incorporate flexibility throughout their life cycles within themselves and with respect to their environments. Rajan et al (2004) examined flexibility in small to medium size consumer products. He says that since evolution and change are inherent in the nature of product design, products should account for these effects. In addition, the product needs to change to retain value during some unknown future. Uncertainty about the future leads to developing a design that can easily accommodate future changes—flexible designs offer manufacturers an option to reduce time to market.

Several researchers have proposed different approaches to designing systems for an uncertain future to better manage the known or recognized uncertainties. Silver and de

[3] An option is the "right, but not obligation, to take some action now, or in the future, for a price." A real option is an option that focuses interest for design, providing flexibility for evolution of the system. ROA are methods to value real options. (de Neufville 2002)

[4] Application of Real Options Analysis techniques to many fields of study include Cardin et al (2008), de Neufville (2006), de Weck et al (2004), Hauser and de Weck (2006), Kalligeros and de Weck (2004); Kalligeros (2006), and Suh and de Weck (2006).

Weck (2007) applies Time-expanded Decision Networks (TDN) to design and analyze flexibility in large-scale complex space systems. Suh (2005) and Kalligeros (2006) consider product platform design and commonality of systems while managing uncertainty in the automotive and petroleum industries, respectively, using network techniques such as change propagation analysis and sensitivity of system connectivity. Each of these efforts focuses on qualitative identification and value of flexibility as a management technique for uncertainty, yet the question of where to embed flexibility lacks quantitative derivation.

Implementing Flexibility in System Design

Most complex engineering systems operate in uncertain environments, and thus the desire for flexibility is based on the heuristic that more flexibility is good since it provides a source of solution to mitigate risks. However, designing systems explicitly for uncertainty can also have major consequences. Systems designed to meet a fixed specification will likely produce a different design than one in which flexibility is incorporated. (de Neufville et al 2004) Fixed specifications allow solutions that can be optimized to accommodate the defined need. Flexible solutions are not designed to meet one particular need, and thus performance that is optimized for a particular context may be compromised to achieve value over a wider range of contexts. Therefore, an explicit focus on uncertainty is not universally suitable for all engineering systems.

System designers must recognize when to implement approaches to design for flexibility. Saleh (2002) proposes:

> "Flexibility should be sought when: 1) the uncertainty in a system's environment is such that there is a need to mitigate market risks, in the case of a commercial venture, and reduce a design's exposure to uncertainty in its environment, 2) the system's technology base evolves on a time scale considerably shorter than the system's design lifetime, thus requiring a solution for mitigating risks associated with technology obsolescence."

The first criterion supports the idea that flexibility can be used to manage system uncertainty as previously described. As uncertainty, its opportunities and risks, increase, the need for flexibility also increases. Systems with multiple uncertainties, or single uncertainties which dominate the design decisions, are candidates for embedding flexibility. The second criterion speaks to the element of time. Uncertainties that are changing rapidly require change to the design before the system completes its lifetime, indicating the potential need for flexibility. Systems that have longer operational life expectancies will likely encounter more uncertainty, and in addition forecast accuracy typically degrades as the time period considered increases.

Although a starting point for understanding when uncertainty is important, Saleh's (2002) criteria are too limiting. He neglects to account for risk's counterpart: opportunity. Rather than only mitigating the downside of uncertainty, flexibility should also be sought when opportunity can increase the potential of the system to deliver additional value. Uncertainty is asymmetrical, and this asymmetry can lead to the upside being much greater than the perceived downsides. Additionally, while Saleh's second criterion speaks only of technology evolution, suggesting flexibility in the physical domain, the frequency of change due to uncertainty is generally important in all domains (social, technical, environmental, etc.)

Because the sources of uncertainty and its attributes (such as frequency of change and likelihood of occurrence) are key factors in determining the need for flexibility, it is important to recognize how engineers and end users think about uncertainty. Both technical and operational uncertainties induce contextual changes for engineering systems. Technical uncertainties include consideration of innovation, emergent technology, and availability of current or dated technology. For example, technology developments often have uncertain maturity/readiness levels and unknown effectiveness for integration in field environments. Operational uncertainties, which include considerations of environment, expected performance, and expected lifecycle durations, are just as important as technical uncertainties. However, the technical uncertainties identified by program managers and engineers are typically disconnected from the operational uncertainties identified by customers or product users. Often the operational uncertainties are not communicated to the technical experts, and thus the system is not able to fully maximize the potential of the system to respond.

The source of uncertainty and its attributes affect how designers can embed flexibility by changing where in the system one looks to effect change. While several efforts have offered similar guidelines for when to design for flexibility, there is a research gap concerning where to focus efforts when designing flexible systems. Suh (2005) and Kalligeros (2006) each provide a foundation to begin the discussion of screening for real options, which is synonymous to how to identify where in the system to embed flexibility. Bartolomei (2007) encouraged a potential methodology that combines the two approaches of change propagation and sensitivity analyses. Chapter 2 presents a discussion of these efforts.

This thesis aims to provide system designers with a method for screening systems for Flexible Design Opportunities (FDOs), or areas of interest in the system which may provide opportunities to embed flexibility. FDOs are characterized by a high likelihood of inducing significant change(s) or high costs associated with change given recognized uncertainties affecting the system. Chapter 2 defines FDO and discusses their characteristics.

Thesis Formulation

A review of current literature identifies a research gap regarding how to identify opportunities for embedding flexibility. Engineering systems research has focused on the importance of valuing flexible systems. ROA has extended financial methods to the valuation of physical systems. However, the system designer must have an intimate knowledge of the system and an understanding of its uncertainties to formulate real options that will provide value. The ROA literature lacks the development of methods to suggest how to formulate real options, leaving system designers seeking options limited by their perceptions of the system and biases based on prior experience. Furthermore, design literature is specific to the industry that is being researched. Approaches to design platforms or process standardizations are context specific and offer little insights for general guidelines for selecting flexibility efforts. As a result, potential opportunities for developing flexible systems may go unrecognized.

The identified research gap motivates this thesis. Its primary goal is to design an approach for identifying where in a system one should look to embed flexibility. Emphasis was placed on developing a practical methodology that is computationally feasible and applicable to a diversity of engineering systems. First, a survey of the state-of-the-art approaches for identifying opportunities for flexibility provided an understanding of the current limitations of these approaches and the potential challenges for developing a generalized method. Next, Bartolomei's (2007) Engineering System Matrix (ESM) framework was adopted to provide structured representation of the system. Then, a combination of the current approaches was applied to a simplified example. The methodology evolved from several iterations and adjustments to the selection of combined approaches such that the simplified example produced intuitive results.

Finally, this research demonstrates the methodology developed using a case study of the Micro Air Vehicle (MAV). It stems from previous efforts and includes a detailed ESM constructed over two years. (Bartolomei 2007) Participating as the former system designer and program manager, the author of this thesis was heavily involved in the construction of the ESM and provided key insights regarding the validity of the results processed from the proposed methodology.

Contributions of this thesis include a survey of the existing approaches for embedding flexibility; a proposed methodology for identifying FDOs using the ESM framework; prescriptive recommendations for applying the methodology to a MAV case study; and policy considerations for implementing design for flexibility within the DoD acquisitions guidelines.

Structure of the Thesis

Outlined below is the structure for the remainder of this thesis. The reader can use this section as a guide to understanding the "big picture" perspective of the presented argument.

Chapter 2 presents an overview of key concepts used in the development of the methodology to identify FDOs. It includes an explanation of FDOs and the multi-domain ESM framework. A literature review of current approaches utilized to identify opportunities for flexibility, including a discussion of strengths and weaknesses, provides the basis for the defining the methodology proposed.

Chapter 3 defines and explains the methodology for identifying FDOs. It is uses the ESM framework, change propagation analysis, and switch cost estimations to assess each component's potential as a FDO. A new metric is introduced, the Desired Flexibility Score (DFS) to provide a one-dimensional comparative measure for ranking system components. A simple example provides additional explanation of the steps in the process.

Chapter 4 presents a case study that demonstrates the methodology for identifying FDOs. Key steps and implications of assumptions are illustrated using a simple MAV system that was developed for DoD. The case study analyzes three different uncertainties as individual scenarios to recommend FDOs for each. Then, in the final step, the results are aggregated to provide a rank-ordered listing of physical components within the MAV which should be considered for embedded flexibility.

Chapter 5 introduces flexible design in the context of the DoD. It identifies key acquisitions policies and stakeholders of interest when attempting to implement design for flexibility. A discussion of enablers and barriers is followed by recommendations for improving the ability of DoD to acquire flexible systems.

Chapter 6 contains conclusions and a review of assumptions inherent in the proposed methodology. It closes with recommendations for future research topics and promising directions.

Chapter 2: Flexible Design Opportunities and Approaches to Design Flexible Systems

This chapter defines Flexible Design Opportunity (FDO) and its relationship to system uncertainty. Chapter 2 also surveys state-of-the-art approaches for identifying where to embed flexibility within systems. Limitations of these existing approaches guide the research and ultimately the developed methodology proposed in Chapter 3.

Definition of Flexible Design Opportunity

Cardin (2008) defines a Flexible Design Opportunity (FDO) as “a physical component enabling flexibility ‘in’ [a] system.” Recall from Chapter 1, flexibility “in” a system is characterized by the system’s internal components adapting in response to a change. Therefore, system components are categorized as FDOs if they offer opportunities for embedded flexibility.

FDOs depend on the contextual change. A scenario can be created for a given contextual change that more specifically defines its characteristics. Then, FDOs are identified for individual scenarios. For example, building larger structural columns to support construction of additional floors in a parking garage allows the design to be flexible to an increase in the future demand for capacity. (de Neufville et al 2006) In this scenario, the contextual change is the increasing demand for parking capacity, and the structural columns are the identified FDO. Because FDOs depend on the contextual change, different components may be categorized as FDOs for differing scenarios. To illustrate, consider a second contextual change that impacts the operations of the parking garage, say a new safety regulation imposes a minimum evacuation time for all parked cars. This scenario may identify the garage exits as the FDOs, where flexibility of the number of exits or the width of exits is desired to respond to the contextual change.

The dependency of FDOs on specific contextual changes restricts the systems designer’s understanding of where to embed flexibility to respond to a particular scenario. Subject Matter Experts (SMEs), or expert engineers, program managers, or operators for a specific system or field of study, may argue that they can intuitively identify where to embed flexibility for simple scenarios such as the parking garage example. However, resources for system development may be limited, thereby restricting the inclusion of all possible FDOs. SMEs may find it difficult to choose which FDO should be selected for inclusion in the design. Therefore, it is important to understand how FDOs compare across multiple contextual changes. This suggests the need for rank ordering FDOs based on characteristics of the contextual change and the FDO itself.

Ranking FDOs

FDOs indicate components that are potential candidates for flexibility; yet, not all FDO are the “best” components to focus efforts. FDOs can be ranked based on a strength scale, where weak FDOs are less critical to overall system flexibility than strong FDOs. Overall system flexibility refers to a system’s ability to respond to the greatest range of system uncertainties recognized. Systems designers should focus efforts to embed flexibility on strong FDOs if resources are limited.

Three factors dominate the strength of FDOs:

- the likelihood that a specific contextual change occurs;
- the cost associated with responding to a specific contextual change; and
- the number of contextual changes in which the FDO is able to respond.

First, a component that is able to respond to a contextual change that is highly likely to occur is a stronger FDO than a component responding to a contextual change that is less likely. Using the garage case from above, the structural columns provide the ability to respond to demand for additional parking capacity, which is very likely to occur in a city experiencing rapid growth rates. Yet, it is less likely that the safety regulation governing the evacuation rate will change. Therefore, the structural columns are stronger FDOs than the garage exits.

Secondly, a component that can minimize costs associated with responding to the contextual change is a strong FDO. Components minimize the cost of contextual changes by reducing the number of downstream modifications required to respond. In other words, a component able to absorb some portion or all of the contextual change, such that it limits the number of other components in the system that will require costly modifications, better controls the costs associated with embedding flexibility. This characteristic will be examined in more detail in subsequent sections discussing the propagation of change. It is important to recognize that cost influences ranking of FDOs.

Thirdly, the ability of a component to respond to more than one contextual change also characterizes a strong FDO. A component that is an FDO for multiple contextual changes is one capable of providing flexibility over a wider range of uncertainty (as scoped by the considered scenarios). System designers may be able to focus efforts on fewer components that possess this characteristic, rather than diversifying across many components that are only responsible for a single contextual change. For example, de Weck (2004) showed that varying design parameters for a single component, or a set of components, may enable a satellite constellation to respond to redeployment on changing orbits and/or changing elevation angles. The ability of this component to enable flexibility for future demands of changing orbits and elevation angles indicates that it is a stronger FDO than a component which only enables potential changing orbits.

FDO Relationship to System Uncertainty

FDOs relate to system uncertainty via their design parameters. For operational uncertainties (i.e. uncertainties regarding field environment, expected performance, and lifecycles), system designers can alter the performance of a system to respond to unfolding uncertainty by varying component design parameters. Technical uncertainties enter the system through deviations to these variables. To illustrate, a new laptop development may incur uncertainty in the availability of a power source (i.e. battery), which is the component impacted by the contextual change. However, design parameters, such as voltage, current, and form factor, are the levers that enable the system to adapt to the new context. Therefore, it is the design parameters of the component that help system designers consider the potential of a component as a FDO.

To identify which components are FDOs, one must know how the system uncertainty maps to the components and which design parameters are associated with each of those components. Suh (2005) implemented a similar approach considering contextual change to the functional requirements of a system. After identifying the functional requirements that are likely to change, he uses Functional Requirement-Design Parameter (FRDP) representation to map the physical design parameters to the functional requirements. Other approaches to designing flexible systems also recognize the need for mapping the relationship between where to embed flexibility and the system uncertainty which requires the flexibility as noted in subsequent sections.

Existing Approaches for Embedding Flexibility

Several well developed concepts have been applied within risk management and product development literature to inform system designers on embedding flexibility. All of these approaches share common challenges, such as the complications from incorporating numerous design variables and parameters and complex path-dependency/ interdependency. This section discusses how each approach attempts to overcome these challenges to identify FDOs. The use of change propagation techniques and the ESM framework in Chapter 3 motivates the detailed discussion of these approaches here.

Interview Approaches

Interviews are the simplest way to identify where to embed flexibility in a system. SMEs and system stakeholders are surveyed to determine how they would respond to possible contextual changes to the system. SMEs develop intuition about systems given extensive experience with the system itself or in the field of study, which can inform what types of contextual change are likely to occur and what components within the system are best suited to responding to those changes.

This approach is particularly effective for considering a single scenario of change. Given a specific contextual change, the SME is not required to weigh the interacting dynamics that occur for multiple changes. Additionally, the interview method may be sufficient for simple systems, or systems in which the components are decoupled. Simple systems do not exhibit the complex second- or third- order knock-on effects that result from highly connected systems. Higher order knock-on effects challenge SME intuition, which is typically limited to only perceiving direct, first-order, effects.

Interview methods require careful attention to limit the biases, which may become problematic during analysis. The surveys or questions posed during the interview must not lead the SME to anticipated conclusions perceived by the interviewer. Approaches for conducting the interview must consider factors that may influence the responses, such as who is responsible for distributing the survey and potential repercussions for participants. Additionally, caution is warranted to recognize biases from SMEs as well. Those that have a stake in the outcome of the survey may be inclined to only consider responses that benefit their needs. Unintentional biases may also occur, given the SMEs limited perspective of the system. Finally, interview methods sometimes lack desired traceability of the information, biases, and assumptions that feed the analysis. Thus, system stakeholders may trivialize the results of the analysis, since the outputs cannot be clearly traced to the inputs.

Social science literature provides guidelines to alleviate potential problems of bias and documentation within the interview method, thereby making the approach viable to consider. Interviews supplement several of the alternative approaches, most of which use them to gather information for system modeling or representation. All of the subsequent approaches use interviews for this purpose.

Sensitivity DSM (sDSM) Approach

The Sensitivity Design Structure Matrix (sDSM) approach developed by Kalligeros (2006) identifies design parameters that are insensitive to changes in functional requirements. Kalligeros suggests that the components that possess these design parameters are standardized components, which do not change when developing design variants from a common platform. These standardized components are not FDOs. Their counterparts, components sensitive to changes in the functional requirements and changing from variant to variant, are FDOs. Therefore, a slight modification to the algorithm allows the sDSM to identify potential FDOs.

Design Structure Matrix (DSM) & Domain Mapping Matrix (DMM)

The sDSM approach builds upon the traditional Design Structure Matrix (DSM) structure. The DSM methodology emerged in the early 1980s as scholars demonstrated how graph theory can be used to analyze complex engineering projects. (Steward 1981) Steward showed how the sequence of design tasks could be represented as a network of interactions. The DSM materialized as an nxn adjacency matrix of nodes and relations with identical row and column headings. Figure 2-1 displays an example DSM representation of a two-component system (component A and component B). Placing a "1" or "X" in a cell of the matrix represents the existence of a relationship between the two corresponding components.

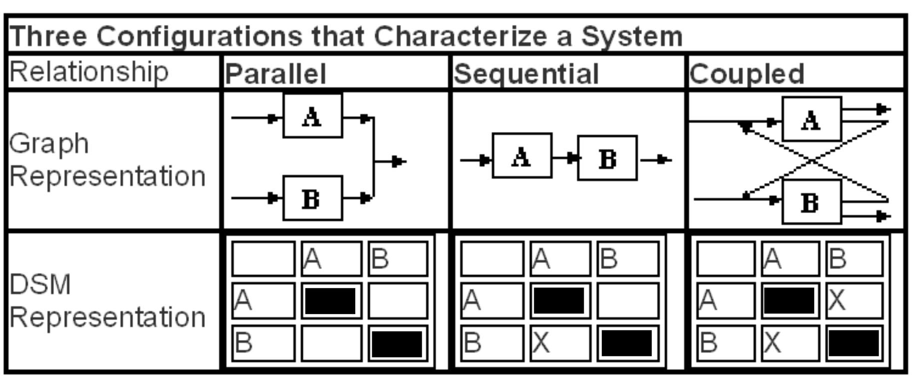

Figure 2-1. Design Structure Matrix Representation (Source: www.dsmweb.org)

A DSM can represent relations among components of a product, teams concurrently working on a project, activities or tasks of a process, and/or parameters within the system. However, the components represented in the DSM must be within a single domain. Five domains describe engineering systems: social, technical, functional, process, and environmental. (Bartolomei 2007) In Steward's model, nodes represent individual design tasks, and relations represent information flows, thereby creating a DSM of the activities or process domain. DSMs have also been used to represent and analyze technical artifacts where nodes represent system components DSM Pimmler and Eppinger 1994; Malmstrom and Malmquist 1998), design and analyze organizations with nodes representing individual members of the team (Eppinger 1997; Eppinger 2001), model the parametric relationships between technical parts (Smith and Eppinger 1997).

Building upon the DSM literature, Danilovic and Browning (2007) present a framework that distinguishes the single- and multi- domain interactions using DSM and Domain Mapping Matrices (DMM). The DMM examines the interactions across domains: the rows represent nodes of one domain, while the columns represent nodes of another domain. Unlike the DSM, the DMM is an mxn rectangular matrix since the rows and columns are not identical. By combining both DSM and DMM methodologies, the analysis results are enriched, providing an expanded view of the system.

The early research is largely focused on product development systems, identifying five domains important to the examination of product development projects. These domains include "the goals domain the product (or service, or result) system; the process system (and the work done to get the product system); the system organizing the people into departments, teams, groups, etc.; the system of tools, information technology solutions, and equipment they use to do the work; and the system of goals, objectives, requirements, and constraints pertaining to all the systems." (Danilovic and Browning 2007) Figure 2-2 depicts a generalized view of the DSM/DMM representation.

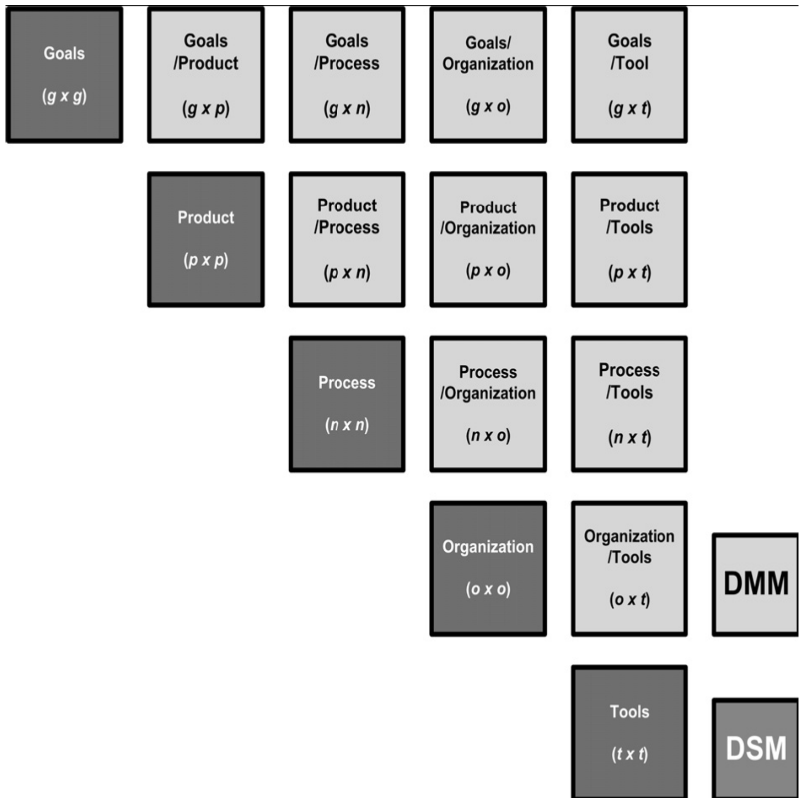

Figure 2-2. DSM/DMM Framework (Source: Danilovic and Browning 2007)

Each element along the diagonal represents a DSM representing the interactions within each of the five domains. The off-diagonal matrices represent the interactions between domains as DMMs.

The DSM/DMM representation is similar to the flow-down matrices of Quality Function Deployment (QFD). (Danilovic and Browning 2007) However, because QFD representation is not easily manipulated for matrix analysis techniques, it is suggested that DSM/DMM methods help to focus the analysis results on interdependencies, interactions, and exchange of information within and across domains.

As expected, the DMM is constructed in the same procedure as a DSM; after all a DMM is a variant of combining two DSMs. Similarly to the DSM methodology, the DSM/DMM framework lacks the capacity to analyze multiple relationships between single node pairs and express time. However, the DSM/DMM methodology provides significant benefits over the DSM framework by expanding the consideration beyond single domain information.

Sensitivity DSM

Kalligeros' sDSM approach begins by constructing DSMs and DMMs to represent the system. The two domains of interest are the functional requirements and the design parameters (technical domain). The technical DSM lists the design parameters along the rows and columns, denoting the coupling of components by entering a "1" in the corresponding cell. Likewise, a DSM is created for the functional domain where functional requirements are listed in the rows and columns and the existence of dependencies are denoted by "1." The DMMs contain information about the traceability of each design parameter to each functional requirement.

Kalligeros then conducts interviews with SMEs to elicit expert knowledge about the sensitivity of each design parameter with respect to each functional requirement for those pairings identified in the DMMs. This sensitivity represents a measure of the percent change in the row variable caused by a percent change in the column variable. The resulting matrix is the sDSM shown in Figure 2-3.

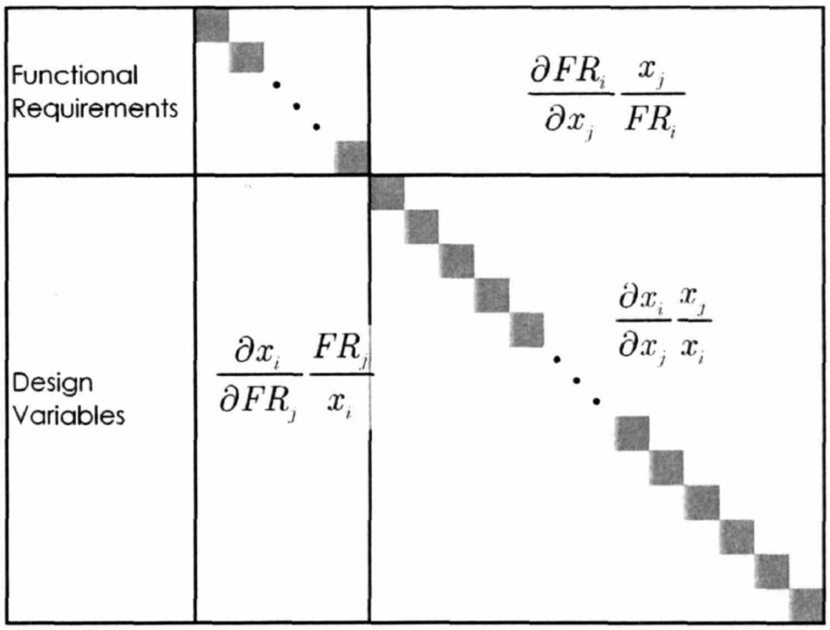

Figure 2-3. Sensitivity Design Structure Matrix (sDSM) (Source: Kalligeros 2006)

He then applies an algorithm to fade-out those parameters that are sensitive to change in order to extract the parameters that are appropriate for standardization. Modifying this algorithm to fade-out parameters that are insensitive to change results in a list of parameters that are sensitive to change, and thus could be mapped to components that are likely FDOs.

This approach enables explicit traceability that is lacking in the interview method. Documenting the mapping of functional requirements to design parameters enables system designers to modify inputs that are challenge based new intuition. Creating the DSMs and DMMs also helps system designers to logically think through the system design when considering opportunities to embed flexibility. Furthermore, the attempt to assign sensitivities to the individual design parameters and functional requirements gives due emphasis to the magnitude, or importance, of the parameter/requirement relative to the systems as a whole. This attribute of the approach enables a filtering effect that highlights where efforts should be focused. Assigning magnitudes to the individual components also allows system designers to fade-out components that are not necessary (due to their insensitivity) in the analysis for identifying FDOs, thereby reducing overall complexity of systems for the analysis.

Disadvantages of this method include the somewhat subjective nature of the assessment of sensitivities gathered via the interview method and the generalization of contextual changes incorporated into a single DSM/DMM representation. Interview questions ask SMEs to determine the sensitivity of the design parameters to changes (not specific) in functional requirements. As noted above, this is thought of as a percentage change in the design parameter due to a percentage change in the functional requirement. Because change for one functional requirement is not the same as change in another, it is unclear if the results are comparable. Additionally, the method does not consider design parameters that do not change significantly given the first-order relationship to the functional requirements, but do create ripples of change throughout the system. Although those changes may be minor, many minor changes may have the same effect as some major changes. Finally, the method fails to provide an explicit mapping of the design parameters to the physical components and is currently limited to only the technical domain.

Change Propagation Approaches

Change propagation approaches seek to understand how a contextual change causes internal changes to propagate through the system. An internal change is defined as a modification or alteration to a component inside the system boundary in response to a contextual change.

Change propagates when the tolerance margins of design parameters associated with the component are exceeded. (Eckert et al 2004) As previously noted, one must know how the system uncertainty maps to the components and which design parameters are associated with each of those components to identify FDOs. Therefore change propagation analysis begins with a DSM, or similar network graph representation, mapping the relationships between components and their design parameters.

Next, contextual changes, called change scenarios, represent the system uncertainties. For each change scenario, the contextual change is introduced to the system through a component, called the change initiator, which is required to respond. The response may be an internal change to the component itself or propagating the change to another component that will undergo an internal change. Note the internal change is not the same for all components in the change path. Rather, the change that is introduced to the initiator may be modified by the change initiator before it passes a change to the next component. The assessment of whether change propagates requires input from a SME or a detailed system model that can determine violations of design parameter tolerances.

Finally, the behavior of each component in the change path suggests potential for embedded flexibility. Components capable of propagating changes to other components are potential FDOs. Eckert et al (2004) classify these components as change multipliers. In contrast, components absorbing change, called absorbers, do not require additional efforts to improve flexibility.

Advantages and Disadvantages of Change Propagation

This approach provides a good analysis of the first-, second- and higher- order effects resulting from the connectivity of the system. Considering each component's relationship with every other component enables traceability within the analysis, such that assumptions of propagation can be challenged if well-documented. Change propagation analysis is particularly suited for identifying FDOs within complex technical systems given the emphasis on understanding change propagation through the various design parameters and physical components. Yet like the sDSM, the current literature only applies the approach to product development, and thus change propagation has not shown its potential to provide results for identifying non-technical aspects of flexibility.

A significant disadvantage of this method is its inability to manage complexity from multiple contextual changes. Similar to the interview method and sDSM, change propagation does not provide a metric for comparing FDOs for many scenarios. Additionally, because the change initiator may be directly connected to more than one component, the change propagation may result in many change paths. This result can be problematic if the change paths merge to create loops. In this case, caution must be taken to avoid "double counting" changes. Also, change propagation fails to give due consideration to the magnitude of the change being propagated. Contextual changes that require minor internal changes to many components may be less significant than those that do not propagate throughout the system, yet incur major change to few components.

Evolution of Change Propagation Analysis

Change propagation analysis has recently evolved through application of the technique to many studies. First, Clarkson et al (2001) presents a framework for analyzing the propagation of change throughout a system using design matrices to calculate the likelihood and impact of change propagating through a rotorcraft design. They call the design matrices change matrices. These differ from traditional DSMs, which represent a directed connectivity graph of the system relationships, in that they represented the change relationships dependent on the contextual change and the change initiator. Thus, a change matrix must be created for each scenario. The disadvantage of this approach is that impacts of the change are not easily known for all cases.

Martin and Ishii's (2002) Design for Variety seeks to measure the amount of change or redesign required for systems to meet future market requirements using the Generational Variety Index (GVI), which is related to the magnitude of the change. By introducing another new metric, the Coupling Index (CI) which describes the connectivity of components, they propose that strong coupling between components will result in more change propagations throughout the system.

Eckert et al (2004) alters the approach by refocusing effort on understanding change behavior of individual components. To do this, they developed a framework to classify change behavior. The classifiers depend on the number of changes being propagated (generated) and received (absorbed) by the component. "Constant are components that are unaffected by change; absorbers can absorb more change than they propagate; carriers absorb a similar number of changes than they propagate; and multipliers generate more changes than they absorb." (Eckert et al 2004)

Suh (2005) extends this effort by introducing the Change Propagation Index (CPI), which measures the total changes propagating "out" of the components less the changes coming "in" to the component. This metric provides a mathematical approach to the previous framework, such that CPI < 0 represented absorbers, CPI = 0 represented carriers or constants, and CPI > 0 represented multipliers.

Giffin (2007) proposed normalizing the CPI with respect to the total number of changes either propagating out or being received by the component. She suggested that normalizing the metric provides a better comparison between components for a given scenario. However, if considering multiple scenarios, the normalization factor is not constant, and thus does not provide equalization for comparison.

While the CPI metric improves the work of Eckert et al (2004), it is limited to counting the changes and unable to reflect this importance or impact. Therefore, Suh (2005) also suggested considering the economic impact of change propagation, called the switch cost. This the cost associated with implementing the internal change to the component. For a physical component, it is the cost of engineering design, additional fabrication and assembly tooling/equipment investment required for the internal change to allow the system to be flexible. However, it is not necessarily constrained to monetary units, it may be in terms of performance output.

Suh considers switch costs for each component identified in the change path. He then normalizes it with respect to the initial investment for that component. The analysis for flexible product platforms then uses this list of switch costs and the classification of change behavior to help identify a list of critical elements to be considered for flexibility.

The switch cost is the first attempt to consider a measure of change magnitude along with change propagation approach. Yet, Suh's conceptualization does not incorporate the magnitude into the change propagation analysis directly. The switch cost for each component is documented only for the individual component, rather than for all downstream costs that result from changing the component itself. Suh also makes the explicit assumption that the components considered in the presented case study are customized for each variant, and thus the switch cost is equal to the initial investment for all components. Therefore, the switch cost does not reflect variations in the magnitude of the contextual or internal change. As noted, "as the magnitude of the … change increases beyond certain threshold, it may require significant structural change, resulting in greater degree of change propagation and possible addition of extra components to accommodate [the contextual] change." (Suh 2005)

Engineering System Matrix (ESM)

Bartolomei (2007) recommends an approach which incorporates the strengths of both sDSM and change propagation analysis. Using his ESM framework for representing a holistic view of a socio-technical system, his nine-step methodology attempts to provide a guideline for further developing a method to identify FDOs, which he calls "hotspots," for socio-technical systems. Because Chapter 3 uses the ESM framework, a brief introduction to the ESM is necessary.

Introduction to the ESM

Bartolomei (2007) developed the ESM in response to the limitations of existing modeling frameworks to represent sufficiently the environmental interactions and influences of time. The methodology reaches beyond the physical, social, and process domains to include the system drivers, attributes, and system evolutions. The reader is encouraged to consult Bartolomei (2007) for a detailed explanation of the ESM.

The ESM methodology includes six domains (environmental or system drivers, social or stakeholders, functional including objectives and functions, physical or objects, and process or activities) used to describe an engineering system. The ESM organizes this information using a matrix structure that can be thought of as a combination of DSMs and DMMs. Figure 2-4 displays a generalized ESM, where the gray submatrices are DSMs and the white submatrices are DMMs.

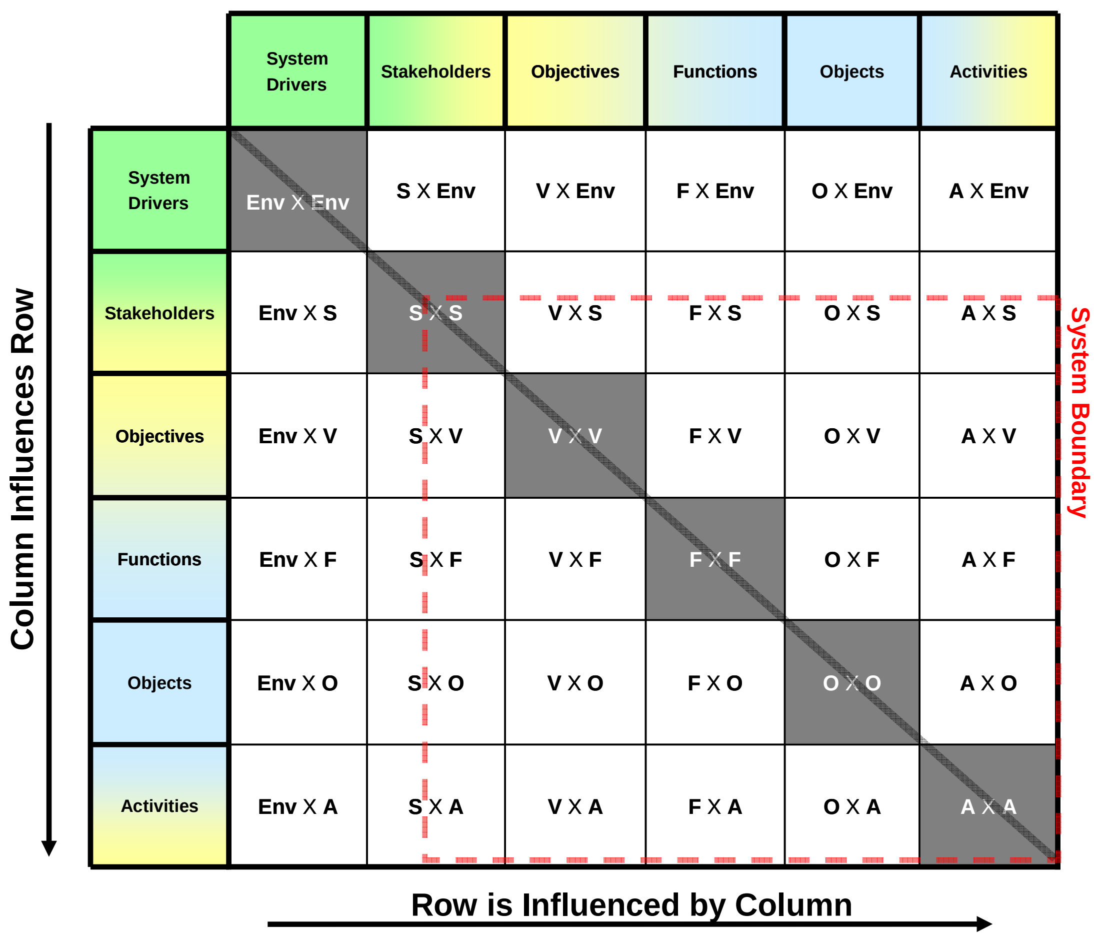

Figure 2-4. The Engineering System Matrix Framework (Source: Bartolomei 2007)

System Drivers represent the non-human components that affect or are affected by the engineering system, or the exogenous factors that influence the system or the system's environment. *Stakeholders* represent the social network of the system and consist of the human components that affect or are affected by the system (including organizations). *Objectives* represent the objectives, goals, and purposes of the engineering system. *Functions* represent the functional architecture of that system. *Objects* represent the physical, non-human components of the system that act or are acted upon. *Activities* represent the processes, sub-processes, and tasks performed by the system. Chapter 4 provides examples of these matrices in the context of a practical application.

Each domain is populated with components and relations similar to the DSM and DMM methodologies. However, in the ESM components and relations in the system can be described with attributes. Attributes define the characteristics for each particular component or relation, which may include specific numeric values, mathematical equations. Attributes for physical components include their design parameters. Additionally, the ESM stores multiple relations in the same matrix, i.e. the matrix is not flat like a DSM or DMM. A DSM or DMM represents only the existence of a relationship between two components in the matrix, typically noted by a "1" or "X" in the corresponding cell. However, the ESM sums the number of defined relationships between the two components. Chapter 3 revisits the representation of multiple relationships in more detail. Finally, the ESM provides a means for storing time information for each component and relationship. This structure enables the ESM to describe system evolution over time.

The ESM is constructed using interview methods and extensive document review. Bartolomei (2007) provides detailed insights and guidelines for building an ESM.

Conceptual Approach to Identify "Hotspots"

Bartolomei (2007) outlined a nine-step process (shown below) to identify system "hotspots." Translating the terminology, hotspots are equivalent to FDOs and the magnitude of hotness reflects the ranking of the FDO when compared to other candidates.

1. Construct the ESM for a particular system
2. Identify sources of uncertainty driving change
3. Define change scenarios
4. Determine the system sensitivity for each change scenario (e.g. Kalligeros' Sensitivity DSM)
5. Identify change modes for each scenario (e.g. Suh's change propagation method)
6. Calculate the cost of change for each scenario (e.g. Suh's cost analysis)
7. Identify Hot/Cold Spots for each scenario
8. Examine Hot/Cold Spots across scenarios
9. Value flexibility using Real Options Analysis

The proposed process seeks to combine change propagation analysis and sensitivity analysis techniques to create a process that considers three factors: 1) the sensitivity of the component to change given potential contextual changes, 2) the ability of a component to propagate change throughout the system (denoted as change modes), and 3) the costs associated with changing the component in response to contextual changes.

Bartolomei represents each of these factors in a three-axis graph shown in Figure 2-5. He then divides the graph into eight parts, each symbolizing the intensity of hotness or coldness. Every component in the social, environmental and technical domains is plotted on the graph for a given contextual change.

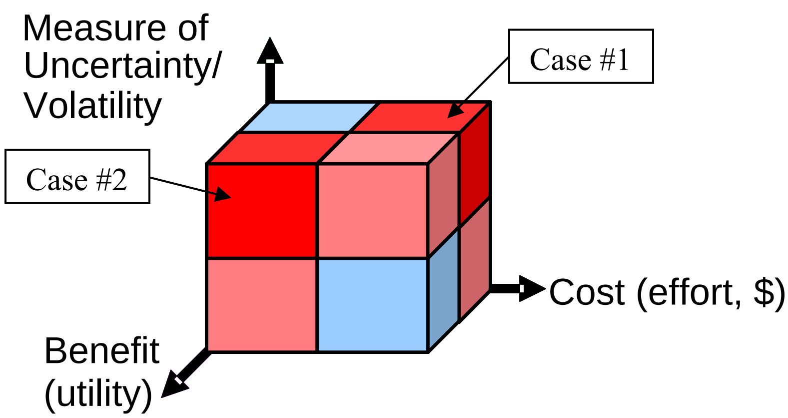

Figure 2-5. Representation of System Hotspots (Source: Bartolomei 2007)

"Measure of Uncertainty/Volatility" refers to the likelihood that the component will change due to the contextual change occurring in the future. This metric is determined using forecasts for the future states of uncertainty. Benefit is measured using Kalligeros' sensitivity techniques to evaluate how much added (or lost) system performance results from changing a component. "Cost" is determined using Suh's switch cost technique.

Therefore, a system hotspot is a component within the system boundary that (1) is *very likely to be desired to change* based on current knowledge of future uncertainties **and** (2) has a *high switch cost* associated with the change, yet *low perceived benefit* to the system performance (Case #1 in Figure 2-5) **or** (3) has a *low switch cost* associate with the change, yet *high perceived benefit* to the system performance (Case #2 in Figure 2-5). (Bartolomei 2007) The intensity of hotness is represented by the coloring of the graph, where red denotes hot and blue denotes cold.

Bartolomei (2007) provides a conceptual thought experiment of the hotspot identification process in his Chapter 7 using a Micro Air Vehicle platform. No formal analysis was conducted, and the process was neither demonstrated nor verified.

Advantages and Disadvantages of the Hotspot Process

The pairing of sensitivity analysis and change propagation analysis, along with estimation of the cost of change, is a positive contribution to the evolution of a methodology to identify FDOs. Also, the ESM framework helps to extend the method to more general analysis, incorporating all domains rather than just technical domain knowledge.

However, the disadvantages of Bartolomei's conceptual process still limit the ability to identify where to focus flexibility efforts. Bartolomei does not indicate how, or if, the three factors are weighted for importance. Some systems may be tolerant of cost changes, yet rigid in terms of system performance, in which case cost may be less important in the determination of hotspots. Additionally, the nine-step process use three factors to determine the classification of hotspots, yet provides no indication of how the hotspots compare to each other (i.e hotspots are not ranked). Available resources may limit the potential to invest in all hotspots, so it is important to be able to rank on a comparable scale. Lastly, although he suggests that the method applies across multiple scenarios, no aggregation technique is presented.

Motivation for a New Approach

The limitations of the above approaches motivate the development of a generalized methodology for identifying FDOs. Table 2-1 assesses the saturation of the approaches presented in this chapter. Chapter 3 proposes a methodology to address:

- Magnitude of change: The method shall consider the magnitude of the change to 1) fade-out insignificant changes to reduce the complexity of analysis and 2) highlight components that undergo extreme change in response to the contextual change.
- Change behavior: The method shall consider the ability of components to propagate change throughout the system. Components that undergo minute change may still propagate large changes downstream.
- Multi-domain analysis: The method shall utilize social and environmental domain knowledge, in addition to technical domain information, to determine system FDOs.
- Traceability / transparency: The method shall provide a framework such that the outputs can be traced back to the assumptions and inputs.
- Ranking: The method shall provide means to compare FDOs to prioritize where system designers should focus efforts to embed flexibility.
- Multiple contextual changes: The method shall allow system designers to analyze multiple contextual changes and aggregate the analysis across the scenarios.

Table 2-1. Approach Saturation Assessment Summary

	Primary Factors		Secondary Factors			
	Magnitude of Change	Change Behavior	Multi-Domain Analysis	Traceability / Transparency	Ranking	Multiple Contextual Changes
Interview Method			✓			
Sensitivity Analysis	✓				✓	
Change Propagation Analysis		✓			✓	
Hotspot Analysis*	✓	✓	✓	✓		
New Method for Identifying FDOs	✓	✓	✓	✓	✓	✓

*Bartolomei (2007) provides a conceptualization only.

Chapter Summary

This chapter presents the state-of-the-art approaches to identifying where to embed flexibility in a system. A review of the advantages and limitations of each approach provides the motivation for the new methodology presented in Chapter 3.

Chapter 3: Methodology for Identifying Flexible Design Opportunities

This chapter proposes a screening methodology to help system designers identify FDOs. The desire of system designers and customers to produce systems that are flexible, such that the product can continue to deliver benefit (or protect from losses) given future uncertainties, requires effort to embed flexibility in individual components that together make up the system. Specific change scenarios are defined to specify the set of uncertainties, while physical components within the system are considered for selection as candidates to improve flexibility.

The method utilizes principles of change propagation analysis and information extracted from the ESM framework to assess a score for each major component in the physical system. A high-scoring component is considered to be a potential candidate for flexibility, whereas a low-scoring component is not. Then, physical components are ranked from the highest to the lowest score to indicate which components are likely interesting FDOs.

This chapter introduces a new metric: the Desired Flexibility Score (DFS). It measures the component's influence on the system as a whole in terms of its potential to propagate change and the cost of change the component given the specified uncertainties. The formulation of DFS is presented in this chapter and is demonstrated in a case study in Chapter 4.

FDO Methodology Overview

This methodology is designed to be utilized in the early stages of product development to screen physical components in the system for potential candidates for embedded flexibility. The use of change propagation tools and the need to estimate costs associated with various change states suggests that the method will be less accurate when used during design conceptualization, however recognizing the need to incorporate flexibility is very important early in the design. The method can also be used to readdress the need for flexibility to new uncertainties later in the product life-cycle.

The methodology uses the ESM framework (Step 1), which represents the system as a network graph of nodes (components) and edges (relationships). It begins by defining the set of uncertainties to which the system should be flexible (Step 2). Then, each possible change resulting from each uncertainty (Step 3) is analyzed as it propagates throughout the system (Steps 4-5) incurring cost for each component impacted by the change, known as the switch cost (Step 5). Each component is assessed based on its contribution to the change propagation and switch cost using the newly introduced metric (Step 6). Finally, all components are ranked to indicate the highest-scoring components; these components are potential FDOs (Step 7). Subsequent sections explain each step in the methodology in detail.

The methodology exhibits two major contributions: the combination of sensitivity and change propagation techniques and scalability. As discussed in Chapter 2, sensitivity techniques emphasize the magnitude of change in performance due to each component, while change propagation techniques assess the change behavior (multiplier, absorber, or carrier) of each component. These techniques used together result in an improved understanding of where to embed flexibility, addressing both magnitude and propagation of change influencing each component.

This methodology is scalable in that it can scale to analyze large, complex systems, in contrast to previous approaches that are not. While developed and demonstrated using a simple system, this methodology can be applied generally to systems of all sizes and complexities by:

1. adjusting the levels of abstraction used in the ESM,
2. iterating the analysis for increasing levels of abstraction, and
3. managing the complexity of the required human-input.

Higher levels of abstraction can decrease the complexity of the analysis. This process reduces the number of components included in the search for FDOs. System designers need to determine what level of abstraction is required to sufficiently answer the question being asked (i.e. do they expect the FDO to be at the subsystem level or component level?). For example, system designers interested in maintaining a power budget must know how power is transferred and used throughout the system. In some cases, knowing that a particular subsystem requires more power may be sufficient, in which case the subsystem level of abstraction suffices. However, it may also be important to understand what component in that subsystem requires excessive power, thus necessitating component-level of abstraction. Using the ESM, system designers may be able to aggregate large systems to higher levels of abstraction by applying clustering techniques. Step 1 below discusses these techniques and how they can potentially help to reduce system complexity.

Iteration is another approach to managing complexity of large-scale systems. First analyzing the system at higher levels of abstraction identifies subsystems as candidate FDOs. Then, system designers may elect to further decompose those candidate subsystems into component-level detail. Repeating the identification methodology, the second iteration results identify components as candidate FDOs. By completing the first pass at higher levels of abstraction, the list of subsystems requiring decomposition is reduced, saving both time for information collection and computational time and power necessary for searching large ESMs.

Finally, it is important to manage the complexity of the human input for large systems. Sensitivity approaches and change propagation approaches require human input to assess the magnitude of change, whether or not it propagates, and the consequent cost. SMEs may be overwhelmed by these factors for large-scale systems containing many interacting subsystems and components. Therefore, decomposing the interactions (or relationships) simplifies the process of thinking through these factors. Steps 3 and 4 discuss how to filter the ESM for particular relationship types. This allows the SME to consider each relationship type as a separate network. For example, an SME can consider power interactions independent of data transmissions. Using this separation, the SME can logically think about what changes occur to each component in the system. Furthermore, this approach first eliminates components that are not included within the particular relationship type network. Thus, the SME is asked to evaluate a filtered list of components, rather than all the components in the system. The methodology aggregates the individually analyzed decompositions into a higher level result, providing system designers information about where to embed flexibility such that the system responds to changes in all relationship types.

Step 1: Construction of the ESM

The first step to identify opportunities to embed flexibility is to construct the ESM representation of the system. This step organizes the information known about the system into a structured framework for the analysis method. As noted in Chapter 2, the ESM framework can be used to represent a holistic view of a system. Each submatrix within the ESM provides input necessary to determine each component's influence on the system as a whole. Construction of the ESM requires extensive data collection through document review, surveys, and key stakeholder interviews. Bartolomei (2007) contains a detailed discussion of how to create an ESM. A summary of the process is included below:[5]

1. Identify the system of interest and define the system boundary.
2. Define the objectives for analysis.
3. Collect data.
4. Code data.
5. Organize coded data in systems-level modeling framework.
6. Examine model for missing/conflicting data and resolve.
7. Iterate for evolving systems as time progresses.

Bartolomei and a team of MIT researchers developed a software tool to simplify the process of representing a complex system in the ESM framework. System Modeling and Representation Tool (SMaRT).[6] It can represent large data sets containing time evolutions and attributes describing components and relationships within a system. Rather than representing only the existence of a relationship between two components, SMaRT can represent multiple, descriptive relationships. It also provides a filtering

[5] The ESM construction process is summarized from pages 108-118 of Bartolomei (2007), where he uses the MAV case study as an example for demonstration. The reader is encouraged to consult the source for additional information on the ESM. This research uses the ESM as a framework for the input required for the FDO analysis, and thus the focus remains on the analysis rather than the ESM construction.
[6] SMaRT is a software application developed by MIT for research use only. The tool also allows document traceability of data entry and other additional advantages to the construction of ESMs. Bartolomei (2007) provides a description of several features of the software. Sylvester (2007) further explains the development of the SMaRT software architecture.

algorithm to enable analysts to view different system representations based on time and/or specific relationship types. Then, the ESM enumerates the entries in the matrix to reflect the existence of multiple relationships between components, whereas traditional DSM software tools use a “1” or “X” to denote the existence of any and all relationships.

The software significantly reduces the time required to organize data and populate the ESM. Traditional DSM software represent only a single time instantiation, and thus evolution requires the construction of multiple DSMs. Additionally, because the DSM indicates only the existence of at least one relationship between two components, analysts desiring to understand the interactions for multiple relationship types require a DSM for each relationship type. The existence of multiple relationships between to components may also indicate a stronger relationship, which suggests the need for weighting those interactions between the components. Another important time-saving feature of the SMaRT is its ability to represent the information in various views, thereby simplifying the data entry process. SMaRT consists of a matrix-view that appears similar to traditional DSMs, where the row headers and column headers are identical lists of components in the six classes. This view normally requires duplication of effort to generate the rows and columns and can sometimes be very confusing when populating the cells with information. SMaRT also provides a list-view in which the components are listed by class. Relationships are easily created using a click-and-drag mouse operation, after which they are displayed as subsets of the components in the list. SMaRT allows analysts to toggle between the views, automatically updating the information reflected in both formats.

In the absence of SMaRT or similar software, simple Excel spreadsheets can be utilized to represent the system; however the time required for data entry may be excessive for large, complex systems. It is important to consider two factors prior to constructing the ESM: system complexity and level of information available.

Complexity of the ESM

System complexity results in complex ESMs. Large-Scale Technical systems contain many components in the technical domain, which may increase the social and environmental domains as well. The result is a very large and complex ESM containing many components.

However, representation of small-scale systems may also produce complex ESMs due to high connectivity between components, resulting in many relationships between a few of them. Simon (1996) defines system complexity in terms of the connectedness of the components. Highly connected systems have highly connected components. This connectivity of the components in the system, or between systems, may result in “knock-on effects” when change is introduced to one or more components within the system, causing the change to propagate up or downstream throughout the entire system. (Eckert et al 2004)

As complexity of the system increases and more components and relationships are included, the ESM will grow exponentially large and increase in density. However, by dividing a large, complex ESM into submatrices, with traditional DSM along the diagonal and DMM off-the-diagonal, matrix manipulation can be simplified. (See the Introduction to ESM Framework discussion in Chapter 2.) Each step in the methodology to identify FDOs requires information contained in these different submatrices in the ESM.

This knowledge of where the necessary information resides within the ESM allows a spotlight effect, or filtering, to focus on only the relevant information for each step. Filtering the matrix reduces the computational time and power required to analyze the matrix and simplifies the required human input.

Level of Abstraction in the ESM

Furthermore, it is important to consider the level of abstraction available for analysis. Early in the design process, information regarding specific physical components may not exist, thus requiring the ESM to be constructed of higher-level information such as subsystems. Likewise, information about stakeholders may reside in the organization or team rather than individual persons. ESMs containing all levels abstraction can be analyzed using this method; yet, the resulting FDO analysis will be at the same level of abstraction included in the ESM.

Using higher levels of abstraction may result in desirable simplification of the ESM. A helpful tool for converting to higher levels of abstraction is clustering algorithms. Traditionally used in DSM research, these techniques reorder the rows and columns of the matrix by grouping highly-related components into clusters, allowing easier identification and examination of the interfaces between the clusters. The clusters contain most, if not all, of interactions (i.e. ticks) internally and the interactions between clusters is eliminated or minimized. (Fernandez 1998; Sharman and Yassine 2004; Yu et al. 2003)

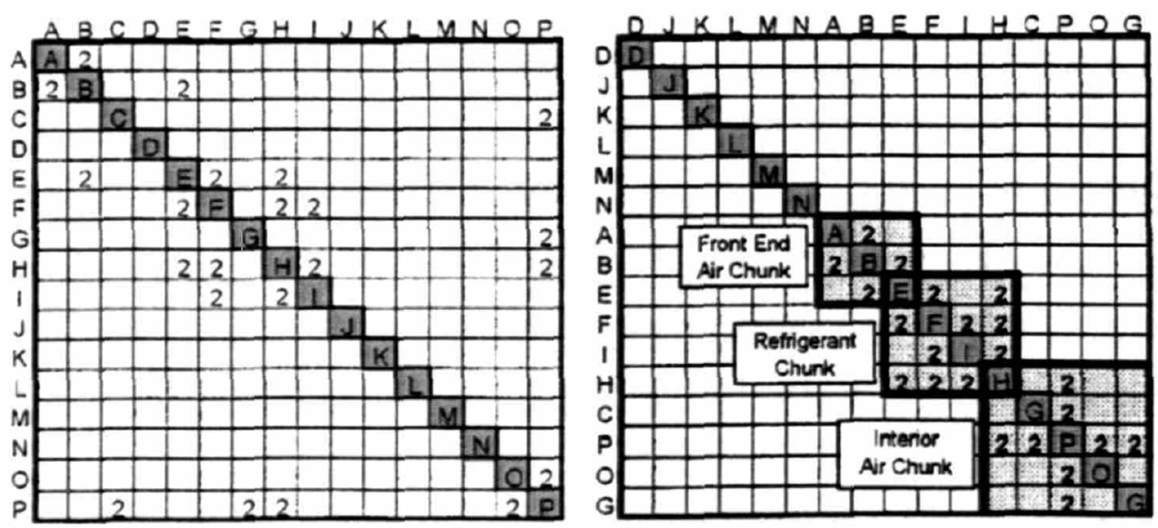

Figure 3-1. Example of Clustering: Original DSM (left) and Clustered DSM (right) (Source: Browning 2001)

The clusters represent higher-levels of abstraction, such as teams/organizations in the social domain or subsystems in the technical domain. While simplifying the ESM provides analysis and data entry advantages, interactions within clusters may provide valuable information when considered in the system context for different types of analysis. For example, when attempting to identify FDOs as in the following analysis, clustering physical objects into subsystems may not be useful if the resulting subsystems all interact at the higher level. Therefore, clustering may only be useful for components are not perceived to have significant influence as an individual, such as the use of the organization level of detail to represent teams of individuals with little decision making authority for the system.

Step 2: Identifying the Change Scenarios

Step 2 identifies what changes are likely to occur in the future. It is accomplished by defining change scenarios, which are events or actions resulting from the change of a single or a combination of multiple system drivers. Each change scenario is defined by the:

1. identification of uncertainties affecting a system driver and
2. probability that the system driver will change in the future.

Recall from Chapter 2 that the system drivers represent the environment in which the system must exist, and thus are uncertain over time. Therefore, these change scenarios are related to the set of uncertainties for which the system should be flexible.

Uncertainty in System Drivers

Designers should carefully consider the uncertainty associated with each system driver and then select those most critical to include in the analysis. A single system driver may have multiple uncertainties. For example, if a designer is considering developing a new laptop, a likely system driver impacting the system is the availability of power source technology, i.e. the battery. Technology trends have shown significant improvement in Lithium-Ion batteries in the past several years, and thus batteries available for incorporation into the design today are soon likely to be obsolete, and potentially unavailable. This uncertainty may have many possible outcomes: allowing increased energy densities means that either the same amount of power can be packaged in much smaller battery cells or more power packaged in the same size battery. Therefore, two potential uncertainties driven by one system driver (new battery technology trends) are the size of the battery (and perhaps the laptop) and the availability of power to the laptop from the battery.

Probability of the Change Scenario Occurring (P_{cs})

The likelihood of the change scenario occurring in the future, P_{cs}, is defined as the likelihood that the system driver(s) actually changes. P_{cs} is used as a weighting factor later in the analysis for the aggregation of multiple change scenarios. P_{cs} can be estimated by considering uncertainty models or future forecasts of how the uncertainty will unfold.

Managing Complexity of Change Scenarios

Upon first look, the task of identifying change scenarios can be daunting, especially for complex systems. Change scenarios can be simplified by decomposing multiple system drivers, and/or multiple uncertainties associated with each system driver, into individual change scenarios.

A simple change scenario includes a change to only one system driver with a single associated uncertainty. In this case, it will be easier to assess the P_{cs} and trace the propagations of change throughout the system in the next steps of the analysis. Simple change scenarios are ideal for the FDO methodology.

In practical application, however, change scenarios often include multiple system drivers, which may or may not be changing at any given time. Using the laptop example, consider a scenario involving two possibly changing system drivers: battery technology (SD1) and display monitor technology (SD2), both of which impact the power design of a laptop. The complexity of the change scenario requires a state representation for each possible state. The example change scenario including two system drivers has four possible states:

1. SD1 changes, SD2 changes
2. SD1 changes, SD2 does not change
3. SD1 does not change, SD2 changes
4. SD1 does not change, SD2 does not change

The analysis then requires conditional logic to allow the analyst to define a probability of change for each state. Alternatively, each state could be represented as an individual change scenario, each with its probability of occurrence. However, this alternative approach increases in the number of cycles and thus time required for the analysis. These two approaches will solve this initial challenge, however tracing the propagation of change throughout the system in later steps may prove challenging given the coupling effects created by the more complicated change scenario. Caution should be used to prevent “double counting” of factors influenced by both system drivers within a single state.

Providing very specific change scenarios further simplifies future steps in the analysis and improves accuracy in the result. Designers should therefore be as specific as possible when defining the change scenario. Revisiting the previous example, when defining a change scenario concerning the availability of a battery for the laptop design, the change scenario definition should include information about the potential voltage, available current, and dimension of form factor size if known. This information will help when considering the possible propagation of the change and cost estimations in later steps of the analysis.

Step 3: Identifying the Change Initiators and Relationship Types

This step identifies where and how the change will enter the system. Each change scenario defined in Step 2 is analyzed individually. First, the ESM is used to trace all components related to the system driver defined in the change scenario. This information is contained in the first row and first column of submatrices in the ESM, as shown in Figure 3-2, thereby eliminating the need to search the entire ESM.

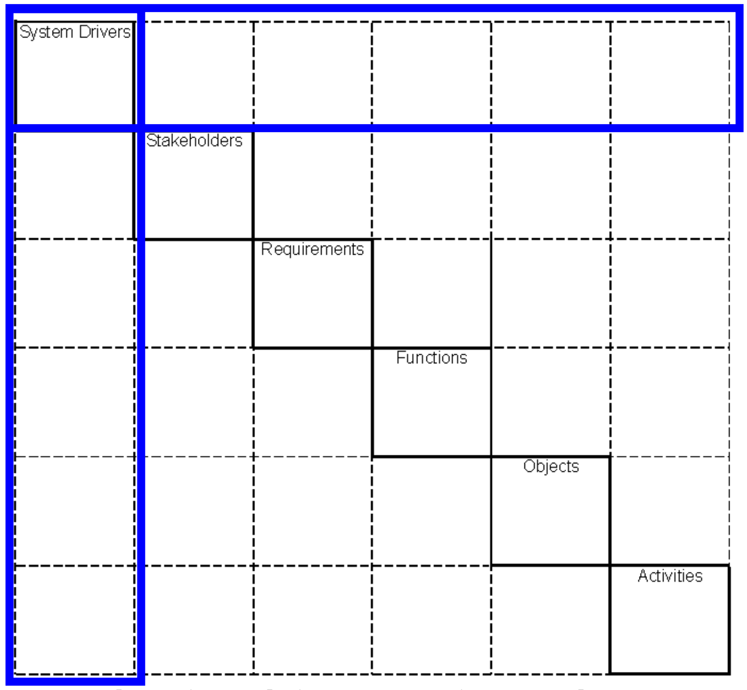

Figure 3-2. ESM Submatrices Relating System Drivers to Other System Components

Change Initiators/Relationship Type (CIRT) Pairings

All components sharing a direct relationship to the system driver are potential change initiators. A change initiator is a component where the change enters the system. From the previous example regarding laptop, the mapping of a change in battery technology (system driver) to the battery itself (physical component) indicates that the battery is a potential change initiator for the change scenario. Each change scenario may have more than one change initiator. All change initiators should be included in the initial list. However, not all change initiators may be activated in response to the change scenario occurring. Thus, the next step is to estimate the probability of the change initiator activating. This can only be done given an understanding of how the system works and the relationship types that will be influenced in response to the introduction of the change.

Each change initiator is related to the system driver through a specific relationship type, which may not be the same for all change-initiator/system driver pairings. Recall from Chapter 2, relationship types are domain-specific. Examples include information transfers, mass flows, and power connections in the physical domain or funding, communication frequency, or location proximity in the stakeholder domain. Therefore, it is necessary to list all these relationship types when identifying the change initiators.

The exclusion of the change initiators – relationship types (CIRT) pairings potentially limits the analysis outcome. Failing to include a potential change initiator may underrepresentation the possible change paths. This outcome may be intended or even appropriate if the designer perceives that the changes introduced through the eliminated change initiators are immediately absorbed by either the initiator or a connected component. In this case, the result is a filtered outcome, giving significance to only the included change initiators and/or relationship types, resulting in a filtered subgraph for the remainder of the analysis.

Probability of CIRT Activation, $P_{i,j}$

The probability of a change occurring for each relationship type, given the change scenario occurs and the change initiator is activated, is assessed for each change initiator. This step is important because it allows the analyst to eliminate unlikely change initiators, and thereby reduce the number of analysis cycles. To simplify the burden placed on the analyst, a matrix can be created for each change scenario using the lists of change initiators and relationship types as displayed in Table 3-1.

Table 3-1. Change Initiator/Relationship Type Matrix

Relationship Types (columns); Change Initiators (rows)

	Type 1	Type 2	•••	Type M
Initiator 1				
Initiator 2		$P_{i,j}$		
⋮				
Initiator N				

To clarify, $P_{i,j}$ is the likelihood that relationship (j) is effected when change initiator (i) is activated in response to the change scenario. Consider the laptop example again. The change initiator is the battery. Possible relationship types between the system driver and the change initiator include power transfer, spatial constraints (size), and hardware interfaces (wiring/interface connections). If the change scenario specifies a change in only the internal chemistry of the battery, then the outer casing of the battery may not be altered at all. Thus, the $P_{i,j}$ for the power relationship type and battery may be high, say a probability of 1.00 or 0.95, while the spatial constraints and hardware interface relationship types may be virtually unaffected, say 0 or 0.05.

To reduce the number of analysis cycles, the analyst may elect to omit the CIRT pairings that are unlikely to occur. As a note of caution, the desire to oversimplify the analysis by only including probabilities of 1 or 0 may cause discrepancies in the final results due to using equal probability of activation for all change initiators. In reality, system designers familiar with the system typically have experience or information allowing them to differentiate between change initiators.

Again, the simplest case for a given change scenario includes only one change initiator. However, if multiple change initiators are included, then the analysis must consider the possible combinations of change initiators activating. Each combination can then be represented as a state, similar to the way in which change scenarios with multiple system drivers is handled in Step 2. Conditional logic is required to implement the analysis for multiple states. The scope of this research is limited to demonstrating the simple case of only one change initiator activating for each change scenario.

Step 4: Reducing the ESM to Subgraphs

Very large ESMs require substantial time and computation to manipulate mathematically. Also, because human input is required for change propagation analysis (Step 5), it is important to reduce the ESM by removing components unrelated to the change scenario for the change propagation analysis, thereby creating a subgraph of the system. This subgraph is not a new representation of the system, but rather the components unrelated to the change scenario are merely faded out to reduce the complexity of the graph.

Components that are not connected to the change initiator can also be eliminated. Finally, if multiple CIRT pairings are included, it may be useful to create individual subgraphs for each relationship type. This technique is demonstrated in Chapter 4, yet caution should be used to implement it only if the relationship types are independent.

This step is repeated to create subgraphs for each change scenario and then for each CIRT pairing within the change scenarios. Therefore, if three change scenarios are considered, each with only one change initiator and four relationship types, the result is twelve subgraphs. Steps 5-6 will each be repeated for every subgraph, requiring twelve iterations. Step 7 will then aggregate the resulting analysis of each subgraph into a single ranking of the system FDOs. The compounding of the number of iterations required, as the number of change scenarios and CIRT pairs increase, is troublesome. However, the creation of the subgraphs significantly simplifies the change propagation analysis, making the human-input tractable for complex system analysis, as will be observed in Chapter 4.

Step 5: Change Propagation Analysis

Recall that the ESM graphs depict the system flows only, with no indication of uncertainty and/or change. Step 5 analyzes the propagation of change throughout the system given the change scenario occurs and the various CIRT pairings are activated in response. This step will be repeated for each subgraph generated in Step 4. It will be decomposed into four actions: indication of change propagation, estimation of probability of change, assignment of switch costs, and calculation of expected expense. A simple example illustrates the process. Consider the system of components with relationships displayed in Figure 3-3.

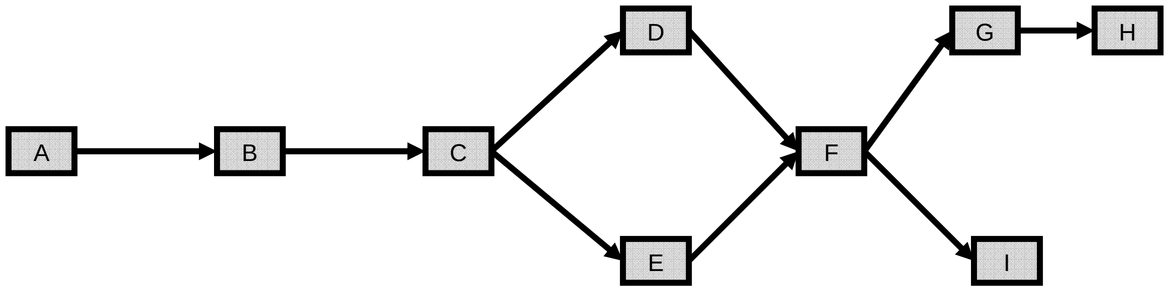

Figure 3-3. Simplified Example System for Methodology Illustration

Change Propagation/Change Graphs

The analyst must indicate the change propagation throughout the system, starting with the change initiator, in response to a change, Δx. As noted in Chapter 2, a change propagates if it violates the tolerance/margin. Note that the incoming change is not the same for all components as it flows through the system, and thus Δx is not constant. Therefore, it is possible the system contains natural change absorbers that prevent the change from propagating down the system flows indicated by the ESM. Figure 3-4 shows how the change propagates throughout the system when component "B" is the change initiator.

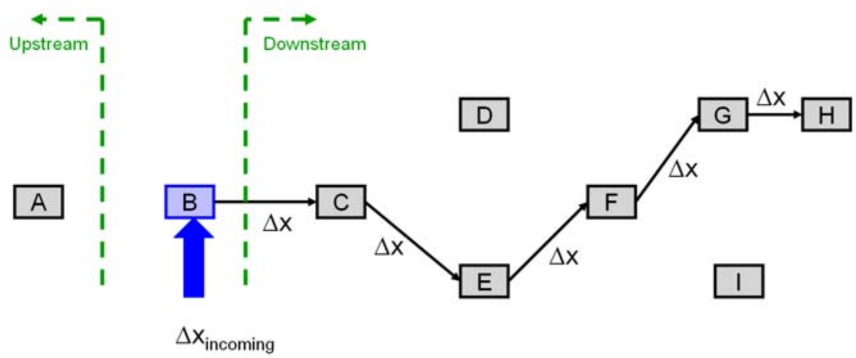

Figure 3-4. Change Graph for Example System

Notice that the change does not propagate upstream to component "A." Also, component "F" acts as a natural change absorber for component "I," but still passes a change to component "G." Component "I" can then be removed, or faded, from the subgraph. Likewise, component "C" propagates a change to component "E," yet shields component "D," which can also be removed. This new graph is called the change graph, and it may differ from the ESM by change in directionality or the nonexistence of relationships.

Probability of Change Propagation (P_c)

Next, the analyst must indicate the likelihood that the incoming change, Δx, violates the component tolerance/margin for each component. This likelihood is known as the probability of change propagation, P_c. It is estimated by asking the question: "What is the likelihood that component "C" will be changed given the incoming change, Δx?" Because some changes are more likely to propagate than others, P_c acts as a weighting factor. If the P_c is sufficiently small, the propagation of change may be negligible and the analyst may choose to remove/fade out the component, and its associated change branch. Table 3-2 provides an example of P_c estimations for the example system for one particular CIRT pairing and change scenario.

Table 3-2. P_c Estimations for Example System

Component	P_c
A	0.0
B	1.0
C	0.5
D	0.0
E	0.1
F	0.4
G	0.8
H	0.7
I	0.0

The analyst may choose to weight all probabilities of change propagation equally, using P_c equal to 1. In this case, the change will always propagate. The solution will be deterministic. However, P_c not equal to 1 represents the possibility that the change may not propagate. This situation will complicate the analysis slightly because the propagation of change then depends on prior events. For example, if component "F," which has a 60% chance of not changing, does not change in the future, then "G" and "H" will not need to change in response. To include this possibility in the analysis, Monte Carlo simulations with conditional logic are required to reach a statistical solution.

Component Switch Cost (SC)

A switch cost (SC) must be assigned to each component remaining in the change graph. Recall from Chapter 2 that this is the cost associated with modifying/replacing the component in response to the incoming change. Table 3-3 displays sample switch costs for the example system to continue the illustration.

Table 3-3. Estimated Switch Costs for Example System

Component	SC
A	0
B	20
C	10
D	0
E	50
F	10
G	0
H	50
I	0

Note that the incoming change is specific to many factors including the specific change scenario, the change Δx introduced to the specific change initiator, the CIRT pairing, the components proceeding the component in the change graph, etc. Therefore, a component's switch cost is not constant for all subgraphs, and may not even be constant for a single subgraph if all P_c are not equal to 1. A detailed cost model and lookup table would be required to consider this very complicated case, which is beyond the scope of this research. Chapter 4 demonstrates this step using the assumption that the switch costs are path independent (i.e. independent of prior events) due to the lack of availability of a detailed cost model to generate the required input.

Component Expected Expense (CEE)

The Component Expected Expense (CEE) is a measure of how each component in the change graph contributes to the overall change required to the system. First, it is calculated for each subgraph generated in the previous steps. This is the CEE for a specific CIRT pairing given the occurrence of the change scenario (CEE_{CIRT}). Assuming switch costs are path independent as previously noted, a deterministic calculation of $CEE_{CIRT,i}$ is defined by

$$CEE_{CIRT,k} = \left(P_{c_k} \times SC_k\right) + \sum_{l=k+1}^{n} \left(P_{c_l} \times SC_l\right)$$

for component k, with n downstream components in the change graph. Figure 3-5 shows the calculation of the CEE_{CIRT} for component "F" in the example system.

$$CEE_{CIRT,F} = (0.4 \times 10) + [(0.8 \times 0) + (0.7 \times 50)] = 7.5$$

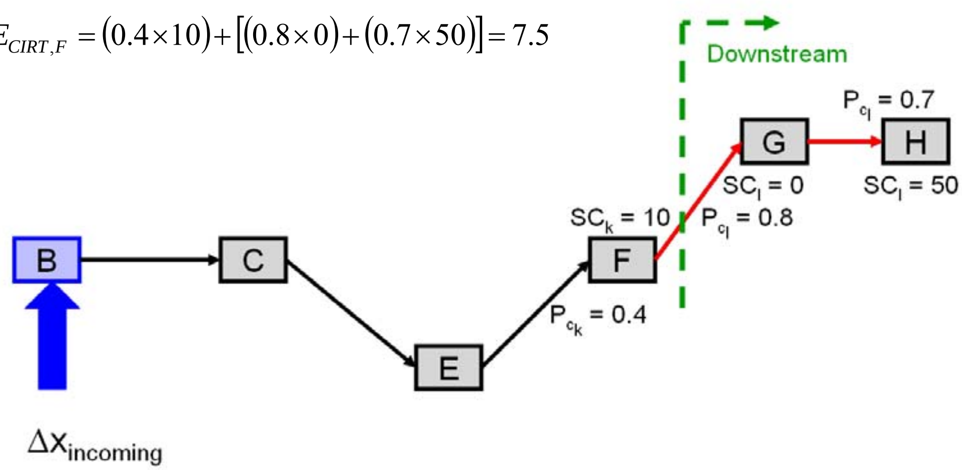

Figure 3-5. CEE_{CIRT} Calculation for Example System

However, if the switch costs are not path independent, then the CEE must be statistically solved using Monte Carlo simulation and a lookup table for the assigned switch costs. For example, one possible outcome may include a change to components "B" (the change initiator), "C," "E," "F," and "G." Another possible outcome may include a change to only components "B," C," and "E," where component "E" acts as a change absorber.

The CEE for every possible outcome can be calculated using the deterministic definition above, where all Pc are equal to 1. Therefore, the CEE for each outcome is defined by

$$CEE_{k_{Outcome}} = (SC_k) + \sum_{l=k+1}^{n} (SC_l)$$

where the switch cost depends on the outcome, thereby requiring the lookup table of path dependent switch costs, and n is the number of downstream components in the change graph. Then, the mean CEE can be calculated for a given number of runs (h), providing a statistically derived CEE for each subgraph. As previously stated, this approach is beyond the scope of this research, but should be investigated in future efforts.

$$CEE_{CIRT,k} = \frac{1}{h} \sum_{y=1}^{h} \left[CEE_{k_{Outcome}} \right]$$

Another note regarding path dependency is required at this point. At first glance, the deterministic CEE calculation appears similar in approach to an Expected Value (EV) calculation in Decision Tree analysis. (de Neufville 1990) However, there is an important distinction. Components in the change graph may have multiple incoming changes, making a roll-back technique impossible without modification of the change graph. Figure 3-6 presents one such case using the example system from Figure 3-4.

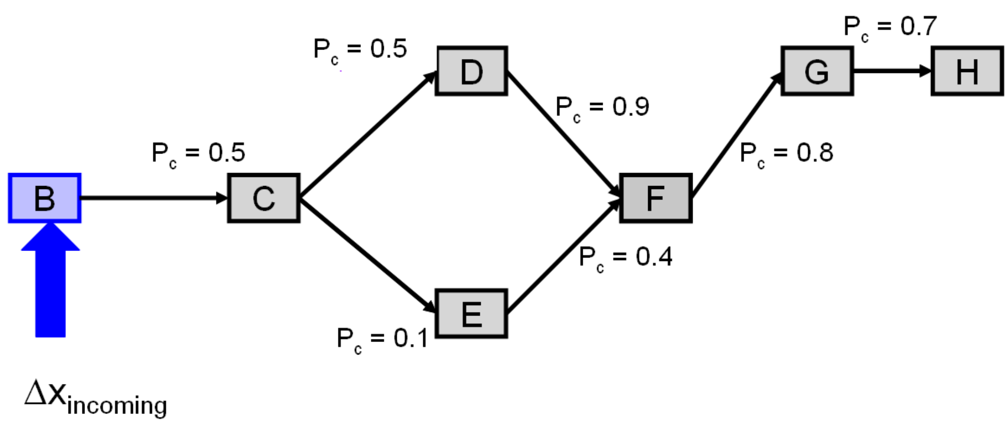

Figure 3-6. Modified Change Graph for Example System

There are many possible ways of handling this challenge. One approach is to attempt to decompose the CEE calculation by considering the portion of the switch cost associated with each incoming change. This approach is depicted in Figure 3-7.

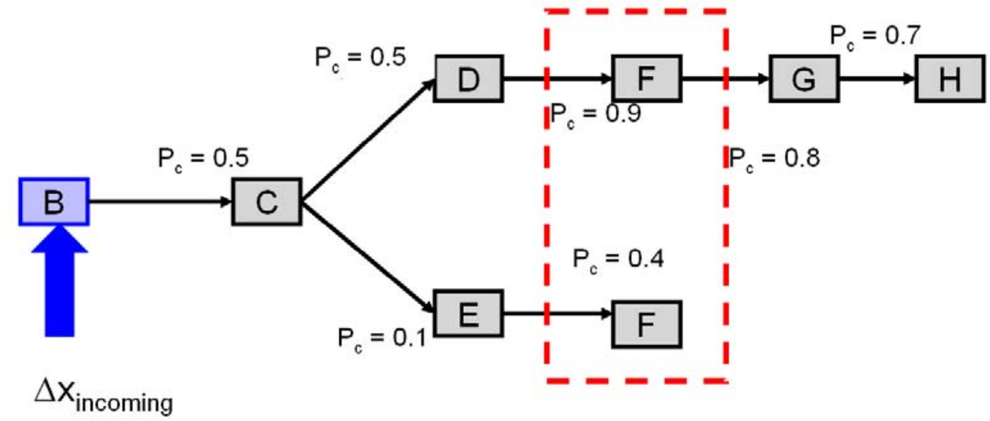

Figure 3-7. Possible Approach for Applying Roll-Back Calculations

However, this approach may require additional conditional logic to govern how the downstream component costs are then calculated and included in the calculation of upstream components (ie which component branch receives the downstream branch). Ideally, the downstream costs can also be decomposed, yet extreme caution must be taken to avoid "double-counting."

Then, the aggregate CEE for the change scenario (CEE_{CS}) is determined by

$$CEE_{CS,k} = \sum_{i=1}^{N}\sum_{j=1}^{M}\left(P_{i,j} \times CEE_{CIRT,k}\right)$$

where N is the number of change initiators, M is the number of relationship types, $P_{i,j}$ is the probability that the CIRT is activated in response to the change scenario (see Table 3-1). The CEE_{CS} is calculated for every component in the system for each change scenario. Given that only one change scenario/CIRT pairing was illustrated in the example system, the CEE_{CS} for each component is equal to the CEE_{CIRT} with $P_{i,j}$ equal to 1. Table 3-4 presents the CEE_{CS} for each component in the example system using the change graph depicted in Figure 3-4.

Table 3-4. CEE_{CS} Calculation for Example System

Component	CEE_{CS}
A	0
B	37.5
C	17.5
D	0
E	12.5
F	7.5
G	3.5
H	3.5
I	0

Step 6: Calculation of the Desired Flexibility Score (DFS)

This step presents a one-dimensional metric that allows direct comparison of the system components in terms of desirability for embedded flexibility efforts. The Desired Flexibility Score (DFS) measures the component's influence on the system as a whole in terms of its potential to propagate change and the associated switch cost given the specified change scenarios. The DFS is calculated by

$$DFS_k = \sum_{z=1}^{q} \left(P_{CS} \times CEE_{CS,k} \right)$$

where q is the number of change scenarios included in the analysis and P_{cs} is the probability that the change scenario occurs. The DFS is calculated for every component in the system. Components not included in any of the analyzed change scenarios, as a result of fading out the components that are not connected to the ESM subgraphs or are removed from the change graph, have DFS = 0. These components are not candidates for flexibility efforts since they remain unchanged given the specified uncertainties. In contrast, high-scoring components are strong candidates for embedded flexibility, known as FDOs.

Step 7: Recognizing FDOs

Finally, a chart depicting the components versus their respective DFS identifies the best FDOs. The components with high scores are the FDOs. The components with lower scores contribute less to the overall system flexibility. Figure 3-8 displays the results from the example system illustrated in Step 5.

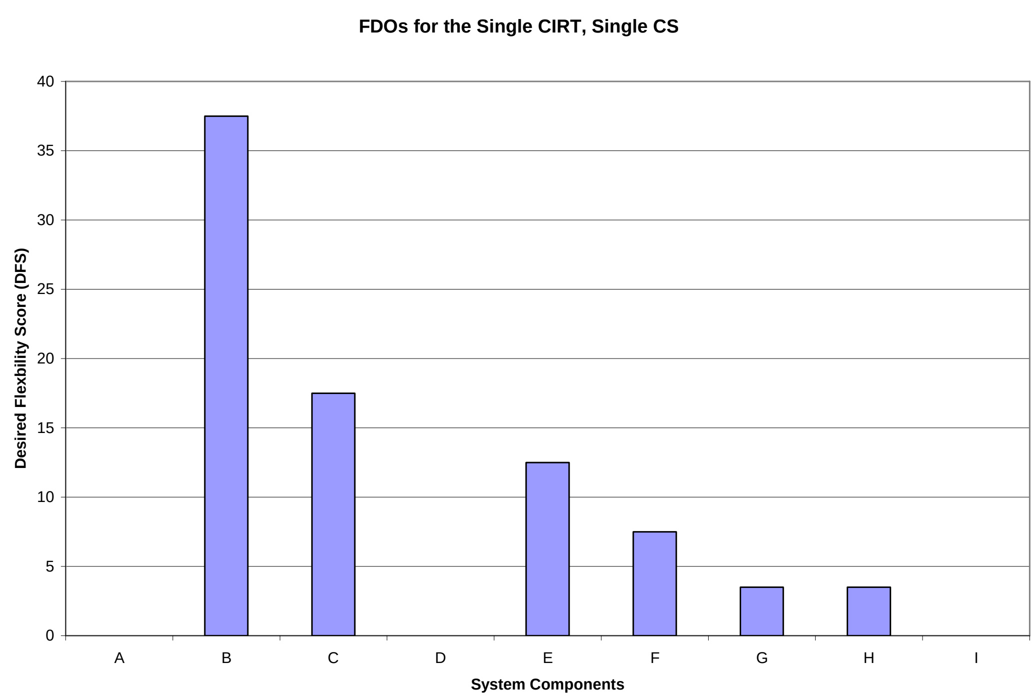

Figure 3-8. FDO Results for Example System

Depending on the resources available to pursue FDOs, the minimum DFS accepted to categorize as a FDO may be adjusted. Also, note that individual components with excessively high switch costs relative to other system components will cause disproportional results. This case may lead to misperceptions about the results, however by adjusting the criteria for categorizing components as FDOs will help alleviate this result.

Chapter Summary

This chapter introduces a methodology for the identification of FDOs. The proposed process begins by abstracting the system uncertainties from the ESM. These uncertainties are then used to define specific change scenarios, including what changes are likely to occur in the future. Next, using the ESM to map the uncertainties to the components in the system, the methodology considers where and how the change will be introduced into the system. The ESM is further used to provide subgraphs of the system flows, each of which will assist in the change propagation analysis to determine how the change will impact the system. Finally, a new metric, DFS, is introduced, which provides a comparative scale for all components in the system. High DFS scores indicate components that are potential FDOs. Chapter 4 demonstrates the methodology a Department of Defense case study.

Chapter 4: Case Study: Micro Air Vehicle Design for Flexibility

Chapter 3 introduced a methodology to identify FDOs. This chapter demonstrates the proposed methodology using the ESM framework through a MAV case study. System designers desire to embed flexibility in the MAV design to accommodate future operational and technical uncertainties. The methodology provides an analysis of the system to determine which components warrant further investigation for embedding flexibility.

The MAV is a relatively simple system, containing seventy-two physical objects, making the system a good candidate for methodology development and demonstration. Bartolomei (2007) studied the representation and data construction of the MAV system, resulting in a detailed ESM for the MAV case study. The availability and simplicity of the case study allows illustration of key steps and assumptions inherent in the methodology.

Case Study Background

DoD is developing a MAV to provide ground forces reconnaissance and surveillance at a greater standoff distance. The MAV is a less-than-one-pound unmanned air system equipped with a visual sensor. Conceptual design of the system continues to progress, as formal requirements evolve. Customers are willing to accept a less than optimal initial design to field immediate improvement of current capabilities, but ultimately strive to acquire a design that can be adapted to changing operational needs. In addition, enabling technologies are evolving at a rapid rate relative to the program's development and production cycle. Customers want to incorporate the improved technologies throughout the MAV's lifecycle.

Initial Program Requirements

The objectives of the MAV program are to develop an asset to augment the currently fielded unmanned air system that will operate covertly to navigate, sense, map, and reconnoiter behind enemy lines. The MAV is designed to be packed and flown by a single user, and be sufficiently inexpensive to lessen the financial impact of attrition and provide affordable solution for greater distribution. Ease of flight is emphasized such that training is minimized and the user base maximized.

Mission scenarios are initially based on personal 'over the hill' reconnaissance. However, the platform possesses potential of providing bomb damage information (BDI) for conventional munition systems. In the BDI concept of employment, the MAV would fly autonomously to the pre-programmed target area and transmit real-time BDI sensor data to either a ground-based or airborne receiver. It would continue to loiter in the target area for several minutes and transmit real-time imagery until the onboard power source was exhausted. Therefore, stakeholders will require the system to incorporate flexibility to accommodate diverse missions.

System Description

MAVs contain three major subsystems: the air vehicle, the ground station, and the operator control unit, which is a software application providing a graphical user interface. To simplify the discussions presented in this thesis, the system analyzed in this case study is restricted to only the air vehicle and the ground station subsystems. The air vehicle will include all components within the physical airframe, including the airframe itself and all avionics. The analysis will be further limited to consideration of hardware components to improve or maintain performance, rather than modifications to the software algorithms within the autopilot, data link or mission controller. While the methodology could certainly be extended to include embedding flexibility in software, the scope of this research omits the technical complexity of algorithm development and interactions to simplify the demonstration of the methodology.

The airframe can be decomposed into smaller physical objects (or components), which can be described in terms of geometric and mass properties. Figure 4-1 shows exterior components of the MAV airframe. Interior components include the propulsion subsystem (motor, electronic speed controller, and propeller), power subsystem, autopilot subsystem, actuators (servos), global positioning system (GPS), data links, and payload subsystems.

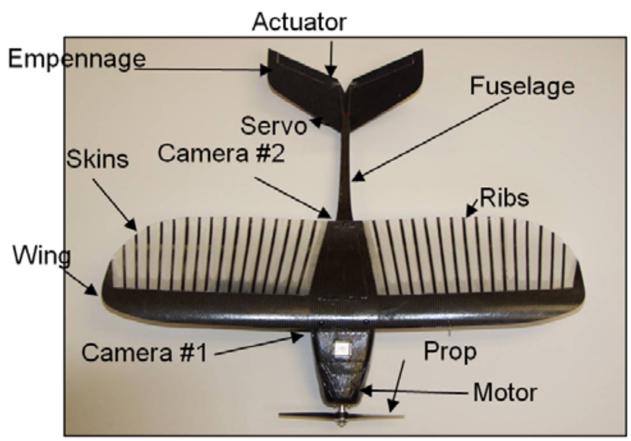

Figure 4-1. The Anatomy of a Micro Air Vehicle (Wilds et al 2007)

A physical model of the air vehicle design was developed using MS Excel© by the USAF Academy (Bartolomei 2005) and validated by Air Force Research Laboratory, Munitions Directorate for a series of MAV designs. The model accepts geometric and mass property inputs for components of the MAV to evaluate performance, such as endurance, range, and airspeed solutions. The model enables designers to quickly compute impacts to performance resulting from changes to the physical design. Such a model may be useful to quickly evaluate performance for a given set of design parameters and value potential flexible solutions, however is not necessary to identify FDOs using the methodology proposed in Chapter 3.

The ground station for the reconnaissance mission provides a single-user interface with the air vehicle that is rugged, lightweight, and easily transported. It consists of three main components: a notebook computer, the Ground Control Station (GCS) hardware, and the Operator Control Unit (OCU) software. The GCS hardware consists of a small, ruggedized electronics box that interfaces between the laptop PC and the air vehicle. It includes data converters, hardware drivers, a digitizer for video downlink, data transceivers, GPS, and a power supply. Figure 4-2 displays the ground station mounted within a backpack for single-user mobile operations.

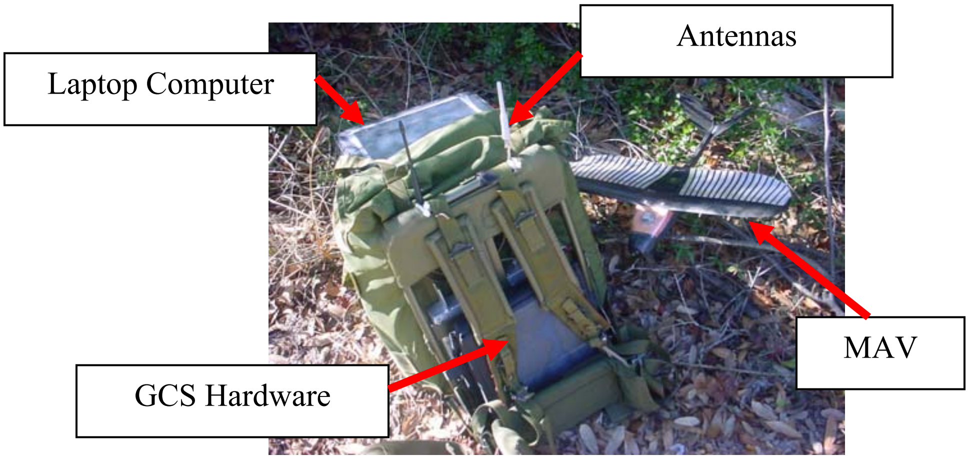

Figure 4-2 Ground station hardware mounted to a backpack

Given the conceptualized MAV system, designers desire to enhance the system's capacity to respond to future changes, especially rapid technology developments and new operational missions and environments. Therefore, the remainder of this chapter applies the methodology presented in Chapter 3 to identify which components within the air vehicle and ground station are the best candidates for embedding flexibility.

Step 1: Construction of the ESM

The first step of the analysis involves the creation of an ESM representing the MAV system. As previously noted, Bartolomei (2007) constructed a detailed ESM for the MAV containing information from the social, functional, technical, and environmental domains. This research refined the environmental and physical domain matrices to include additional information about the system interactions to provide improved resolution of the analysis for flexibility "in" the system. Appendix A provides a sample survey that can be used to elicit the information for constructing the ESM (see Part 3), giving special attention to minimizing the interviewer bias.

Bartolomei's ESM (2007)

The MAV ESM was constructed over twenty-four months (December 2004 to December 2006) to represent the product development of the MAV spanning forty-six months of effort (February 2003 to December 2006). Data was collected in the form of interview transcripts, program documentation, and physical demonstrations. While surveying a vast number of resources, the ESM strongly reflects the perspective of the MAV program manager. The MAV ESM was constructed using SMaRT, yet the data is exported to other analytic software applications, such as MS Excel© and MATLAB, for analysis.

Level of Information for the MAV

The MAV ESM represents the six classes of information (System Drivers, Stakeholders, Objectives, Functions, Objects, and Activities) within the social, technical, and environmental domains. A summary of the content included in each class follows.

- The system driver matrix contains forty-seven constraints or enablers including concepts of operations for the DoD customer, environmental threats, technology developments, social domain drivers, and external System of System interaction requirements. Very few of the system drivers interact with other system drivers, and thus the matrix is very sparsely populated. However, the importance of system drivers is their relationship to the other domains, especially the physical objects, when considering embedded flexibility. Relationships connecting the system drivers to other domains include influences, informs, and connections.
- The stakeholder matrix for the MAV includes the lead organization consisting of the program manager, a team of supporting engineers, and contracting agents; contractors and subcontractors responsible for individual technical subsystems; customers from DoD and other government agencies; and external stakeholders that are able to influence the system, operational context, and/or regulatory environment. Funding, managing, developing, and informing relationships describe the interactions between stakeholders and other domains. This matrix contains sixty-nine stakeholders.
- The objectives matrix contains the combined purpose/goals of the system that are defined by the system stakeholders. The objectives are derived from the formal requirements documented by the primary DoD customer. These objectives contain requirements for the system size and weight, interoperability, payload capabilities, and flight performance. Relationships between objectives include influential interactions, while most relationships between objectives and other domains represent traceability. This matrix contains sixty-five objectives.
- The function matrix is based on a functional decomposition of the objectives produced by Cooper (2005), which describes what the system must do to achieve the system objectives. Major functions for the MAV include providing intelligence, surveillance, and reconnaissance (ISR); providing air/flight operations; providing ground to air functions; and providing human-computer interfacing. This matrix includes a total of seventy-eight functions for the MAV system.
- The objects matrix itemizes the physical components and subsystems in the air vehicle and ground station, number fifty objects/subsystems. Physical relationships between objects and subsystems include electrical power, hardware interface, information exchange, and geometric constraints.
- The activities matrix includes process descriptions for the MAV program development. Although Bartolomei included this information in the original construction of the ESM, the system activities will not be analyzed in this research due to the lack of data verification and completeness.

Because the MAV was already in development when data collection began, knowledge regarding specific components existed, allowing the ESM to contain more detailed information. The stakeholders matrix includes information at the organizational, team and individual level of abstraction. Likewise, the physical objects matrix consists of both subsystems and individual objects.

The choice to mix levels of abstraction involves the program manager's perception of importance or influence of each stakeholder or physical object within the system. For example, the lead organization for product development is decomposed to include individual persons, whereas the contractors and subcontractors are represented at the organization/company level. Caution should be taken to alleviate duplicative representations. If the organization is listed, listing the individual persons may be duplicative. Duplication may cause problems in the analysis by adding additional weight, or emphasis, to the component.

Complexity of the MAV ESM

The MAV system is a simple physical system with few subsystems and objects, relative to a large aircraft such as the Joint Strike Fighter. However, the compact-size airframe requires objects to be placed in close proximity to one another spatially, with minimal spacing for shielding. Weight also requires the system to make efficient use of onboard components, encouraging multi-functional components. For example, the air vehicle autopilot consists of all electronics necessary for flight control and additional components to interface with the data link, GPS receiver, and payload subsystems. Each of these subsystems/objects relies on the autopilot to function, since additional weight and space are not available to allow self-supporting electronics and wiring. This dependence creates a highly-connected system, which creates increasing complexity. Therefore, the MAV system is more complicated than initially perceived.

The ESM framework provides a structure to lessen the burden of analysis for system complexity due to high connectivity. The ability to store information concerning several relationship types allows system designers to give adequate importance to components that are related to other components in multiple ways. For example, the relationship between the autopilot and the power source is singular: the power supply "powers" the autopilot. Yet, two relationships exist between the GPS and the autopilot: the autopilot "powers" the GPS and the GPS "transmits data" to the autopilot. To identify FDOs, it is important to consider each relationship type that is influenced. Additionally, since the ESM does not just sum the number of relationships, the system graph can be filtered by specific relationship type. Analyzing individual relationship types reduces the computational time and power required to analyze the matrix and simplifies the required human input.

Refining the ESM for FDO Analysis

Recall that FDOs are physical sources of flexibility within a system. Therefore, the results of the methodology identify components in the physical objects matrix as potential candidates for embedding flexibility. The MAV ESM, particularly the physical objects matrix, requires sufficient resolution (more detailed lower-levels of abstraction) such that it distinguishes relationships between subsystems and physical objects. Several of the identifiers (names) used in Bartolomei's physical objects matrix were ambiguous descriptors, leading to confusion amongst system designers during initial data verification. Therefore, the author has refined the physical objects matrix, interjecting technical expertise, to improve the system representation for the FDO analysis.

Additionally, the system driver matrix was modified to include attribute information to assist in recognition of the system drivers that are most likely to occur. Important attributes include what the future state is likely to produce (both the upside and downside potentials) and the likelihood that the system driver will change over time. This information is used to establish the change scenarios in Step 2.

The Objects Matrix

The modified objects matrix includes a physical decomposition of the ground station and the air vehicle to the component level, resulting in seventy-two subsystems and physical objects (as opposed to the fifty components defined originally). The additional count results from the decomposition of the autopilot and payload subsystems to provide detailed information for FDO analysis. In many cases, the object identifiers are only clarified to be more descriptive.

Four types of relationships are recognized as existing between the physical components: "power" (electrical flows), "data transmission" (information flows), "hardware interface" (a spatial relationship indicating adjoining parts or physical connection), and "housing" (a geometric constraint relation indicating physical location). Because the MAV is an electric-powered system, no mass flow relationships exist with the exception of the air through the pitot tube. The resulting matrix is sparsely populated; however the system as a whole is highly connected, which indicates a tightly integrated system. Figure 4-3 depicts the modified MAV physical objects matrix used in this research.

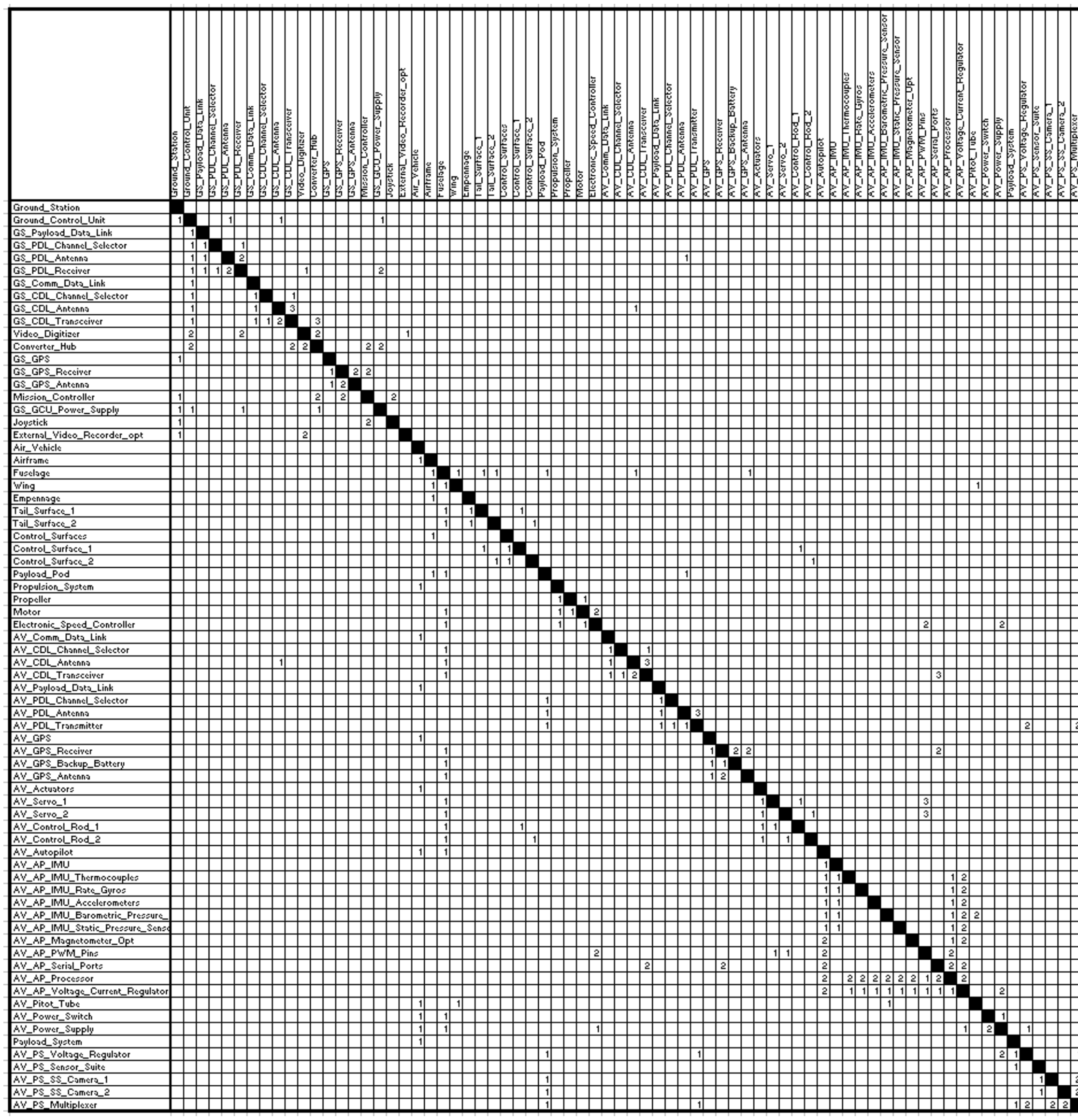

Figure 4-3. Physical Objects Matrix for the MAV System

The System Driver Matrix

Bartolomei's ESM includes forty-seven system drivers as shown in Figure 4-4. As noted before, the matrix is expected to be sparsely populated since the most important relationships to system driver exist in the off-diagonal DMMs, representing the relationship of system drivers to components in other domains. However, Bartolomei did not define relationships between system drivers and other domains in his effort.

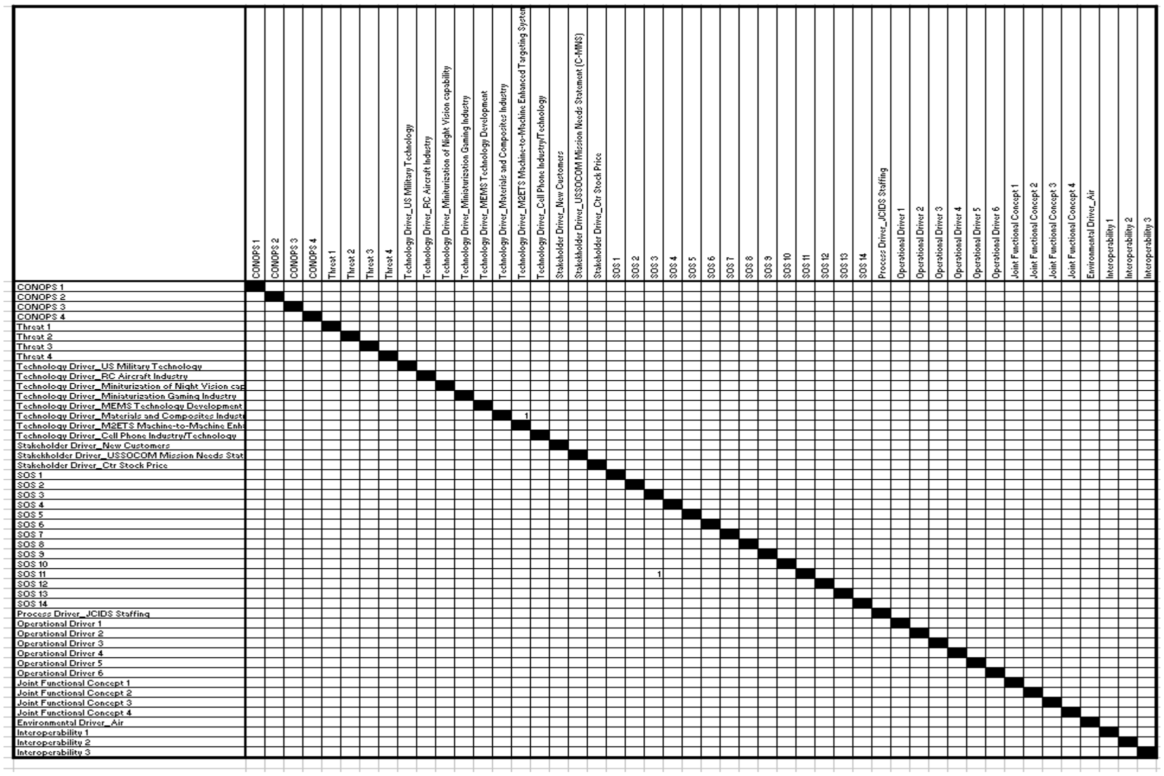

Figure 4-4. Bartolomei's System Drivers Matrix (Bartolomei 2007)

To reduce the number of system drivers, and thus simplify the matrix, several system drivers were combined using a hierarchical structure, resulting in the condensed matrix shown in Figure 4-5. For example, Bartolomei defines six individual tactical operational drivers. SMEs and key stakeholders agree that these tactical drivers influence the system components in other domains similarly. Therefore, these six drivers have been combined under a single Tactical Operational Drivers. It is the similarity of the influences that allow the drivers to be grouped. Caution is advised in grouping drivers that may influence the system differently, which results in misrepresentation of the system leading to potential inaccuracies in the data.

	CONOPS	Threats	Technology Driver_US Military Technology	Technology Driver_RC Aircraft Industry	Technology Driver_Miniturization of Night Vision capability	Technology Driver_Miniaturization Gaming Industry	Technology Driver_MEMS Technology Development	Technology Driver_Materials and Composites Industry	Technology Driver_M2ETS Machine-to-Machine Enhanced T	Technology Driver_Cell Phone Industry/Technology	Stakeholder Driver_New Customers	Stakekholder Driver_USSOCOM Mission Needs Statement (	Stakeholder Driver_Ctr Stock Price	SoS Interactions	Process Driver_JCIDS Staffing	Tactical Operational Drivers	Joint Functional Concept	Environmental Driver_Air	Interoperability
CONOPS																			
Threats																			
Technology Driver_US Military Technology																			
Technology Driver_RC Aircraft Industry																			
Technology Driver_Miniturization of Night Vision capability																			
Technology Driver_Miniaturization Gaming Industry																			
Technology Driver_MEMS Technology Development																			
Technology Driver_Materials and Composites Industry														1					
Technology Driver_M2ETS Machine-to-Machine Enhanced Targeting Sy																			
Technology Driver_Cell Phone Industry/Technology																			
Stakeholder Driver_New Customers																			
Stakekholder Driver_USSOCOM Mission Needs Statement (C-MNS)																			
Stakeholder Driver_Ctr Stock Price																			
SoS Interactions																			
Process Driver_JCIDS Staffing																			
Tactical Operational Drivers																			
Joint Functional Concept																			
Environmental Driver_Air																			
Interoperability																			

Figure 4-5. Simplified MAV System Driver Matrix

It is necessary to map the relationships of the system drivers to other components within the system to continue the methodology. However, due to time constraints, the refined ESM only includes the relationships for the system drivers selected for the FDO analysis.

Time Evolution and Iteration

Construction of the ESM is an iterative process. System stakeholders review the ESM for completeness and accuracy to correct any data conflicts or missing information. Additionally, the SMaRT tool is capable of storing time-related existence attributes to allow the ESM to be filtered for different time instantiations for data analysis. Since the system is likely to continue changing over time, this capability enables the analysts to update the ESM representation as more information becomes available. For the purpose of the FDO analysis presented in this case study the MAV ESM includes data to represent the system as of August 2006. New information about the system uncertainties can easily be incorporated into the ESM, and the analysis can be repeated to reflect the updated information.

Step 2: Identifying the Change Scenarios

Part 4 of the survey provided in Appendix A suggests questions to elicit information about potential uncertainties and change scenarios. In this case study, three system drivers were selected from those included in Figure 4-5 as the most critical to include in the FDO analysis:

1. A technological change in the state-of-the-art payload/sensor capabilities
2. An operational threat change due to adaptation or improvisation of an evolving enemy force
3. A stakeholder change (new customer) imposing additional/modified performance requirements

The uncertainties associated with these system drivers dominated the discussions of key stakeholders during the drafting of the initial requirements documentation. Additionally, SMEs and program managers agreed that most planning efforts included elements of each.

Uncertainty

Each system driver has one or more uncertainties which will influence the ability of the system to perform in the future environment. This section describes the uncertainties associated with each selected

System Driver #1: Technological Change in Available Payloads

Infrared imaging technology continues to provide US military forces with a significant advantage over low-tech enemy threats. DoD acts as a major contributor to the development of IR imaging devices for weight/size-sensitive applications. Technological advancement of composite materials and digital electronics are rapidly progressing to enable innovative imagers, lenses, and assemblies. However, it is unknown to the system designers when these developmental efforts will be available for system integration.

Unit cost, survivability in operational environments, time period for maturation, and stakeholder utility are uncertain for these emerging payloads. Additionally, these efforts are currently in the conceptualization stage of development. Very few efforts have produced working prototypes. Therefore, technical uncertainties for the emerging payloads include input power requirements, heat emissions and temperature sensitivities of the imager, data transmission format, and overall size and weight of the improved imager.

System Driver #2: Threat Change Due to Adaptive Enemy

Threats to military forces are not constant. The enemy continues to adapt to advances in technology and tactics. Increasing range of small arms fire demands extended standoff distances for ground forces; the new age of electronic warfare, especially frequency jamming capabilities[7] requires agile data transmission technologies; and improved camouflage, concealment, and deception techniques necessitates improved sensors that see beyond the visual spectrum.

For the MAV, stakeholders agree that the two most uncertain of these is the small arms and frequency jamming threats. Each theater of operations faces a different threat concerning the availability of small arms and the effectiveness of the enemy to employ

[7] Frequency jamming refers to the use of electronic equipment to radiate highly concentrated energy signals to interfere with the use of other electronic equipment.

small arms fire. Planning for the worse case scenario may cause excessive constraints for defending against this threat, and therefore it is desirable that systems can adapt to the changing environment. Additionally, because small arms fire threatens the lives of troops rather than just the performance of the system, this threat is at the forefront of discussion amongst stakeholders.

Frequency jamming is also an important consideration for the MAV since a primary function of the system is to provide wireless data transmission. The data links for both command and control and sensor transmission are susceptible to low-cost, low-tech jamming techniques. The MAV's reliance on GPS for semi-autonomous operations puts the system at further risk given an enemy capable of jamming the signal.

As an additional note, the growing complexity of electronic equipment use in the battlespace has caused oversaturation of the frequency spectrum. While DoD continues to manage the allocation of frequencies for all theaters of operation, the MAV frequency allocation is uncertain. Therefore, flexibility to change frequency is extremely desirable.

System Driver #3: Stakeholder Change Resulting in Modified Performance Requirements

Military personnel in key decision-making roles rotate every two or three years to provide career broadening opportunities. The program manager in for MAV system was a military officer for the first three years of development effort. All customers for the system were represented by military personnel, as well as the key decision-maker for the System Program Office (SPO). In each of these positions, the military persons enter and exit the program multiple times during the course of the program.

Stakeholder preferences and priorities may change when new people occupy key positions. Additionally, new stakeholders entering the system may also require an adjustment to the performance goals. In the case of the MAV, many stakeholder positions and preferences are uncertain, however system designers are aware of which positions are likely to change and how the change may influence the preferences.

Change Scenarios

Based on these uncertainties, several change scenarios were identified as likely future environments in which the system may be required to operate. Three such scenarios enumerated below are the focus of this case study.

Change Scenario #1 (CS #1): Payload

A developing payload looks promising and may be available for integration into the MAV system. This payload contains both day and night imaging sensors. Unknown design parameters include input power and data transmission format. Size and weight requirements were provided as constraints, and therefore are known.

Change Scenario #2 (CS #2): Range

The enemy has acquired new techniques to improve the accuracy of small arms fire. Ground forces must adapt their tactics to operate at extended standoff distances. The

MAV system may be required to operate over longer ranges, however this distance is uncertain.

Change Scenario #3 (CS #3): Endurance
A new customer is introduced to the MAV system. The customer operates using different tactics and requires a change in the anticipated MAV mission, necessitation extended operational endurances. The MAV will be expected to fly significantly longer than previously expected. The addition of other customers is likely, however their needs for endurance is unknown.

Notice that each of the scenarios reflects only one system driver. This assumption can be removed. However conditional logic is then required to represent the interaction between system drivers.

Assumption #1: Each change scenario only reflects one system driver.

Probability of Change Scenario Occurring (P_{cs})

Each scenario is weighted by the probability that the change will occur in the future. Table 4-1 defines the P_{CS} for the three change scenarios considered in this case study. They reflect forecasted likelihoods by SMEs and the user community using the current intelligence advice and knowledge assessments of technology maturity levels.

Table 4-1. Probability of Change Scenarios Occurring

Change Scenario	P_{CS}
Payload (CS #1)	0.8
Range (CS #2)	0.4
Endurance (CS #3)	0.7

Step 3: Identifying the Change Initiators and Relationship Types

Change scenarios ask the question: "If component A is required to change due to resolved uncertainty, what other components will also change?" In this example, component A is the change initiator, or point where the change is introduced into the system. There may be multiple change initiators for a given change scenario, which occurs when the change is introduced into multiple components simultaneously or the change can enter the system in different ways.

Change Initiators

The ESM includes a mapping of the system drivers to other components in the system. Tracing the system drivers selected for analysis identifies change initiators for each of the scenarios. The scope of this research restricts results to identifying physical objects for opportunities for flexibility. Therefore all change initiators are traced to objects. This assumption can be relaxed in future applications to consider embedding flexibility in the social or environmental domain.

Assumption #2: This research seeks opportunities for flexibility "in" the system. All change initiators are physical objects.

Figure 4-6 illustrates how to trace system drivers to change initiators. The red solid line represents the selection of a single system driver (Note that in this example from Bartolomei (2007) the system driver matrix is included at the bottom of the ESM. The order of the domains is not important, as long as the analyst is cognizant of the matrix titles.) By looking across the system driver row, each cell containing a tick mark is a potential change initiator. For example, the blue dotted line (vertical) identifies an object that influences the system driver. Following this line horizontally (the green dashed line) indicates the traceability of that object to other components in the system. These relationships indicate the second order effects as related to the system driver. Each system driver may have multiple change initiators (indicated by multiple blue dotted lines).

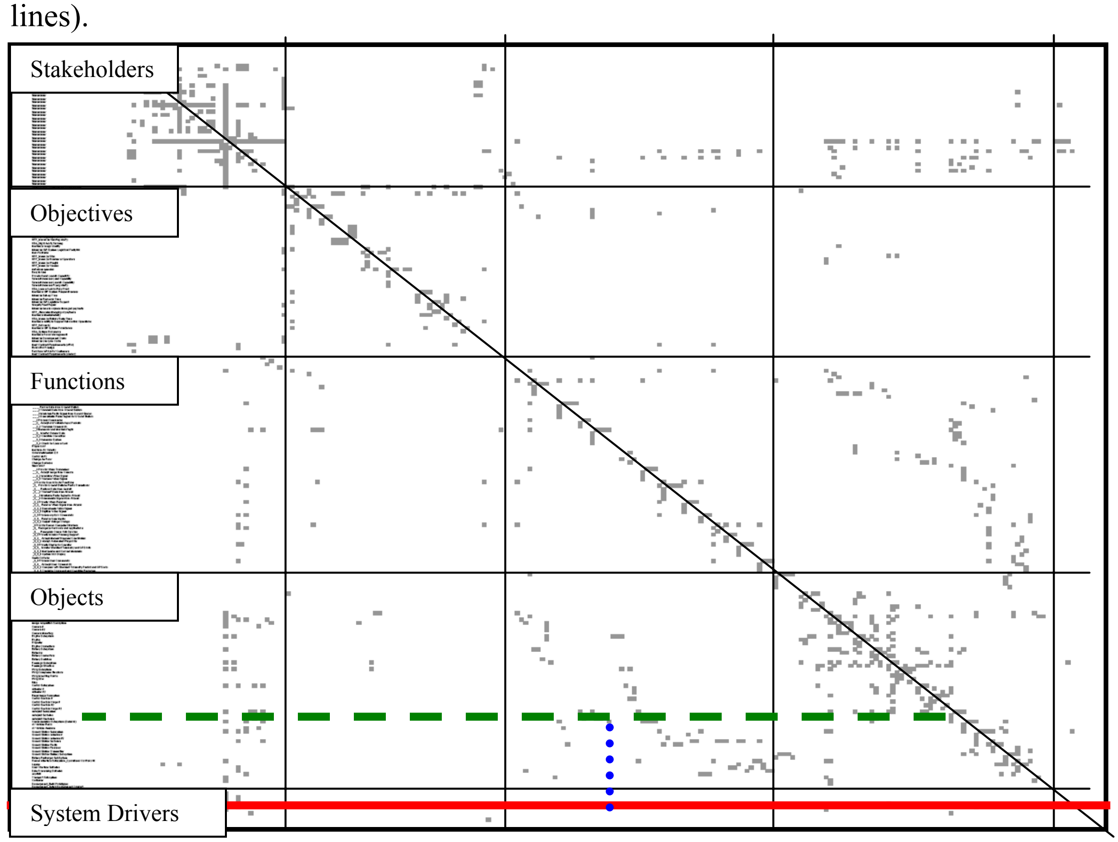

Figure 4-6. Example of Mapping System Driver to Change Initiator

Interviews with Subject Matter Experts (SMEs) were also conducted to determine the change initiators for each. SMEs were asked to consider which components within the system would likely be changed in direct response to the change scenario. For example, the first change scenario considers a change in available technology for the payload. The SME indicated that the existing payload is the primary change initiator in the system to respond to a new or upgraded sensor, which validates the information in the ESM.

In a less intuitive scenario, CS #2 and CS #3 require a flow down to the stakeholder and objective/functional requirements to identify the physical objects as change initiators. For example, in CS #2 the ESM and SME interview identified four possible change initiators by tracing the stakeholder to a objective, then functions, and finally to physical objects. The addition of a new customer (system driver), the US Army (stakeholder), required extended endurance (objective). To accomplish this, the MAV must fly (function) longer. The MAV requires a propeller, motor, power supply, and wing (objects) to fly. Similar logic is applied to CS #2.
Table 4-1 displays the identified change initiators for each change scenario.

Table 4-1. Identified Change Initiators for Particular Change Scenarios

Change Scenario	Change Initiator(s)
CS #1: Payload	▪ Camera 1 ▪ Camera 2
CS #2: Range	▪ Payload Data Link ▪ Payload Antenna ▪ Comm Data Link ▪ Comm Antenna
CS #3: Endurance	▪ Propeller ▪ Motor ▪ Power Supply ▪ Wing

Since Cameras 1 and 2 share a common interface to all other components in the system, a single change initiator (Sensor Suite) is defined for CS #1. Furthermore, Comm Data Link and Comm Antenna in CS #2 refer to the command and control data link and antenna, respectively. The MAV system uses separate data links for command and control data and payload sensor data transmission.

Relationship Types

The SME was then asked to identify which relationship types.) most directly affect physical objects in each change scenario:

- Data Transmission: transfer of information
- Power: transfer of electrical current
- Hardware Interface: physical connection between components
- "Houses": geometric constraint imposed by one component containing the other component

Because the physical objects DSM was limited initially to only four types of relationships, all were included in the analysis. However, in a more inclusive data set, filtering the connections that are not effected by the change scenario may reduce the computational complexity of the analysis.

$P_{i,j}$ Table

Recall from Chapter 3 the likelihood of a change occurring for each relationship type given the scenario occurs and the initiator activates is summarized in the $P_{i,j}$ table. To reduce the subjectivity of assessing these likelihoods and discourage fence-sitting (choosing 50-50 chance), a scale ranging from not likely to most likely is used as depicted in

Figure 4-7. $P_{i,j}$ values used in the case study are provided in Table 4-2.

Table 4-2. Change Initiator / Relationship Type Matrix for MAV

	Change Initiator	Relationship Types			
		Data Transmission	Power	Hardware Interface	"Houses"
CS #1	Sensor Suite	0.8	0.8	0.2	0.2
CS #2	Payload Data Link	0	1	0	0.2
	Payload Antenna	0	0	0.2	0
	Comm Data Link	0	0.8	0	0.2
	Comm Antenna	0	0	0.2	0
CS #3	Propeller	0	0.2	0	0
	Motor	0	0.8	0	0.8
	Power Supply	0	1	0	0.8
	Wing	0	0	0.8	0

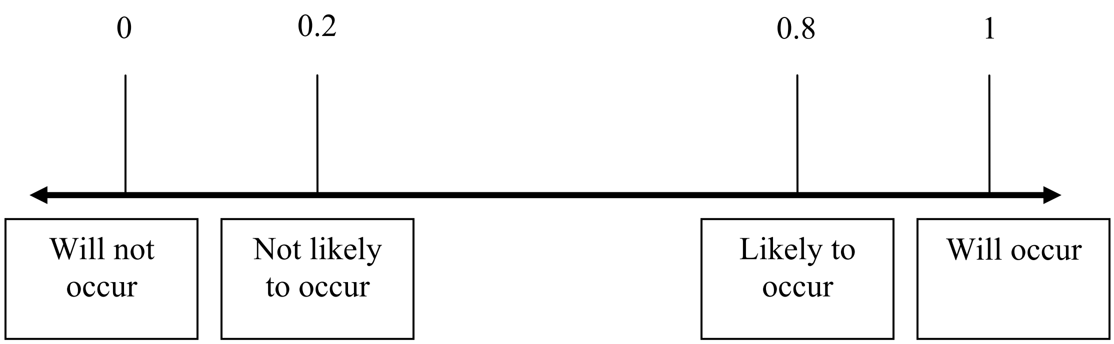

Figure 4-7. Scale for Assessing Likelihoods of Occurrence in $P_{i,j}$ Table

Similar to Assumption #1, only one change initiator activates at a time. This assumption eliminates the need for conditional logic required to represent the interaction between multiple change initiators. Given multiple activations, each possible state must be assigned a different $P_{i,j}$ for each relationship type.

Assumption #3: Only one change initiator activates at a time.

Step 4: Reducing the ESM to Subgraphs

Step 4 requires an algorithm that filters the physical objects matrix (since all change initiators are physical objects) to include only the types of relationships affected in each change scenario. Recall that the objects matrix represents a directed connectivity graph.

This graph may include relationship directions according to the system flows; however those directions may not be representative of the change flows depending on where the change is introduced in the system. Because changes can propagate both upstream and downstream from where the change initiator is located, the matrix must first be altered to reflect an undirected graph. Given a particular scenario, the identified change initiators, and the respective relationship types affected, the algorithm searches the matrix for all defined connections between objects matching the relationship type. The result is an undirected subgraph including only the objects within the new network filtered by relationship type.

Note: This research developed a MATLAB script to read in the objects matrix from an XML file exported from SMaRT. Then an algorithm was created to draw the undirected graphs for identified change initiators and relationship types.

For example, CS #1 has one change initiator (Payload Sensor Suite consisting of both Cameras 1 and 2) and four relationship types (data transmission, power, hardware interface, houses). Therefore, four undirected subgraphs are generated by the filtering algorithm. Figure 4-8 depicts the filtered undirected matrix and subgraph for the data transmission relationship type for a change in the payload technology (CS#1). A total of sixteen subgraphs were created for this case study and are included in Appendix B. CIRT pairings with a $P_{i,j} = 0$ do not require subgraphs since they will not occur (mathematically, the result is multiplied by 0).

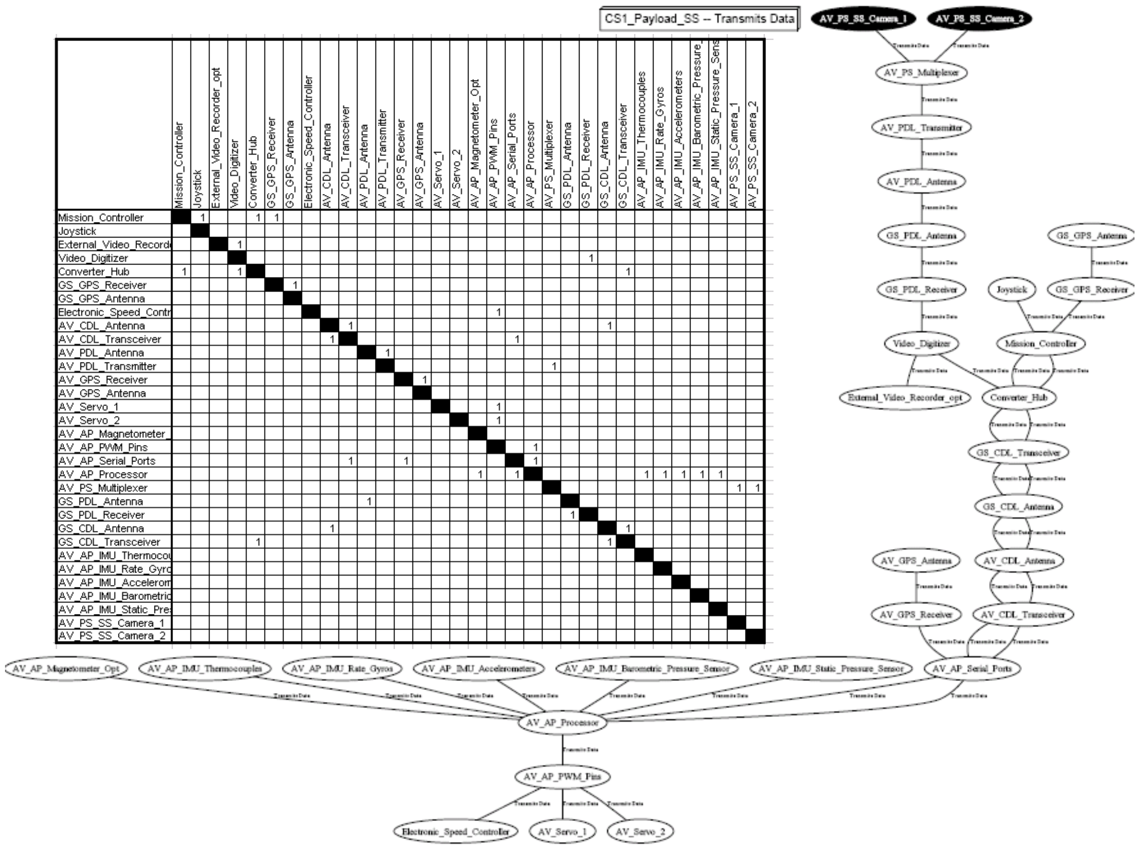

Figure 4-8. Undirected Matrix and Network Graph for Payload Change Scenario (CS#1)-Transmits Data

Step 5: Change Propagation Analysis

Step 5 requires input from SMEs to indicate how change propagates through the undirected graph. As noted in Chapter 3, a change propagates if the contingency margin is violated by the incoming change.

Change Graphs

To facilitate generation of change graphs, a MATLAB script creates list of components and relationships for each subgraph so that the SME can evaluate each of the included relationships by answering the question "Which direction does the change flow?" for a given change scenario and relationship type. It is important to note that the SME's response is dictated by the level of understanding of the overall system and the individual components. A thorough knowledge of the contingency margins within the system is ideal since the propagation of change is highly dependent on these margins.

This step allows the SME to explicitly document the perceived direction of change flow and provide reasoning for the elimination of any edge in the filtered graph. For example, in CS #1 the undirected subgraph (see Figure 4-8) indicates existing data flows from the ground station converter hub (Converter_Hub) to the ground station communications data link (GS_CDL_Transceiver), which then connects all components receiving information from the communications data link. However, the SME indicated the converter hub effectively shields those components from any change in the payload data transmission since the communications data link operates on a different radio frequency than the payload data link. Therefore, those components are eliminated from the subgraph. Figure 4-9 displays the directed filtered matrix and subgraph for CS#1 data transmission.

CS1_Payload_SS -- Transmits Data

	Mission_Controller	External_Video_Recorder	Video_Digitizer	Converter_Hub	AV_PDL_Antenna	AV_PDL_Transmitter	AV_PS_Multiplexer	GS_PDL_Antenna	GS_PDL_Receiver	AV_PS_SS_Camera_1	AV_PS_SS_Camera_2
Mission_Controller				1							
External_Video_Recorder_opt			1								
Video_Digitizer									1		
Converter_Hub			1								
AV_PDL_Antenna						1					
AV_PDL_Transmitter							1				
AV_PS_Multiplexer										1	1
GS_PDL_Antenna					1						
GS_PDL_Receiver								1			
AV_PS_SS_Camera_1											
AV_PS_SS_Camera_2											

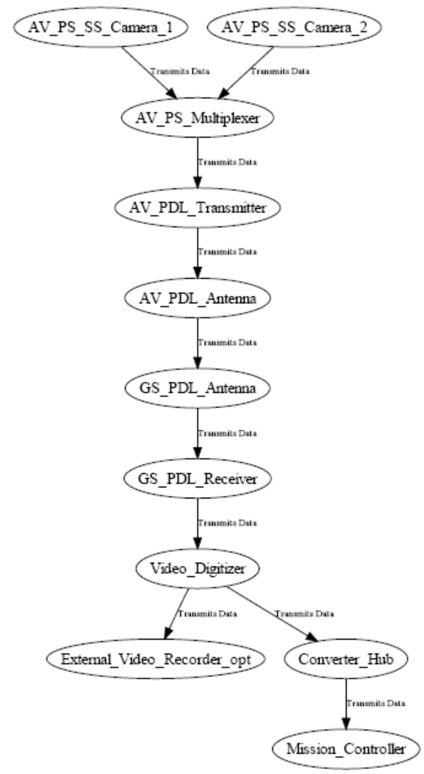

Figure 4-9. Direceted DSM and Subgraph for Payload Change Scenario (CS#1)-Transmits Data

Probability of Change Propagation (P_c)

Next, the SME identifies the probability that the change propagates along the edges of the change graph. Assume that the probability of change propagation is conditional on prior events. Therefore, a $P_c = 0$ indicates that the component absorbs the incoming change, which terminates the change path. This assumption allows SMEs to simplify the change graph if it is known that a component's contingency margin absorbs the change, or if the propagation is highly unlikely. The same scale is used to represent the likelihood that is presented in Step 3 for evaluating $P_{i,j}$. Table 4-3 presents the P_c values for CS #1 data transmission change graph. Appendix B includes P_c values for all change scenarios and CIRT pairings.

Assumption #4: The probability of change propagation is conditional on prior events.

Table 4-3. Probability of Change Propagation for CS#1-Transmits Data

Physical Object	P_c
Payload_Sensor_Suite	1
AV_PS_Multiplexer	0.2
AV_PDL_Transmitter	0.2
AV_PDL_Antenna	0.2
GS_PDL_Antenna	0.2
GS_PDL_Receiver	0.2
Video_Digitizer	0.8
External_Video_Recorder_opt	0.2
Converter_Hub	0.2
Mission_Controller	0.2

Component Switch Cost

Each component in the change graph with a $P_c \neq 0$ incurs a switch cost. In the absence of a detailed cost model, the switch cost for each component is assumed to be path independent.

Assumption #5: Absent a detailed cost model, switch costs are path independent.

In most practical applications, switch cost are path dependent, which means that a costs associated with the change vary according to changes to other components in the system. For example, a change in the size of the motor may result in a change to the geometry of the fuselage. Similarly, a change in the size of the power supply may also require a change to the fuselage. The cost to change the fuselage to accommodate the new motor may be different than that to accommodate the power supply, and thus the switch cost is path dependent.

However, if the two costs cannot be differentiated due to lack of a detailed cost model, a conservative approach is to account for the replacement of the object. Suh (2005) also makes this assumption in his assessment of switch costs for an automobile. In this case, the switch cost of the fuselage includes new tooling and design for all changes. Further investigation to integrate cost models is necessary to improve accuracy of the methodology.

Switch costs for physical objects in the MAV system are presented in Table 4-4. Note only switch costs for objects identified in the subgraphs are included. These switch costs reflect realistic estimations based on commercial-off-the-shelf pricing.

Table 4-4. MAV Physical Objects Switch Costs

Physical Object	Switch Cost ($)
AV_Power_Supply	200
GS_GCU_Power_Supply	200
AV_PS_Sensor_Suite	15000
Fuselage	2500
Wing	3000
Motor	100
AV_CDL_Transceiver	150
GS_CDL_Transceiver	150
AV_PDL_Transmitter	200
GS_PDL_Receiver	300
AV_AP_Voltage_Current_Regulator	50
AV_PS_Voltage_Regulator	50
AV_CDL_Antenna	25
AV_PDL_Antenna	25
GS_CDL_Antenna	100
GS_PDL_Antenna	150
Payload_Pod	1000
AV_PS_Multiplexer	250
AV_Power_Switch	50
Electronic_Speed_Controller	150
Mission_Controller	1000
Video_Digitizer	100
Converter_Hub	500
Ground_Control_Unit	200
Propeller	50
AV_Pitot_Tube	20
External_Video_Recorder_opt	100
AV_AP_Serial_Ports	0

Component Expected Expense (CEE)

The CEE for each component is determined using the switch costs, probability of change propagation, and the change graphs. First, the CEE is calculated for each subgraph generated in Step 4 using the deterministic equation:

$$CEE_{CIRT,k} = \left(P_{c_k} \times SC_k\right) + \sum_{l=k+1}^{n} \left(P_{c_l} \times SC_l\right)$$

Table 4-5 displays the CEE calculation for CS #1 for the Transmits Data relationship type. Notice that Video_Digitizer include both branches from the External_Video_Recorder_opt and Converter_Hub (see Figure 4-9).

Table 4-5. CEE_{CIRT} for MAV CS #1-Transmits Data

Physical Object	P_c	SC	CEE_{CIRT}
Payload_Sensor_Suite	1	15000	15585
AV_PS_Multiplexer	0.2	250	585
AV_PDL_Transmitter	0.2	200	535
AV_PDL_Antenna	0.2	25	495
GS_PDL_Antenna	0.2	150	490
GS_PDL_Receiver	0.2	300	460
Video_Digitizer	0.8	100	400
External_Video_Recorder_opt	0.2	100	20
Converter_Hub	0.2	500	300
Mission_Controller	0.2	1000	200

Next, aggregate the CEE of each component for the change scenario using the equation:

$$CEE_{CS,k} = \sum_{i=1}^{N} \sum_{j=1}^{M} \left(P_{i,j} \times CEE_{CIRT,k} \right)$$

Table 4-6 displays the results of the aggregation of all four relationship types for CS #1. Finally, Figure 4-10 illustrates potential opportunities for embedding flexibility if only CS #1 is considered. Notice after the AV_PS_Multiplexer the slope flattens, indicating a potential delineation for FDOs (depicted in the figure by the red dashed line).

Table 4-6. CEE_{CS} for MAV CS#1

Physical Object	CEE_{CS}
Payload_Sensor_Suite	27804
Payload_Pod	3919
AV_PS_Multiplexer	804
Fuselage	507
AV_PDL_Transmitter	436
AV_PDL_Antenna	408
GS_PDL_Antenna	392
GS_PDL_Receiver	368
Video_Digitizer	320
Converter_Hub	240
AV_PS_Voltage_Regulator	176
AV_Power_Supply	168
Mission_Controller	160
Electronic_Speed_Controller	24
External_Video_Recorder_opt	16
AV_Power_Switch	8
AV_AP_Voltage_Current_Regulator	8
AV_CDL_Antenna	7
AV_CDL_Transceiver	6

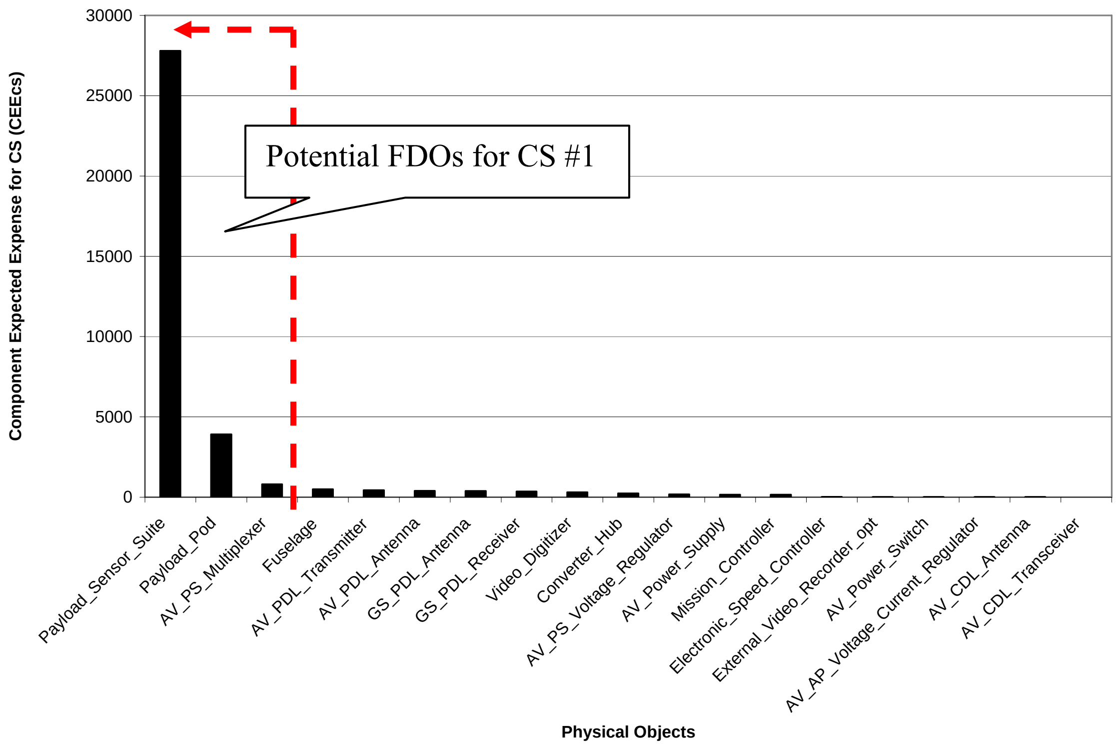

Figure 4-10. Preliminary Results for MAV CS #1

Step 6: Desired Flexibility Score (DFS)

Now, using the new metric presented in Chapter 3, aggregate again to compare across multiple change scenarios. Recall DFS is calculated by:

$$DFS_k = \sum_{z=1}^{q} \left(P_{CS} \times CEE_{CS,k} \right)$$

Table 4-7 and Figure 4-11 display the DFS for each component included in the change graphs. All other components in the system have DFS = 0.

Table 4-7. DFS for Components in MAV Case Study

Physical Object	DFS
AV_PS_Sensor_Suite	22243.2
Fuselage	3965.6
Payload_Pod	3151.2
Wing	2808.96
AV_Power_Supply	1883
Motor	1422.4
AV_PS_Multiplexer	643.2
AV_PDL_Transmitter	552
GS_PDL_Receiver	523.2
AV_PDL_Antenna	395.6
GS_PDL_Antenna	343.2
AV_CDL_Antenna	327.6
Electronic_Speed_Controller	312.4
Video_Digitizer	256
AV_PS_Voltage_Regulator	244.6
Converter_Hub	232
AV_CDL_Transceiver	175.2
Mission_Controller	128
GS_GCU_Power_Supply	104
AV_AP_Voltage_Current_Regulator	93.4
AV_AP_Serial_Ports	74.4
AV_Power_Switch	26.2
Ground_Control_Unit	16
External_Video_Recorder_opt	12.8
Propeller	9.8
AV_Pitot_Tube	8.96

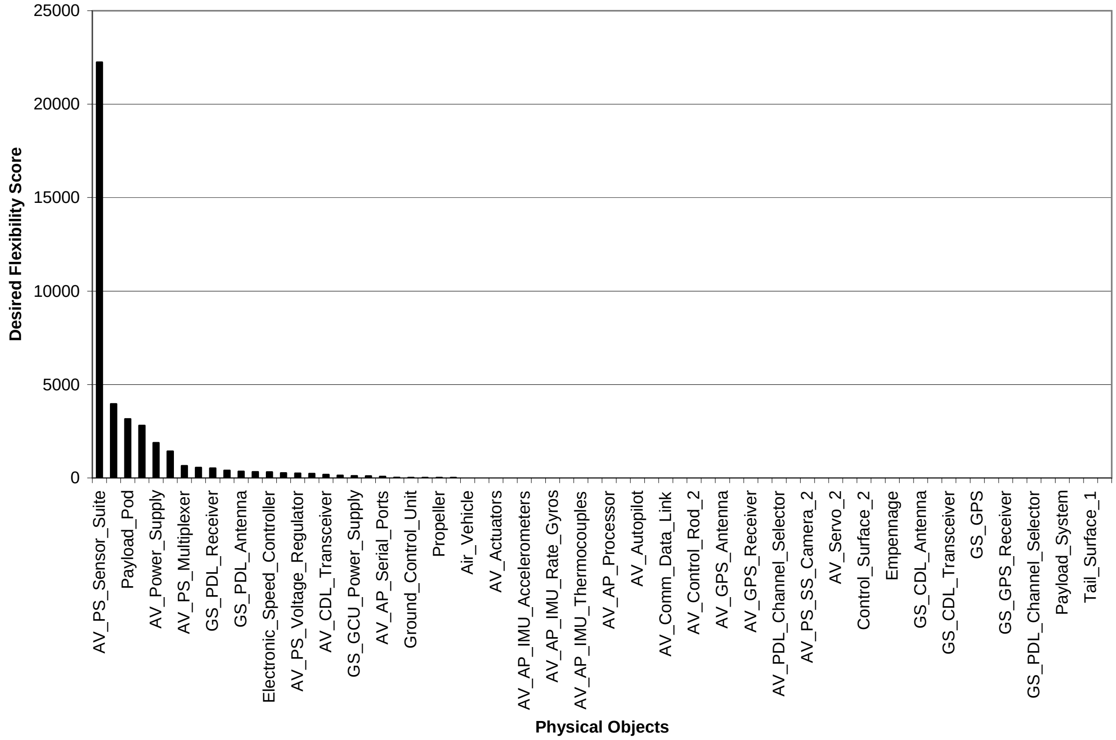

Figure 4-11. DFS Results Chart for MAV Case Study

Step 7: Recognizing FDOs

Not all objects with DFS $\neq 0$ are FDOs. Therefore, it is useful to have guidelines for identifying good FDOs. One guideline is to look for the point where the slope of the curve approaches zero (or is relatively flat in comparison). Additionally, the selection of FDOs may result from limitations of available resources, requiring a more indepth cost analysis to determine where to draw the line.

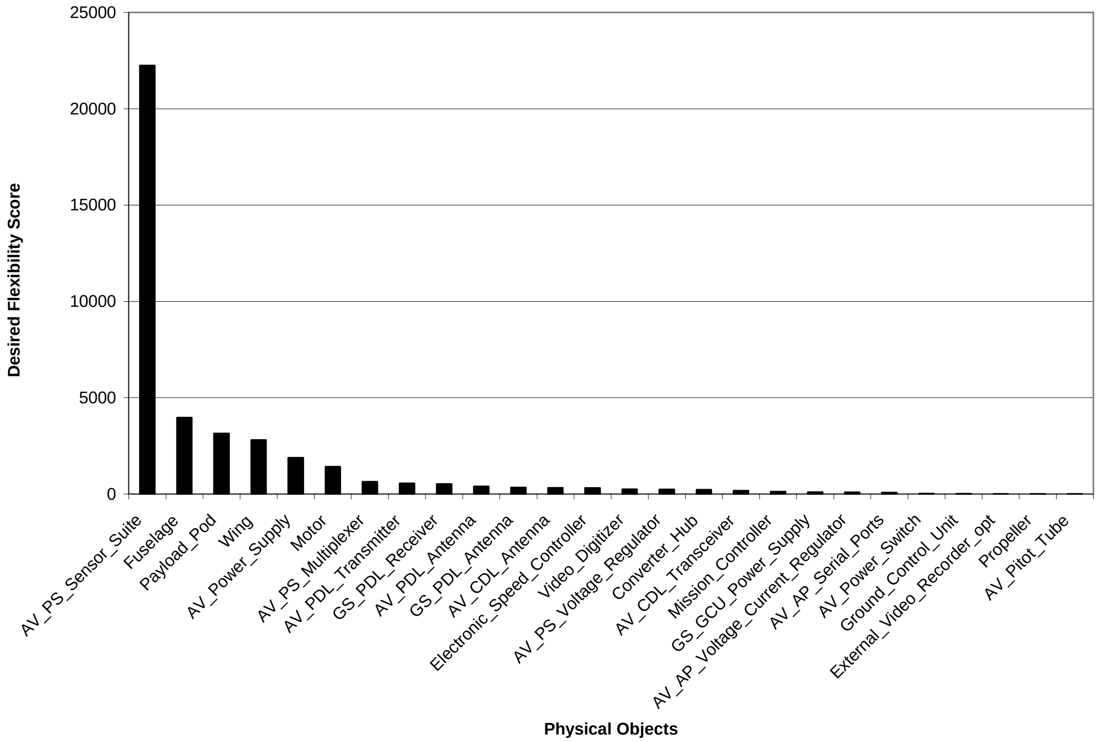

Figure 4-12. Closer Look at MAV FDO Results

Figure 4-12 enlarges the region where DFS is greatest by eliminating from Figure 4-11 all objects with DFS = 0. From this view, it is easy to see the leveling of the slope after the top six ranked objects. Thus, the following objects are identified as FDOs:

1. AV_PS_Sensor_Suite (Cameras 1 and 2)
2. Fuselage
3. Payload_Pod
4. Wing
5. AV_Power_Supply
6. Motor

AV_PS_Sensor_Suite (Cameras 1 and 2) unquestionably appears at the top of the list because the switch cost is by far greater than all other objects in the system. Costing an estimated $15,000, the AV_PS_Sensor_Suite is a prime opportunity for embedded flexibility. To reduce the cost of procurement, customers may elect to only order a minimal number of MAVs equipped with the upgraded capability. Therefore, ensuring that the system can easily include/exclude the Sensor_Suite is potentially a valuable option.

Notice that the second, third, and fourth FDOs are major components of the physical airframe. The Fuselage and Payload_Pod serve as containers for electronics and other subsystems, imposing geometric constraints and providing hardware interfaces. It makes sense that they provide opportunities for embedded flexibility since any change in size or location of the contained components may violate the already narrow contingency margins. Furthermore, these components have low unit costs (due to the use of prefabricated composite materials and simple manufacturing procedures), but high capital costs associated with tooling requirements. Revisiting Assumption #5, not all changes to these components will require retooling. Therefore, use of a detailed cost model may reveal that the containers are slightly less important.

The Wing provides another interesting case. It does not contain any internal components and only has two hardware interfaces: Wing-Fuselage and Wing-AV_Pitot_Tube. However, the Wing is required for flight and relatively expensive to manufacture. The Wing is the third most expensive component on the MAV (behind the Payload_Sensor_Suite and AV_Autopilot). Changing the geometry of the wing will have some impact on flight endurance and stability of image, although it is not the leading component to effect flight performance due to the size of the MAV platform.

AV_Power_Supply and Motor are both objects in the MAV propulsion system, which is responsible for the primary function, flight. As previously noted, the wing and aerodynamics have less of an impact on flight performance due to the small size of the MAV. To accommodate smaller wing span, the propulsion system must provide excess thrust to both propel the MAV forward and help keep it aloft. The Motor and AV_Power_Supply interface through the Electronic_Speed_Controller. However is does not appear in the top list of FDOs. One reason might be that ESCs typically have large contingency margins, and thus are less likely to require change.

From this list of FDOs, system designers should attempt to design the MAV to accept modular payload designs, which allows the system to operate economically with the original day sensor payload and upgrade to the new night sensor payload only when necessary. Additionally, a modular Payload_Pod and Fuselage components enables streamlined aerodynamics when carrying small components, but expands when necessary. A detachable wing provides similar capability, allowing customers to select the appropriate wing for the desired performance. Finally, designing common interfaces for the AV_Power_Supply provides reduces switch costs for system designers to incorporate newly available power sources to continue improving system performance.

Conclusions

The MAV case study demonstrated that the proposed methodology provided useful insights about the opportunities to embed flexibility. The results were verified by the author's experience with the system and knowledge of current improvements to the MAV. Furthermore, system stakeholders have agreed use of this methodology could help to:

- determine how to allocate research and development funds,
- provide justification for requirements, and
- manage operational and technical uncertainties.

Chapter 5: Policy Implications for DoD Acquisition of Flexible Systems

This chapter addresses flexibility issues at the interface of technology and policy. Current DoD acquisitions process policies may inhibit the application of the proposed methodology to identify FDOs presented in Chapter 3. Furthermore, identifying opportunities for embedding flexibility is useless for DoD unless they can be exploited at a future date.

This chapter considers the rationale for current DoD acquisitions policy, including the effect of recent reformation. Then it presents the political, legal, and financial aspects of implementing a process to design flexible military systems, together with their impact on the array of stakeholders, and the barriers that stand in the way of exploiting that flexibility in the future. Implementation strategies and recommendations are proposed for improving the DoD acquisitions process to enable flexible system development and procurement.

Policy Rationale

Military acquisition programs involve many stakeholders from organizations that are only loosely aligned. They include defense contractors, congressional representatives, Pentagon leaders, military services, and down to individual program managers. Each organization, with slightly different motivations, perceives problems through its own "organizational sensors," resulting in variations of perceived options based on processed information. (Allison 1969) Therefore the behavior of leaders in organizations represents less of a choice, and more of an output derived from standard patterns of behavior.

To coordinate the activities of many organizations to encourage a common goal, leaders establish standardized procedures to ensure (1) comparability of processed information at higher levels and (2) accountability for deliverables. This need for standardization is exactly the intent of the DoD acquisitions framework. Standard Operating Procedures (SOPs) are developed rules guiding the process of a desired outcome. Allison (1969) utilizes an example of a football team, in which the quarterback (leader) calls upon previously established plays (SOPs) that require the players (stakeholders in the outcome) to execute in a coordinated manner to achieve the goal. This analogy translates almost directly to the role of the program manager of a weapon system development or procurement and the relationship to the DoD acquisitions framework. At higher levels, DoD leaders and Congressional policymakers are similar to coaches, providing a repertoire of plays for the quarterback to draw upon in various scenarios.

Increasing the number of plays in the repertoire may seem imperative to respond better to a wide range of scenarios. However, too many choices results in confusion and digression back to uncoordinated outcomes. Organizations or individual program managers are likely to master very few plays, and thus attempt to apply less fitting strategies to programs with special needs. Furthermore, scenarios that do not exhibit characteristics of the "standard" cases will not be adequately addressed by SOPs. In this case, SOPs that serve the purpose of providing faster responses actually retard the response to non-standard scenarios. Thus, the organizational behavior is sluggish and unduly formalized to account for the abnormality. Likewise, the introduction of new SOPs to encompass these non-standard cases can over-constrain the system.

Carrying this example further, Allison (1969) suggests that coaches (i.e. DoD and Congressional policymakers) can not control the organizational processes, but rather create disturbances that might influence the outcome. Franklin Roosevelt observed that organizations "so large and far-flung and ingrained in [their] practices" are almost "impossible to get the action and results [he] want[ed]…" The same phenomenon is true of the frustrations noted by DoD and Congress today. While organizations operate with quasi-independence in the acquisitions framework, few programs (including technology developments and weapon system procurements) fall exclusively within the domain of a single organization, thereby complicating the resulting outcomes. Results are less choice and more products of the processes. Therefore, acquisition reform is not as simple as issue new directives for organizational processes.

Acquisition Reform

The DoD Acquisition Management Framework is a collection of many SOPs spread across many stakeholders and organizations. Thus, even providing disturbances (via changes in guidance) to the organizational processes is risky, since the outcomes are very uncertain when not all externalities (how each organization responds) are recognized. Additionally, SOPs are very slow to change, and if pressed too quickly, organizations may resist any changes, no matter how small. Allison (1969) identifies three potential conditions in which dramatic changes are accepted: 1) periods of budgetary feast, 2) periods of budgetary famine, and 3) dramatic performance failures. All three of these conditions were present in the late 1980s and early 1990s in regards to the DoD acquisitions process.

The end of the Cold War was a catalyst for acquisitions reform. At the end of the Cold War, the DoD's perception of military threat underwent a major transformation. During the Cold War, the enemy was well defined and the race for cutting-edge technologies was better understood. However, today the technology threat is perceived to require countermeasures for the technologies currently available, now that the victor (US) of the race has overwhelmingly triumphed thus dominating the technology. Enemy forces today will utilize weapons developed by the US, or inferior weapons of the defeated former Soviet Union. But those enemies are unknown, and organizations fear the unknown since "standard" procedures may not apply. Therefore, the DoD acquisitions process has required a dramatic shift in SOPs to increase the portfolio of technologies for uncertain enemies and operational requirements.

In the 1990's, DoD leadership implemented the "total system performance responsibility strategy" for several key acquisition programs. The strategy ultimately relieved defense contractors from the pressures of many reporting requirements, which in turn prevented the government sponsors from properly overseeing expenditure of funds. Program managers claimed to have "no contractual means to pressure prime contractors" and often had "no warning or insight into the contractor's growing technical and cost problems." (Chirstie 2006) DoD began to lose control of rapidly escalating cost and schedule overruns and realize that the real work in the acquisitions process was in contract management, i.e. paying attention to the risks and uncertainties after the contract was awarded. This realization undoubtedly led to an emphasis on employing program managers with less technical and more management skills.

Since 1998 the Government Accountability Office (GAO) annually investigates DoD acquisitions and recommends improvements for "best practices" for the acquisitions process. DoD has been very responsive to the recommendations, agreeing with most, and has attempted to adapt policies guiding weapons procurement. GAO has been attempting to implement the commercial practices within the DoD market. These practices included increased technology maturity prior to transitioning to product development, separation of technology development and product development, and increasing program managers' authority to act on information regarding risks and uncertainties.

Evolutionary Acquisition

DoD responded to the GAO recommendations by proposing and implementing the Evolutionary Acquisition (EA) process[8], which became the preferred acquisition strategy for major weapons systems in 2002. EA focuses on demonstrating capabilities rather than meeting strictly specified requirements. Additionally, the development is intended to be able to keep pace with newly emerging technologies by allowing incremental production. This provides the warfighter with "an initial capability which may be less than the full requirement as a tradeoff for earlier delivery, agility, affordability, and risk reduction.

EA includes both spiral and incremental development. Spiral development (SD) defines a desired capability, but the end-state requirements are not known at the program initiation. The requirements are continually refined through demonstration and risk management with involvement of the end-user feedback. Incremental development is similar in that the program defines a desired capability, however the end-state requirement is also known from the start. Each increment or spiral of capability is defined by the maturation of the technologies and the evolving user needs.

EA provides a conducive environment for enabling design of flexible systems. It allows for re-evaluation of plans periodically and insertion of new technologies and capabilities over time. The strategy emphasizes risk reduction, however does little to address the upside opportunities for embedding flexibility. It focuses efforts on delivering core capabilities and following up with future increments, yet the process does not stress the importance of the uncertainty facing those future increments.

Furthermore, EA is still confined by DoD Acquisitions Management Framework within the current state of DoD acquisitions. The next section presents an introduction to the

[8] Evolutionary acquisition is defined in Under Secretary of Defense (AT&L) Memo dated 12 April, 2002.

stakeholders and a brief overview of the processes required for military systems acquisitions.

Current State of DoD Acquisitions

The Integrated Defense Acquisition, Technology and Logistics Life Cycle Management Framework (refer to as DoD Acquisitions Management Framework in this research) encompasses the activities of design, fabrication, test, manufacture, operations, and support for military systems. It requires strong communication and collaboration between all stakeholders to develop, procure, and sustain these systems.

Stakeholders and Their Roles[9]

This section identifies the stakeholders involved in the DoD Acquisitions Management Framework. It discusses the roles each stakeholder plays should be used as a reference in the subsequent explanation of the processes.

- ***User Community (or Warfighter):*** The operational user, or warfighter, will engage future conflicts with the system being acquired. Typically, the user community is represented by a single lead command, either a combatant command (COCOM) or major command (MAJCOM), which identifies deficiencies and capability requirements. The user community possesses unique knowledge of current operational tactics and equipment that is essential to the definition of system requirements and concepts of operation. Furthermore, the user community must advocate funding for the acquisition.

  Technology Development Agency (or Government Laboratory): The technology development agency develops key or enabling technologies and/or integrating the system. The technology development agency consists of an internal team of a program manager, finance personnel, contracting personnel, technical experts and advisors, and engineering support. It participates in the maturation of technologies and provides Technology Transition Plans to the acquisition agency. Ideally, the development agency communicates directly with both the acquisition agency and the user community to assure that the appropriate technologies will be available for incorporation into the system providing the needed capability.

- ***Acquisition Agency (or System Program Office):*** The acquisition agency, known as the System Program Office (SPO), plans and executes the acquisition strategy. The acquisition agency also consists of an internal team of a program manager, finance personnel, contracting personnel, technical experts and advisors, and engineering support. SPOs ensure all program constraints are met while following all applicable acquisition laws and regulations and oversee the test & evaluation stages of development. They also maintain the production contracts with contractors and provide the formal interface between contractors and the user

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[9] Information presented in this section builds upon Dare's (2003) identification of key stakeholders for Air Force Acquisitions and DAU (2005).

community. SPOs do not have appropriated funds; they receive funds through the user community and in turn manage budgets for program acquired for the user.

It is important to note that in many cases the development agency is the same as the acquisition agency. In the event of an upgrade to an existing system, the acquisition agency generates Engineering Change Proposals (ECPs) that modify a current acquisition contract to include the upgrade. However, sometimes a government laboratory, or other organization, may participate in a parallel development effort, in which case these two stakeholder groups are independent.

- ***Contractors:*** Contractors, both in the development and production phases, respond to solicitations, propose solutions, conduct research and development, and design, produce, support and upgrade defense systems. These contractors are responsible for providing the tangible goods and services to the DoD. However, contractors are also motivated by profits and stockholder's interest, market share, and technological achievements.

- ***Test & Evaluation Community:*** The Test & Evaluation (T&E) community includes both Development and Operational T&E personnel that ensure the system meets performance requirements and can be successfully integrated into the intended operational environment. These stakeholders also document and issue concerns for sustainability to be considered prior to the full-rate production phase.

- ***Congress and DoD Policymakers***: Congress and the Executive Branch provide legal appropriation and oversight of DoD acquisitions. Several committees within Congress interact with the DoD acquisitions management framework including:

  - Authorize defense programs: the Senate Armed Services Committee and the House Armed Services Committee,
  - Appropriate funding: the House Appropriations Committee and the Senate Appropriations Committee,
  - Set spending limits: Senate and House Budget Committees,

  Additionally, the Congressional Budget Office, the Government Accountability Office, and individual member of Congress have legislative oversight of defense activities. Major participants within the Executive Branch include the President, the Office of Management and Budget, the National Security Council and the Department of Defense. Table 5-1 below characterizes the perspective, responsibilities and objectives of the stakeholders in this group.

Table 5-1. Congress and Executive Branch Roles and Interests (Source: Modified from DAU 2005)

	Perspectives	Responsibilities	Objectives
Congress	▪ Constituent interests ▪ Two-party system ▪ Checks and balances ▪ Patriotism ▪ Personal ambition ▪ Reelection	▪ Conduct hearings ▪ Raise revenue; allocate funds ▪ Pass legislation ▪ Oversight and review	▪ Balanced national security and social needs ▪ Distributed federal dollars by district/state ▪ Maximize competition ▪ Control industry profits ▪ Control fraud, waste, and abuse
Executive Branch	▪ Formulate, direct, and execute national security policy ▪ Patriotism ▪ Personal Ambition ▪ Reelection	▪ Sign legislation into law (President) ▪ Commander-in-Chief (President) ▪ Negotiate with Congress ▪ Make decisions on major Defense acquisition programs (USD AT&L) ▪ Issue directives/ regulations ▪ Contract with Industry	▪ Satisfy national security objectives ▪ Maintain a balanced force structure ▪ Field weapon systems to defeat threats to national security ▪ Prevent undue congressional interest/scrutiny ▪ Eliminate fraud, waste, and abuse in federal procurement

The user community, development agency, SPO and contractors are the primary stakeholders that interact with the individual programs on a daily basis. Figure 5-1 depicts the relationships between these stakeholders throughout the acquisitions process.

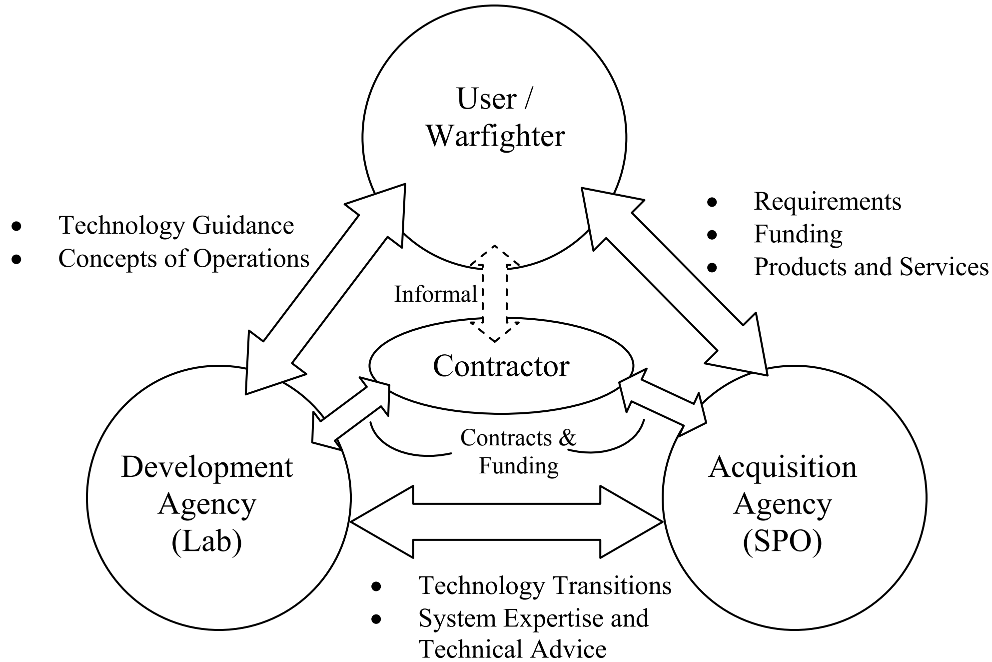

Figure 5-1. Primary Stakeholder Relationships for DoD Acquisitions Management Framework

DoD Acquisitions Management Framework[10]

The DoD Acquisitions Management Framework consists of five phases:

- Concept Refinement: refines initial concept and develops enabling technologies and the development strategy;
- Technology Development: reduces technology risks and determines the appropriate set of technologies to integrate into a full system to satisfy the need;
- System Development & Demonstration (SDD): develops a system or increment of capability and demonstrates system integration, interoperability, safety, and operational utility;
- Production & Deployment (P&D): achieves operational capability that satisfies the need; and
- Operations & Support: executes support for sustainment and disposal of the system.

Each phase concludes with a decision point or milestones to determine whether or not the concept or program continues. Table 5-2 summarizes the three decision points and three milestone decisions.

[10] The Integrated Defense Acquisition, Technology, and Logistics Life Cycle Management Framework Chart (Version 5.2, August 2005) is the source of information summarized in this section. The chart represents a compilation of policies and guidance from DoD documents and websites as noted within the text.

Table 5-2. DoD Acquisition Milestones and Decision Points

Milestones	**Execution**	**Decision**
Milestone A	End of Concept Refinement	Go/No Go to continue to Technology Development
Milestone B	End of Technology Development	Go/No Go to continue to System Development & Demonstration
Milestone C	End of System Development & Demonstration	Go/No Go to continue to Production & Development
Decision Points		
Concept Development	End of capability gap analysis and validation of need	Required to start Concept Refinement
Design Readiness Review	End of system integration within SDD	Go/No go to continue to system demonstration within SDD
Full-Rate Production Design Review	End of Low-Rate Initial Production within P&D	Go/No go to continue to Full-Rate Production and Deployment within P&D

DoD policies and guidance outline processes to support military acquisitions. DoD Directive 5000.1 and DoD 5000.2 instruct the acquisitions system and operations, respectively. These policies are supplemented by additional joint-service directives and individual service policies that define acquisition processes. At the highest level these processes include:

- Joint Capabilities Integration & Development System (JCIDS),
- Defense Acquisition System (DAS), and
- Planning, Programming, Budgeting, & Execution Process (PPB&E).

Effective interaction between these processes is essential for DoD program decision support. Subsequent sections discuss the roles of each process.

Joint Capabilities Integration & Development System (JCIDS)

JCIDS is a need-driven procedure established to identify, assess, and prioritize joint military capability needs as directed by CJCS Instruction 3170.01E and CJCS Manual 3170.01B. The procedure begins with an analysis to define capability gaps and understand the existing joint force operations and deficiencies, which leads to a series of three documents: the Initial Capabilities Document (ICD), the Capability Development Document (CDD), and the Capability Production Document (CPD).

Each document represents a different phase of the program development. The ICD describes the capability gap and why non-materiel changes alone are not adequate to fully provide the capability need. This document is used to support the Concept Development decision point required to start an acquisitions program. The CDD defines an affordable and militarily useful capability with regards to logistical support and technology maturity. The CDD supports program initiation at Milestone B. The CPD captures production elements specific to the approved system design prior to entering P&D. The CPD supports Milestone C. All documents are developed by high-performance teams (HPTs) comprised of representatives from the SPO, the user community, system developers (including SMEs or engineering support personnel), and the test and evaluation community. Individual and joint service review is required before finalizing the documents.

All documents are then entered into a common data database. This database allows the document to be vetted for review and approval. Figure 5-2 displays the JCIDS document flow for each document. This process can take up to 18-24 months for completion for a single document.

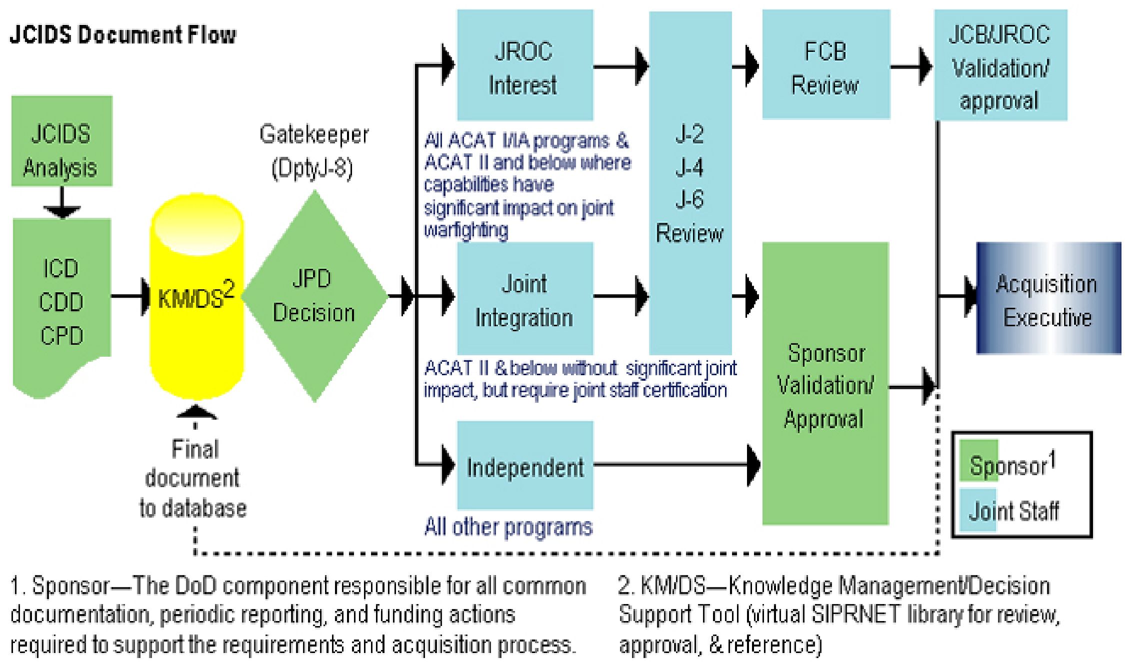

Figure 5-2. JCIDs Document Flow (Source: https://acc.dau.mil/IFC/back_pg3.htm)

Defense Acquisition System (DAS)

DAS is an events-driven process guided by Under-Secretary of Defense (Acquisitions, Technology & Logistics) oversight and directed by DoD Directive 5000.1 and DoD 5000.2. The process includes six major components: Oversight & Review, Contracting, Major Products, Logistics/Sustainment, Technical Efforts (i.e. systems engineering, test & evaluation, supportability), and Cost. Guidance for each of these components focuses on documentation and program management to provide information for milestones and decision points and program accountability. Responsibility for DAS primarily resides with the SPO and the developing organizations, incorporating the user and test & evaluation communities as necessary. Because the process is event-driven it keeps pace with the technology development and integration, with the exception of delays for documentation requirements.

Planning, Programming, Budgeting, & Execution (PPB&E)
The PPB&E process allocates resources for all operations, including weapon system acquisition. The process guides the requests for funding and assures the appropriate amount and type of funds (research and development, test and evaluation [RDT&E], procurement, operations and maintenance [O&M], etc) is available to execute the desired program. PPB&E oversight is provided by the Deputy Secretary of Defense.

Planning consists of reports that set forth broad policy objectives and military strategy along with programming guidance for the Program Objectives Memorandum (POM). The POM is a six-year planning budget for all military programs and is developed by DoD components and issued by the Office of the Secretary of Defense. *Programming* results in the development of the Program Decision Memorandum which highlights issues and directs appropriate courses of action for the POM. *Budgeting* refers to the Budget Estimate Submission, which reflects the first one or two years of the POM. The BES is reviewed by the Under Secretary of Defense Comptroller and the Office of Management and Budget for incorporation each period to the President's budget. *Execution* involves the evaluation of actual output against planned performance and adjustments to resources as appropriate.

The PPB&E process is a calendar-driven process given the necessity to incorporate funding requirements into the President's budget due every February. DoD 7000.14-R notes that it is essential to convert each program's event-driven strategy and phasing into the PPB&E funding timelines to receive necessary funds.

Enabling and Exploiting Flexibility within DoD Acquisitions Management Framework

This section investigates the policy, legal, and financial implications associated with enabling and exploiting flexible design. Enabling flexible design refers to the creation acquisitions management that allows sufficient recognition, understanding and management of uncertainty and embedding flexibility such that systems are designed to be flexible to future needs. Exploiting flexibility refers to implementing appropriate acquisitions and funding processes that allow system stakeholders to react to unfolding uncertainty such that the system continues to deliver the best possible value.

Policy Implications

Policy implications include the enablers and barriers associated with DoD SOPs and training and employment policies. This section considers how the use of Simplified Acquisitions Processes can enable exploitation of flexibility, while potentially hurting design for flexibility. Furthermore, many policy barriers are considered including oversight and accountability, resource allocation scheduling, and the lack of technical expertise and appropriate SOPs for uncertainty analysis.

Policy Enablers

Congress, the Deputy Secretary of Defense, and the DoD have commissioned the Joint Rapid Acquisition Cell (JRAC), which "provides Combatant Commanders with a process to address Immediate Warfighter Needs (IWNs) in the year of executions, and to quickly facilitate the resolution of Joint Urgent Operational Needs (JUONs)." (Wolfowitz 2004) Motivated by the dynamic threat environments of OEF and OIF, JRAC operates outside the DoD 5000.1 and 5000.2 guidelines to deliver capabilities within 120 days (or a maximum of two years) for programs that, if left unfulfilled, will "seriously endanger personnel and/or pose a major threat to ongoing operations."

Individual military services and COCOMs also have similar mechanisms including

- US Army Rapid Equipping Force = Operational Needs Statements
- US Navy = Capability Rapid Deployments
- US Air Force = Combat Capability Documents
- US Marine Corps = Universal Needs Statements
- Special Operations Command= Combat Mission Needs Statement
- Joint Forces Command = Limited Acquisition Authorities

Deliberate acquisitions processes following the Acquisitions Management Framework require four or more years to deliver products or implement change in program direction. This duration is far too long for exploiting flexibility for uncertainties that are changing more rapidly than the process cycle time. Simplified acquisitions processes are capable of delivering products in less than two years, which enables stakeholders to react as the uncertainty unfolds. Capability needs that do not meet the extreme requirements for initiation as IWNs may still qualify for "limited" acquisition processes, which can deliver products or services in two to four years.

There are disadvantages however to the use of these shortened processes. First, while they allow more opportunities to exploit flexibility, these rapid acquisition processes decrease the ability to design for flexible systems. Urgent needs typically define only the immediate need with less regard to how the system will respond to future uncertainties. The solutions often incorporate temporary fixes that are not sustainable or may require additional solutions for interoperability in the operational environment. Second, these processes may become over-utilized by the user community in attempt to fulfill less urgent operations "wants" rather than needs. Given the shortened response time, individual user communities may be tempted to forward programs to COCOMs for fast tracking. Ultimately, this will result in flooding groups like JRAC with many tasks and programs and thus begin to slow the process. Finally, simplified acquisition processes act as a "band-aid" for the DoD 5000.1 and 5000.2 policy's inability to enable and exploit flexibility. Without a pressing need for reform, the current policy may be left unresolved.

Policy Barriers

There are several policy barriers that potential hinder flexibility within military systems.

- ***Requirements for Oversight and Accountability:*** Gregory (1989) found that Congressional and DoD oversight is causing excess paperwork and delays. Unfortunately, acquisition reform has not lessened these delays significantly. As mentioned earlier in this chapter, DoD policy is a compilation of SOPs to help provide oversight and accountability for military acquisitions. However, reformation to decrease paperwork requirements has in fact had the effect of increasing oversight since less documentation exists.
- ***Resource Allocation Scheduling:*** The POM budgeting process is a calendar-driven schedule, which is not conducive for enabling or exploiting flexibility. Forcing programs to align with POM funding cycles reduces the effectiveness of using an events-based scheduling approach such as the Defense Acquisition System. Funding is required to enact almost all changes yet, given the current policies, is difficult to allocate or appropriate on condensed schedules. This problem is further exacerbated by the convention of estimating program costs with no inclusion for contingencies.
- ***Lack of Incentives to Introduce Flexibility:*** Program managers lack incentives to implement acquisition strategies than enable flexible systems. The rules-based environment makes government personnel risk averse and discourages innovation, or the program manager's desire to attempt non-standard acquisition strategies. (Wilson 1989) Furthermore, military program managers rotate every two to three years, and thus continuity of planning is difficult. Program managers that design systems for flexibility are not likely to be responsible for exploiting that flexibility in the future.

  Contractors lack incentives to design flexible systems due to the ability to increase profits by creating inflexible systems. In the absence of flexibility, DoD will be required to procure new systems to adapt to future needs. Contractors will profit from new contracts, where learning curves are well established and capital investments are reduced given the existing infrastructure. Congress also has disincentives to require flexible systems. They benefit from new start programs, which can be redistributed to include their congressional districts/states.

- ***Lack of Technical Knowledge to Enable or Exploit Flexibility:*** The lack of technical proficiency will constrain the government's ability to plan, design, and implement flexibility in systems. SPOs will become reliant on contractors to assist in decisions for embedding flexibility, and as noted above contractors lack incentives to promote flexible systems.

  DoD program managers lack the expertise to provide technology assessments of complex systems, including adequate analysis of related uncertainties. The government is contracting out the role of systems integrator and losing the ability to understand the technologies to manage programs better. The escalation of defense research and development during the Cold War blended the roles of the government and the private contractors. The government became dependent on private contractors for technologies to equip the military forces. And as the technologies grew in complexity, the government began to shift the role of systems integration to the contractor, a role once assumed in-house to provide the checks and balances necessary to assess the programs and plan for future iterations. Now, the government suffers from a lack of broad and specific technical competency for weapons development, procurement, and sustainment.

- ***No Requirement for Uncertainty Identification and Assessment:*** Program managers are not trained to identify the technical and operational uncertainties and anticipate future projections. Because this information is not required by the acquisition process, adequate resources are not dedicated to understanding how program decisions based on current information will impact future decisions. Even provided the incentive to analyze the relevant uncertainty, McCray and Oye (2006) recognize the following problems with foresight predictions:

    1. limited knowledge at the time of forecasting;
    2. technical and methodological deficiencies;
    3. pervasive difficulties integrating knowledge across disciplinary lines; and
    4. reluctance of decision makers to engage directly with many elements of uncertainty.

    Updating information is nearly as important as initially identifying uncertainty because it is almost guaranteed that analysts will get the forecast wrong the first time. Stakeholder acceptance of the new information is a recognized challenge for the DoD in updating the information.

    The intent of EA is to encourage updating information. However, DoD does not allocate sufficient resources to assessing and tracking program uncertainties. Note, in this context, uncertainty is not risk. DoD does report program risk assessment for decision makers, including metrics of availability of resources, technical maturity and ability to meet scheduled milestones (ie cost, schedule, performance risk). However, each of those risks has an associated uncertainty (probability of the outcome). As time unfolds, the uncertainties should be updated to provide better information to decision makers.

Legal Implications

Statutory authority from the Congress provides the legal basis for DoD acquisitions. Title 10 of the US Code, Armed Forces contains most of the laws impacting DoD processes. Major legislation includes the Federal Procurement Policy Act (1983), Competition in Contracting Act (1984), Department of Defense Reorganization of 1986 (Goldwater-Nichols), and Federal Acquisition Streamlining Act of 1994. This section considers the legal enablers and barriers to enabling and exploiting flexibility.

Legal Enablers

Multiyear task and delivery order contracts enable the design and exploitation of flexible systems. These contracts allow program managers and contractors to rapidly redirect efforts or add additional tasks or products for delivery over a period of ten years. The tendency of operators to include all desired capabilities into a single task order is mitigated by multiyear task contracts, which reduce the time required to initiate a contract effort. Examples of these contracts include Indefinite Delivery/Indefinite Quantity (IDIQ) contracts and Undefinitized Contract Actions (UCAs). However, program mangers should monitor the use of these contracts to ensure contractors do not lose incentives to design flexible systems as a result of too much stability/comfort with long running contracts.

Furthermore, the use of procedures other than competition, such as sole source selections, can allow simplified exploitation of flexibility. Non-incumbent winners result in potential loss of investment and discontinuity between the legacy systems and the new system. (DSB 2003) Sole source selections that choose the incumbent can alleviate discontinuity and ensure that exploiting flexibility in the future is accomplished by the incumbent. However, limiting competition may also discourage the design of flexible systems due to contractors not having to compete with systems that do offer increased flexibility.

Legal Barriers

The Packard Commission (1986), an organization dedicated to streamlining the DoD Acquisitions Management Framework, concluded that Congress was legislating "minute details" of acquisitions. Congress has overconstrained the acquisitions process by attempting to generate SOPs for non-standard cases to improve oversight, even since the implementation of EA. As a consequence, it reduces the ability of program decision makers to execute flexible acquisition strategies. Rigid acquisition strategies act as barriers to flexible systems because the strategy itself cannot be adapted to respond to changing program needs.

Additionally, Intellectual Property Rights (IPR) may act as a barrier to exploiting flexibility. Current DoD policy (as stated in the Defense Federal Acquisition Regulations Supplement [DFARS]) is to limit the acquisition of property rights, however the need to exploit flexibility in the future may require the exchange of IPR between contractors or between the government and contractor. Otherwise, the government may be locked into sole source strategies to implement future designs or modifications. In the case of small business, this lock-in may require the government to support these companies so that they will be available in the future. Financially, procuring the IPR or incentivising contractors to share IPR may be a better value.

Financial Implications

Cost As an Independent Variable (CAIV) is an acquisition management strategy that involves setting aggressive, yet realistic cost objectives to balance needs against resources. This financial guidance is intended to focus the user community on cost performance trade-offs and prioritize cost as a program metric. Excessive importance placed on cost may replace mission success as the primary driver in managing programs. (DSB 2003) Using flexibility to ensure mission success may also then place secondary to cost. Program managers are unable to spend more initially to design flexible systems that will cost less in the future. Additionally, CAIV metrics do not consider future benefits. Instead, cost is reported using only ratios of budgeted costs and actual costs.

Another potential financial barrier to enabling flexibility is the collective action dilemma: who pays for the flexibility? This problem arises in programs that serve multiple customers, each with different future needs. For example, the MAV case study in Chapter 4 demonstrated a change in stakeholders to include a new customer, US Army. The original customer, US Air Force, did not want to pay to add flexibility to later accommodate Army needs. In this simple case, Army provided funding to develop systems for their needs. However, rather than making the existing MAV flexible to perform new capabilities, a new platform was created and diverged from the original design since Army wanted ownership of their product in return for funding. The result was more cost to the government and the development of two products each with separate logistics chains. Reconciling stakeholder preferences is not always possible. Therefore, solving the collective action problem is critical to funding flexible design.

Finally, current budgeting practices lack incentives to save program dollars. Programs that finish under cost are not rewarded, but rather punished. The leftover funds are not returned to the program. Congress and DoD decision makers view cost underruns as inefficient initial estimations of program costs. They interpret the excess funds as dollars the program did not need and thus future years are adjusted to reflect less funding. Therefore, program managers are encouraged to expend all program dollars prior to the end of the fiscal year, and thus cost savings resulting from flexibility are not always valued.

Stakeholder Control of Implications

summarizes which stakeholders are impacted by each of the recognized policy, legal and financial implications.

Table 5-3. Implication Impact on Stakeholders

			User / Warfighter	Development Agency (Labs)	Acquisition Agency (SPO)	Contractors	T&E Community	Congress & DoD Policymakers
Policy Implications	Enablers	Simplified Acquisition Processes	✓		✓		✓	✓
	Barriers	Oversight and Accountability Requirements		✓	✓			✓
		Resource Allocation Schedules	✓		✓			✓
		Lack of Incentives for Flexibility		✓	✓	✓		✓
		Lack of Technical Government Workforce		✓	✓			
		No Formal Requirement for Uncertainty Identification and Analysis		✓	✓	✓		✓
Legal Implications	Enablers	Multiyear Task and Delivery Order Contracts	✓	✓	✓	✓		✓
		Non-Competition Strategies		✓	✓	✓		
	Barriers	Legislating "Minute Details" of SOPs						✓
		Lack of Procurement for Intellectual Property Rights		✓	✓			
Financial Implications	Barriers	CAIV Metrics		✓	✓			✓
		Who Pays for Flexibility?	✓					
		Lack of Incentive to Save Program Funds	✓	✓	✓	✓		✓

Recommendations for Enabling and Exploiting Flexibility

The following recommendations should be considered to improve the DoD Acquisition Management Framework to enable and exploit flexible system design.

Recommendation #1—Restoring Technical and Managerial Expertise in Government Program: To mitigate the challenges imposed by asymmetric information resulting from reliance on contractor reporting, the government needs to stop contracting the role of management and systems integration. The government needs technical expertise and systems managers in the acquisition profession to provide checks and balances to the contractor counterpart.

Recommendation #2—Require initial uncertainty analysis for acquisition programs: To be able to correct error in the initial assumptions, program managers must first be made aware of the uncertainties relevant to the assumptions on which the decisions are based. Additionally, the uncertainties will foster development of the indicators that should be used to measure program progress, rather than limiting to the metrics of cost, schedule, and performance. Currently, DoD uses universal, one-size-fits all metrics for monitoring program progress. Although advantages for using standard metrics is argued to allow cross-portfolio comparisons, customized metrics in addition to the universal metrics may allow program managers to improve management of the complex programs. Large programs with many stakeholders may not be able to mobilize renegotiations to react to changes in the information, however, program managers should provide an impact statement to help convey the value of renegotiations if warranted.

Recommendation #3—Include uncertainty-driven indicators as a metric for knowledge assessment reported at program reviews: Supplemental to Recommendation #2, program managers should identify relevant (or customized if necessary) indicators for program evaluation. These metrics should be tracked and updated throughout the program lifecycle to enable stakeholders to adjust to the new system environment.

Recommendation #4—Require key program management tours to be a minimum of four years (DSB 2003): Program managers that are responsible for key programs rotate very two to three years, resulting in a lack of continuity in the program strategy and/or execution. These program managers do not have adequate time to come up to speed on the program details, investigate or update uncertainty analysis, and affect the long-term goals of the program. Longer tenures would greatly improve incentives to design for flexibility and accountability for responsibilities.

Recommendation #5—Restore responsibility, authority, and accountability to lower levels of the Acquisitions Management Framework: DoD policies must focus authority, responsibility and accountability at lower levels of program acquisition. This requires a change in the paradigm for selecting program managers with the appropriate technical skills and reducing rotation of personnel as noted in Recommendations #1 and #4. Additionally, the Secretary of Defense and military service secretaries should clearly define who is accountable on a program for what, and then they must hold people accountable when responsibilities are not met. Authority to execute programs must accompany this responsibility and accountability of program managers. Finally, improving the use of award fees to only reward excellent performance can serve to hold contractors accountable for delivery of flexible systems.

Recommendation #6—Improve cost estimation to include contingency funds: DoD currently advocates cost estimation that results in a 50-50 chance for cost overruns. The lack of planning for these contingencies means that other performance goals, technology developments, or units for procurement will be cut to accommodate the overrun. The calendar-based funding cycle is not flexible enough to allow reprogramming of funds to absorb overruns. DSB (2003) has suggested movement to an 80-20 cost estimation model, where the cost is estimated such that there is only a 20% chance for overruns. However, lack of incentives to return funding challenge implementation. Therefore, it is necessary for DoD to establish procedure to place a percentage of the budget for each program into a contingency fund, which feeds back into programs in the out-years if not used.

Conclusions

As the costs of weapons systems continue to increase and the buying power of the government decreases, acquisition of flexible weapon systems is critical to maintain operationally ready forces. Flexible weapon systems acquisition will require designs that are capable of self-correction and processes that allow the maturing technology to self-correct when new relevant information becomes available. Changes in the DoD requirements to develop flexible systems will not alone be sufficient. DoD also needs to alter the acquisitions framework to allow decision makers to exploit the new flexibility under changing conditions as indicated by the metrics of uncertainty. DoD Acquisitions needs a means for reconsidering earlier decisions if and when our understanding changes sufficiently to call earlier decisions into question. Noting the previous recommendations will be critical on the road to recovery.

Chapter 6: Conclusions and Future Work

A review of current literature identifies a research gap regarding how to identify opportunities for embedding flexibility. Approaches to design platforms or process standardizations are context specific and offer little insights for general guidelines for selecting flexibility efforts. As a result, potential opportunities for developing flexible systems may go unrecognized.

The goal of this research is to design an approach for identifying where in a system one should look to embed flexibility. This research effort includes:

- a survey of the existing approaches for embedding flexibility;
- a proposed methodology for identifying FDOs using the ESM framework;
- prescriptive recommendations for applying the methodology to a MAV case study; and
- policy considerations for implementing design for flexibility within the DoD acquisitions guidelines.

Emphasis was placed on developing a practical methodology that is computationally feasible and applicable to a diversity of engineering systems. Furthermore, special consideration was given to assuring that the proposed methodology can be scaled for large, complex systems.

The proposed methodology combines the strengths of sensitivity and change propagation techniques to identify FDOs. Bartolomei's (2007) ESM framework was adopted to provide structured representation of the system, extending the analysis to include non-technical domains. The methodology evolved from several iterations and adjustments to the selection of combined approaches such that the simplified example produced intuitive results.

Finally, this research validates the proposed methodology through demonstration using a case study of the MAV. It stems from previous efforts and includes a detailed ESM constructed over two years. (Bartolomei 2007) Participating as the former system designer and program manager, the author of this thesis was heavily involved in the construction of the ESM and provided key insights regarding the validity of the results processed from the proposed methodology. Thus, the effort proved worthwhile and capable of identifying FDOs.

Contributions

This research results in two major contributions:

1. development of a worthwhile methodology that combines the benefits of analyzing change behaviors and magnitudes to identify FDOs; and
2. management of analysis complexity using filtering techniques to provide a scalable solution.

Table 6-1summarizes past approaches and the proposed methodology's ability to address multiple aspects of saturation.

Table 6-1. Approach Saturation Assessment Summary

	Primary Factors		Secondary Factors			
	Magnitude of Change	**Change Behavior**	**Multi-Domain Analysis**	**Traceability / Transparency**	**Ranking**	**Multiple Contextual Changes**
Interview Method			✓			
Sensitivity Analysis	✓				✓	
Change Propagation Analysis		✓			✓	
Hotspot Analysis*	✓	✓	✓	✓		
New Method for Identifying FDOs	✓	✓	✓	✓	✓	✓

*Bartolomei (2007) provides a conceptualization only.

Future Work

Additional research is required to promote the application of the methodology in practical work. The proposed methodology can be improved by further review of the inherent assumptions, development of software algorithms to lessen the human-input burden, and validation using additional case studies. Finally, this and similar efforts should be encouraged to pursue collaborative research with new metrics to quantify flexibility.

Investigation of Assumptions

Five assumptions were presented in Chapter 4 through demonstration of the methodology:

- ***Assumption #1: Change scenarios include only one system driver.*** This assumption omits the need for conditional logic to represent the change scenario in state form. Including algorithms to accommodate conditional logic is not difficult, and it potentially reduces the number of analysis cycles by combining multiple change scenarios that represent single system drivers. Furthermore, multiple system drivers influence most systems simultaneously, and thus conditional logic improves the accuracy of the results.

- ***Assumption #2: Identify flexibility "in" the system.*** This assumption restricts selection of the change initiators to physical objects within the system. The focus of this research was to identify opportunities for embedded flexibility in the physical system. However, the proposed methodology can be extended to consider change ways to incorporate flexibility into the social, functional, and environmental domains as well.

- ***Assumption #3: Change initiators activate individually.*** Similar to Assumption #2, disallowing multiple change initiators to activate simultaneously omits the need for conditional logic. Again, including algorithms to accommodate conditional logic is not difficult. It can simplify the analysis by combining states of multiple CIRTs and capture the dependencies of CIRTs, thereby improving the accuracy of the results.

- ***Assumption #4: The probability of change propagation is conditional on prior events.*** This assumption terminates change paths when a component acts as a known change absorber. However, further investigation is warranted to understand whether or not the change path terminates prematurely.

- ***Assumption #5: Switch costs are determined using path independence in the absence of a detailed cost model.*** This assumption allows rapid calculation of the CEE, and ultimately the DFS indicating if the component is a FDO. However, in practical application the switch cost associated with changing a component is typically depends on changes that occur upstream. Additional research is required to understand how to integrate cost models and the sensitivity of the results in the absence of detailed cost models.

Improve Software

Software used in Chapter 4 to implement the methodology is only a temporary solution. Effort to integrate the SMaRT input and analysis algorithms in MATLAB will alleviate cumbersome human interaction, and reduce time required for analysis cycles. Furthermore, the results of analysis are currently being exported and processed in MS Excel. A computer-savvy research could likely develop a wrapper to incorporate all these tools into a single user interface.

Validation Using Additional Case Studies

This research provided demonstration of the proposed methodology using a simple, yet practical, MAV application. Additional case studies are required to examine extension of the methodology to:

- Identify flexibility in non-technical domains;
- Use in analyzing large, complex systems;
- Validate repeatability of results.

Emphasis on diversifying case studies to draw from several fields of technology is important, especially investigation of the methods applicability to software and information technology systems. Furthermore, future research should consider applying the methodology to commercial case studies to prove worth in non-military systems.

Quantifying Flexibility

The proposed methodology identifies where to embed flexibility in a system. However, analysts and decision makers may also be interested in comparing the flexibility of different designs, which requires a metric for quantifying flexibility. Future research should investigate pairing the methodology and filtered outdegree (f-OD) to help guide designers to generate and embed flexibility to enable value-driven flexible systems.

Ross (2006) introduces the concept of f-OD as a quantified measure of the perceived degree of changeability of a system. The outdegree is the number of possible end states for a design when analyzed within a tradespace network, which is formed through the enumeration of transition rules that specify how a given design can be changed. The more end states available, the more flexible the system. The filtered outdegree is filtered by the transition cost acceptability threshold, which varies across decision makers.

The methodology presented in this thesis and f-OD can be used in concert to increase flexibility at a system level. Designers can use change scenarios to motivate system transition options or paths, and use f-OD to find system designs that are more flexible. The OD function can provide decision makers with a visual representation of the tradeoff between cost incurred in exercising transitions and the variety of transitions available from which to choose. Since the cost of transition is directly related to aggregate switch costs, the CEE can be used to determine where in the system those costs are incurred, and identify portions of the system that could benefit from redesign (e.g. through the addition of options) to reduce transition costs and/or to increase the variety of transitions available at a given cost. This hypothesis warrants further investigation.

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Appendix A: Sample Survey for Application of FDO Methodology

Survey for Engineering Systems Matrix and Analysis

POC: [Interviewer, Contact Info]

Date:____________________________________

Project Title:______________________________

Name:___________________________________

Organization:_____________________________

Title/Position:_____________________________

Role/Relationship within the System: (Please provide a brief description of your responsibilities and number of hours you work on the project per week.)

Area(s) of Expertise:

Are you available for follow-up interview? Yes / No   If yes, please provide your preferred contact information and availability.

Part 2. Intuition Experiment

Using the list of components/subsystems provided, answer the following questions using only your knowledge of the system.

1. Review the provided list of components/subsystems. Do you feel any have been omitted? Do you feel any that are listed that should not be listed?

2. What components/subsystems in the system are most concerning? What do you spend most time thinking about or worrying about? Why?

3. Which components are most likely to change in the system?

4. Which components contribute most to the cost of the system?

5. Which components if changed will likely have the most significant impact on cost? (Indicate both positive and negative impacts.)

6. Which components if changed will likely have the most significant impact on schedule? (Indicate both positive and negative impacts.)

7. Which components if changed will likely have the most significant impact on performance? (Indicate both positive and negative impacts.)

8. What does flexibility mean in the context of this system? How important is flexibility to this system?

9. Which components would you most likely desire to embed flexibility? With respect to what do you desire to have flexibility? (Specific objectives? Technology advancements? Performance?)

Part 3. Constructing the ESM

1. Identify major system objectives. Rank the objectives in terms of overall mission effectiveness/criticality. [NOTE: Consider all potential stakeholders starting with the internal stakeholders and moving to external stakeholders.]

2. Identify the design parameters for each objective. Rank the parameters with respect to objective sensitivity. (There will be some overlap of design parameters for multiple objectives. Be sure to list under each applicable objective.)

3. Identify major physical subsystems. These subsystems are the physical objects in the ESM. If desired, further decompose subsystems into major components.

4. Identify the design parameters for each physical object. Rank the parameters with respect to object sensitivity.

5. Identify the major types of relationships connecting components in the system. Examples include information flows, power flows, mass flow (air, fuel, water, etc), and geometric constrainers.

6. Draw the system flows for each of the relationship types identified.

7. Consider each connected pairing of physical objects. Rank the relationships identified between the pairing. (For example: Component A and Component B share three relationships: rel1, rel2, and rel3. However, rel2 is the dominant relationship between Component A and Component B.)

Part 4. Development of Change Scenarios

1. What are the uncertainties in the system?
    a. Operational Uncertainties? (How the system will be used—examples include operational radius, operating environments, CONOPs, etc.)

    b. Technical Uncertainties? (What technology will be available—examples include rapidly progress technologies, technical deficiencies, etc)

    c. Managerial Uncertainties? (What procedures are required for development and acquisition, i.e. scheduling, funding cycles, funds, etc)

2. Which three or four of the above identified uncertainties are most likely to occur? Rank order these uncertainties.

3. Which three or four of the above identified uncertainties will have the strongest impact to the system (performance, cost, schedule)? (either positive or negative impacts—please specify) Rank these uncertainties.

Part 5. Change Propagation

Using the list of subsystems/components provided, consider each changes scenario independently to answer the following questions.

1. Given the change scenario, which components would you likely want to change in response to the scenario? (Only indicate where you would introduce a change, i.e. the first-order effect only. This component will be known as the change initiator. In some cases, a change scenario may be resolved by choosing from several components to initiate change. Indicate all that apply in a rank ordered list.)

2. Identify the relationship types that are important given the change scenario. Rank order with respect to impact of change.

3. For each change initiator, draw the change flows for each relationship type identified above. These change flows create the change network.

4. A change is propagated if a tolerance/contingency margin is violated. For each connected physical object, consider what tolerance margins exist for the given relationship type between connected objects. (For example, given the power supply is a change initiator and component A receives power from the power supply, consider the tolerance of component A to changes in the power supply voltage or current supply.) Repeat for all components in the change network.

Part 6. Switch Cost Assessment
Using the list of subsystems/components provided, consider each changes scenario independently to answer the following questions.

Estimate the cost associated with each edge in the change network. All edge costs will then be summed to calculate a total switch cost for the change given the change initiator and change scenario.

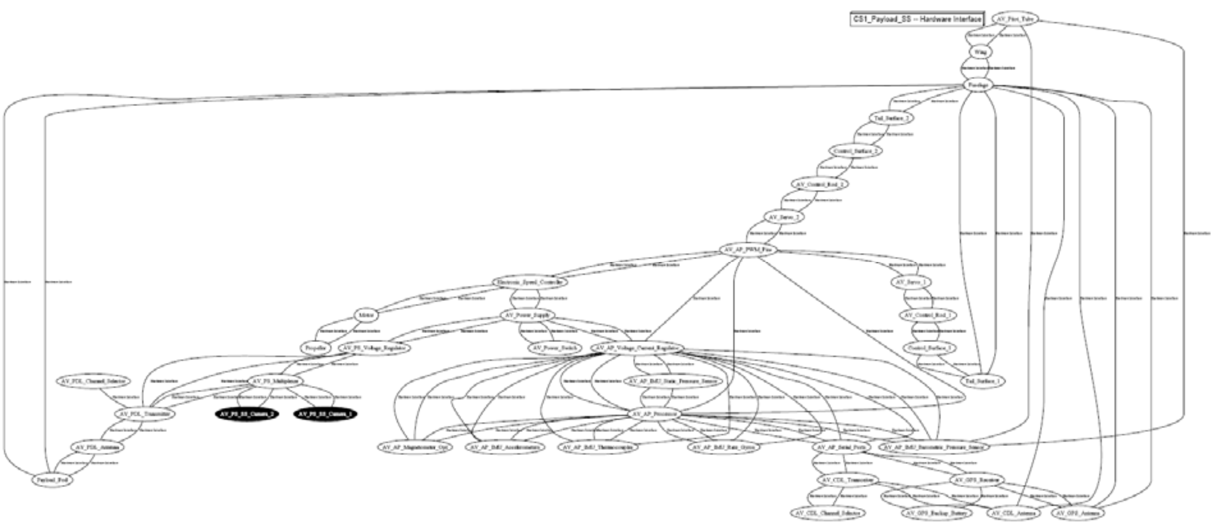
Appendix B: MAV Case Study Data

This appendix includes data used in the MAV Case Study presented in Chapter 4. The system connectivity graph represents the system flows filtered for the identified change initiator and relationship type (CIRT) pairing (Step 4). The change initiators are highlighted in the graph. CIRT change graphs depict the change flows as indicated by SMEs (Step 5). The CEE Matrix documents the likelihood of change propagation for each segment of the change graph and the CEE for all components (Step 5).

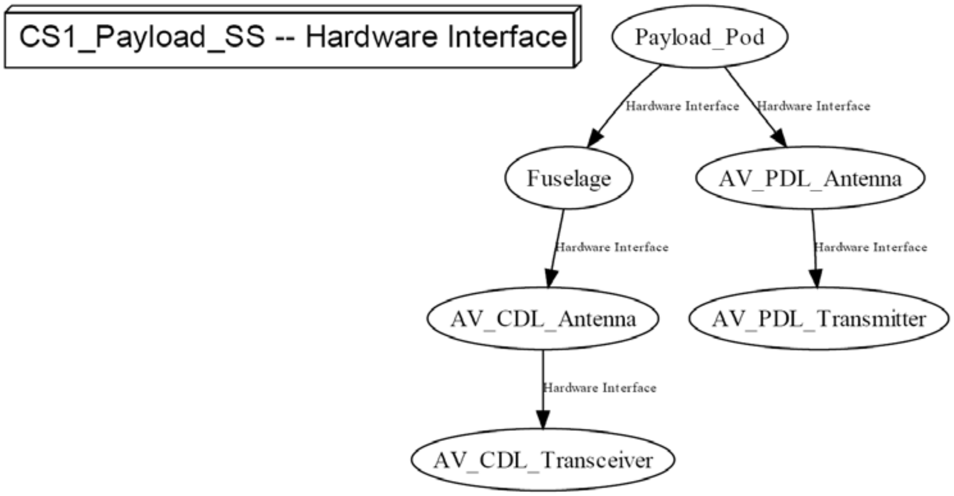
Change Scenario #1: Payload Sensor Suite Technology Upgrade

Change Initiator: Cameras 1 and 2
Relationship Type: Hardware Interface

System Connectivity Graph



CIRT Change Graph

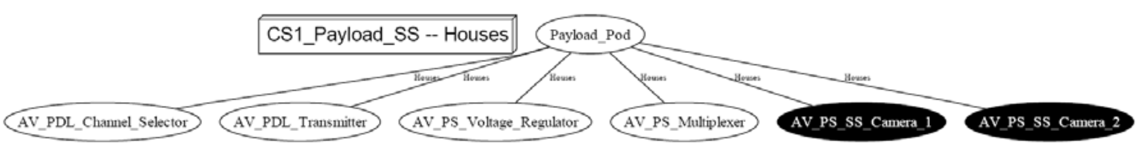


CEE Matrix

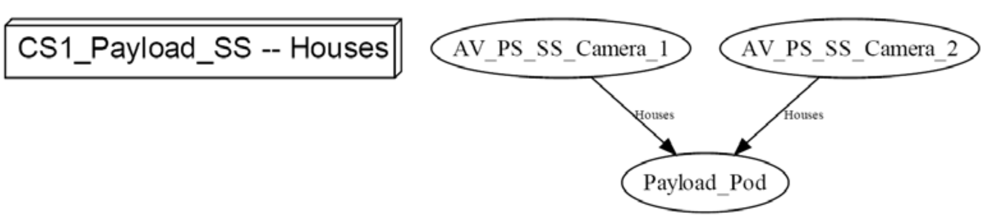
	Pc	Cost	CEE	CEE*
AV_PDL_Transmitter	0.2	200	40	8
AV_PDL_Antenna	0.8	25	60	12
Payload_Pod	1	1000	3595	719
Fuselage	1	2500	2535	507
AV_CDL_Antenna	0.2	25	35	7
AV_CDL_Transceiver	0.2	150	30	6

Change Initiator: Cameras 1 and 2
Relationship Type: Houses

System Connectivity Graph



CIRT Change Graph



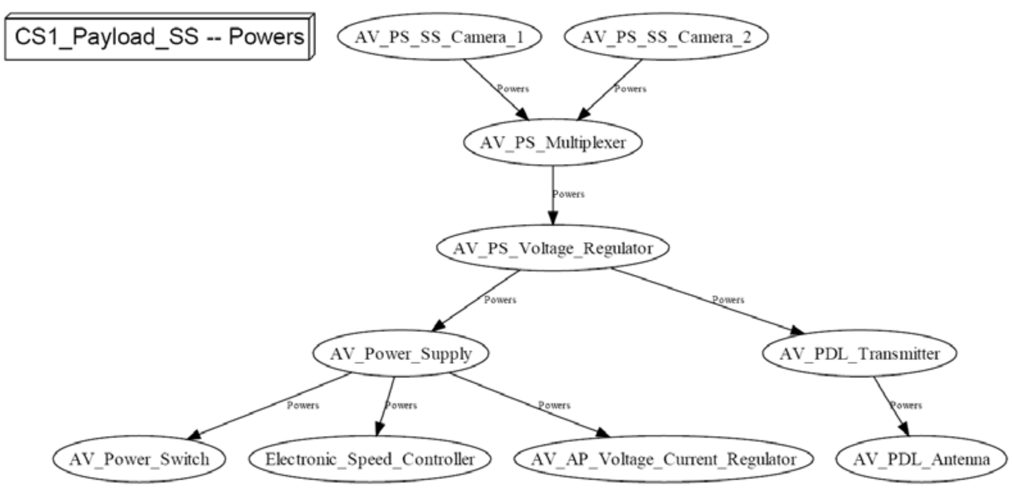
CEE Matrix

	Pc	Cost	CEE	CEE*
Payload_Sensor_Suite	1	15000	15000	3000
Payload_Pod	1	1000	16000	3200

Change Initiator: Cameras 1 and 2
Relationship Type: Powers

System Connectivity Graph

CIRT Change Graph

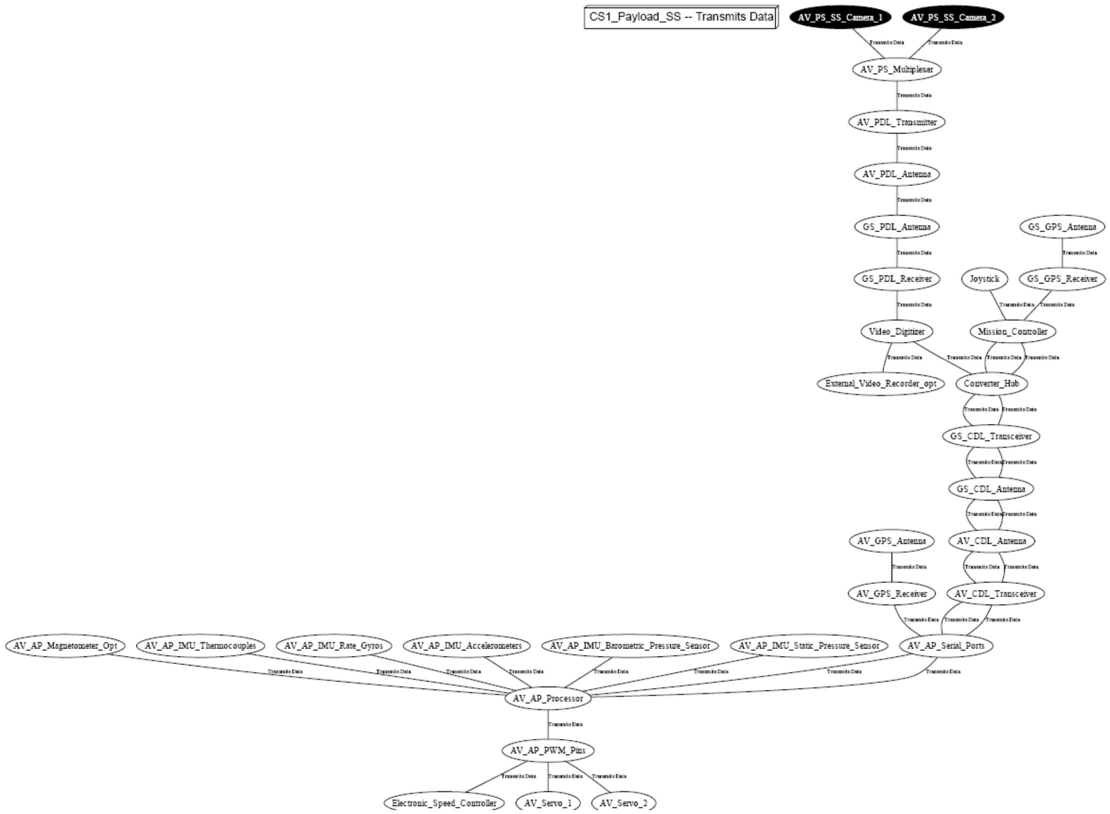


CEE Matrix

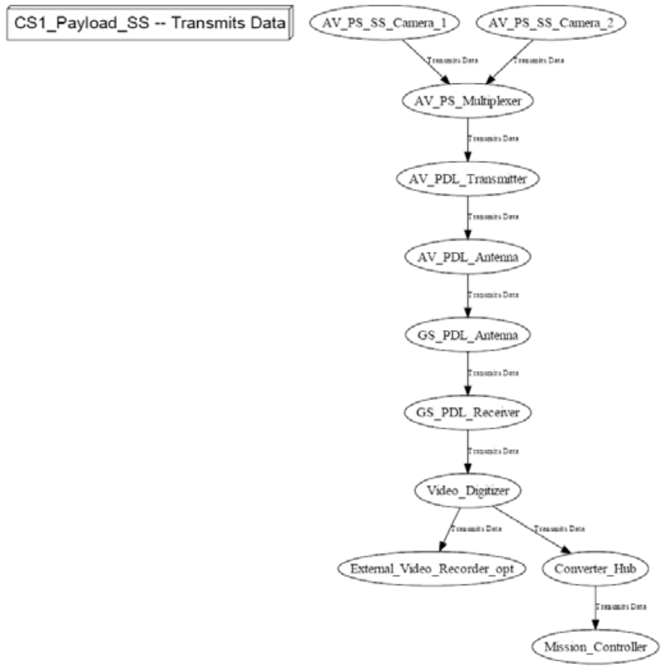
	Pc	Cost	CEE	CEE*
Payload_Sensor_Suite	1	15000	15420	12336
AV_PS_Multiplexer	0.8	250	420	336
AV_PS_Voltage_Regulator	0.2	50	220	176
AV_Power_Supply	0.8	200	210	168
AV_Power_Switch	0.2	50	10	8
Electronic_Speed_Controller	0.2	150	30	24
AV_AP_Voltage_Current_Regulator	0.2	50	10	8
AV_PDL_Transmitter	0	200	0	0
AV_PDL_Antenna	0	25	0	0

Change Initiator: Cameras 1 and 2
Relationship Type: Transmits Data

System Connectivity Graph



CIRT Change Graph



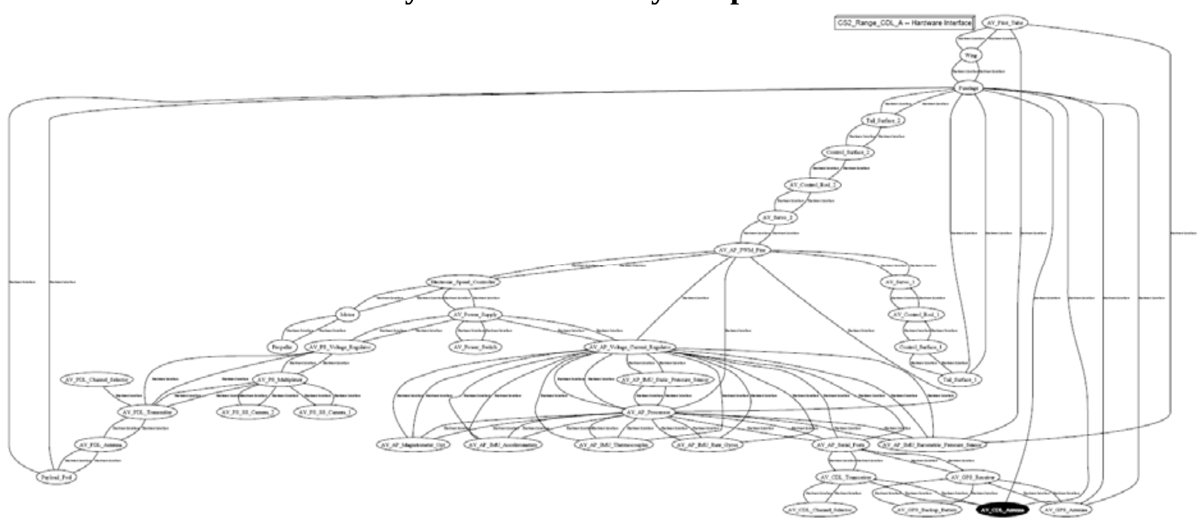
CEE Matrix

	Pc	Cost	CEE	CEE*
Payload_Sensor_Suite	1	15000	15585	12468
AV_PS_Multiplexer	0.2	250	585	468
AV_PDL_Transmitter	0.2	200	535	428
AV_PDL_Antenna	0.2	25	495	396
GS_PDL_Antenna	0.2	150	490	392
GS_PDL_Receiver	0.2	300	460	368
Video_Digitizer	0.8	100	400	320
External_Video_Recorder_opt	0.2	100	20	16
Converter_Hub	0.2	500	300	240
Mission_Controller	0.2	1000	200	160

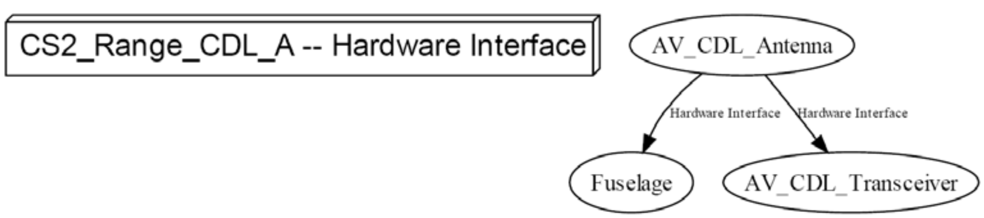
Change Scenario #2: Threats Requiring Change to Range Performance Objective

Change Initiator: Comm_Data_Link_Antenna
Relationship Type: Hardware Interface

System Connectivity Graph



CIRT Change Graph

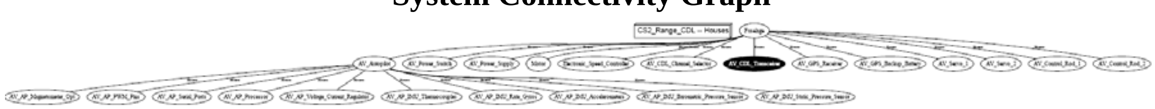


CEE Matrix

	Pc	Cost	CEE	CEE*
AV_CDL_Antenna	1	25	4025	805
Fuselage	0.8	2500	2000	400
AV_CDL_Transceiver	0.2	150	30	6

Change Initiator: Comm_Data_Link
Relationship Type: Houses

System Connectivity Graph



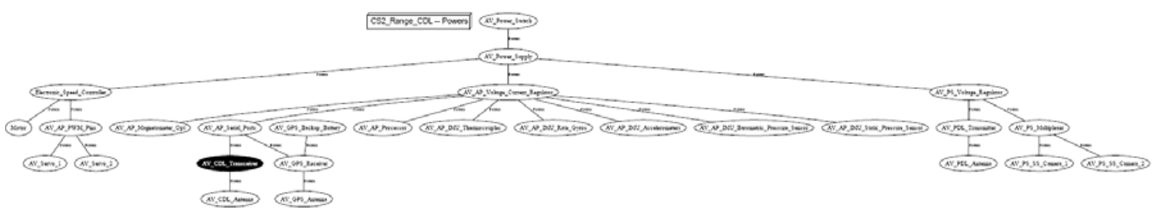
CIRT Change Graph

CEE Matrix

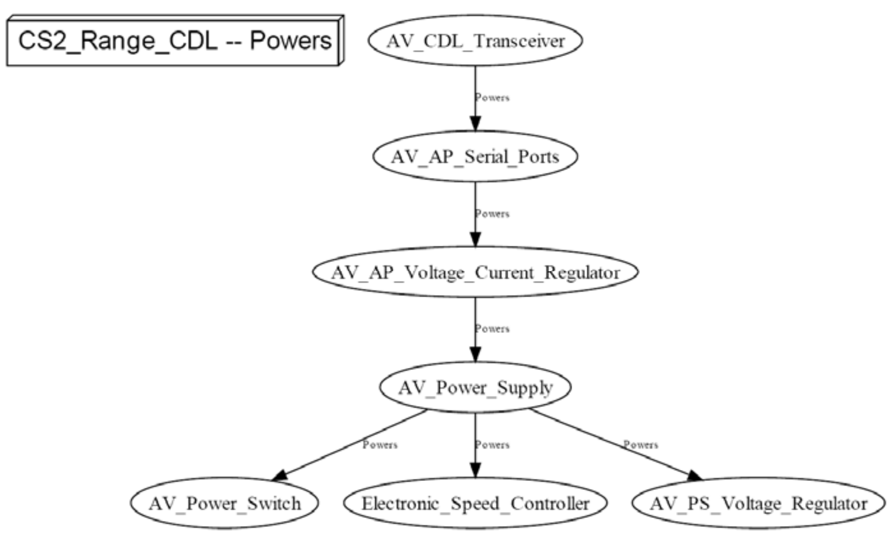
	Pc	Cost	CEE	CEE*
AV_CDL_Transceiver	1	150	650	130
Fuselage	0.2	2500	500	100

Change Initiator: Comm_Data_Link
Relationship Type: Powers

System Connectivity Graph



CIRT Change Graph

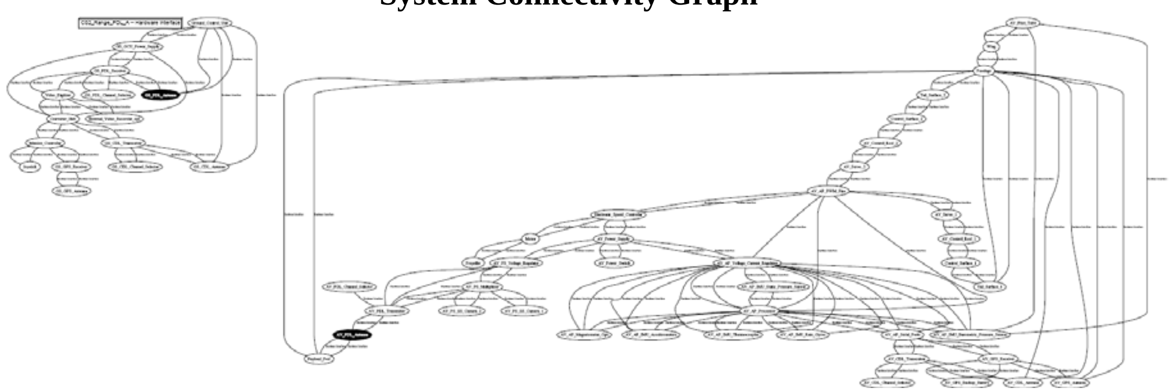


CEE Matrix

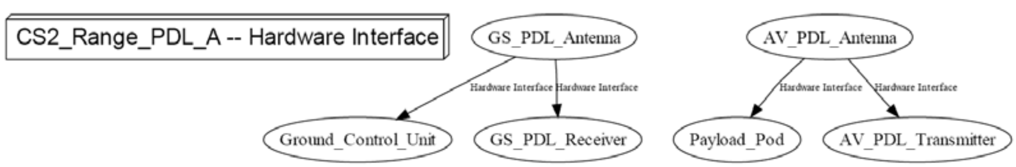
	Pc	Cost	CEE	CEE*
AV_CDL_Transceiver	1	150	370	296
AV_AP_Serial_Ports	0	0	220	176
AV_AP_Voltage_Current_Regulator	0.2	50	220	176
AV_Power_Supply	0.8	200	210	168
AV_Power_Switch	0.2	50	10	8
Electronic_Speed_Controller	0.2	150	30	24
AV_PS_Voltage_Regulator	0.2	50	10	8

Change Initiator: Payload_Data_Link_Antenna
Relationship Type: Hardware Interface

System Connectivity Graph



CIRT Change Graph



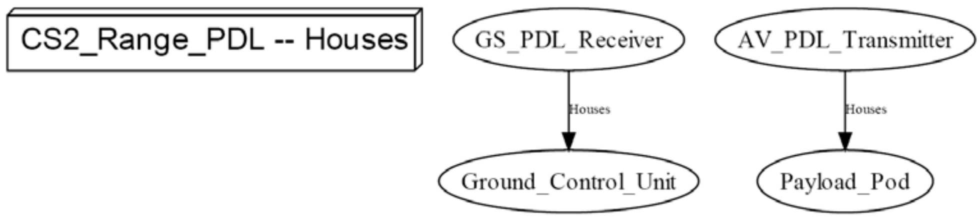
CEE Matrix

	Pc	Cost	CEE	CEE*
GS_PDL_Antenna	1	150	370	74
Ground_Control_Unit	0.8	200	160	32
GS_PDL_Receiver	0.2	300	60	12
AV_PDL_Antenna	1	25	865	173
Payload_Pod	0.8	1000	800	160
AV_PDL_Transmitter	0.2	200	40	8

Change Initiator: Payload_Data_Link
Relationship Type: Houses

System Connectivity Graph

CIRT Change Graph

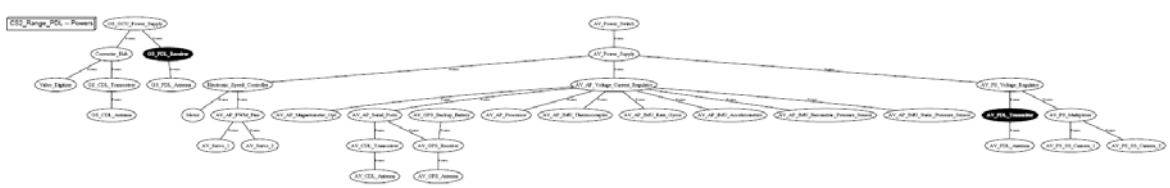


CEE Matrix

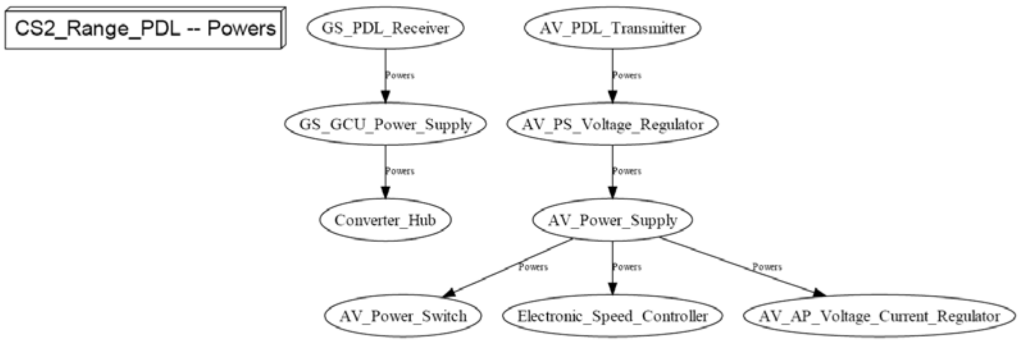
	Pc	Cost	CEE	CEE*
GS_PDL_Receiver	1	300	340	68
Ground_Control_Unit	0.2	200	40	8
AV_PDL_Transmitter	1	200	400	80
Payload Pod	0.2	1000	200	40

Change Initiator: Payload_Data_Link
Relationship Type: Powers

System Connectivity Graph



CIRT Change Matrix



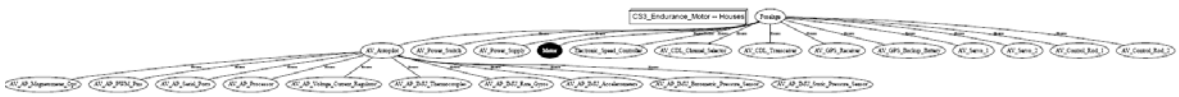
CEE Matrix

	Pc	Cost	CEE	CEE*
GS_PDL_Receiver	1	300	560	560
GS_Power_Supply	0.8	200	260	260
Converter_Hub	0.2	500	100	100
AV_PDL_Transmitter	1	200	420	420
AV_PS_Voltage_Regulator	0.2	50	220	220
AV_Power_Supply	0.8	200	210	210
AV_Power_Switch	0.2	50	10	10
Electronic_Speed_Controller	0.2	150	30	30
AV_AP_Voltage_Current_Regulator	0.2	50	10	10

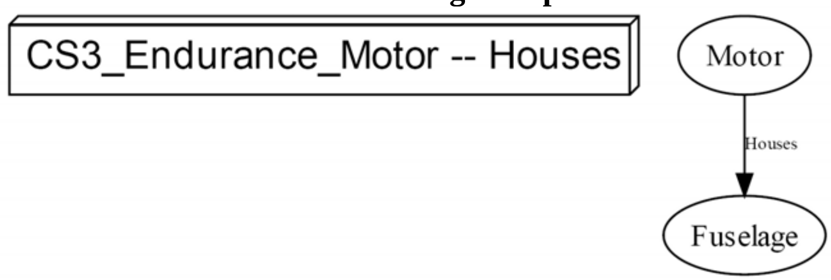
Change Scenario #3: New Customer Requiring Change to Endurance Performance Requirement

Change Initiator: Motor
Relationship Type: Houses

System Connectivity Graph



CIRT Change Graph

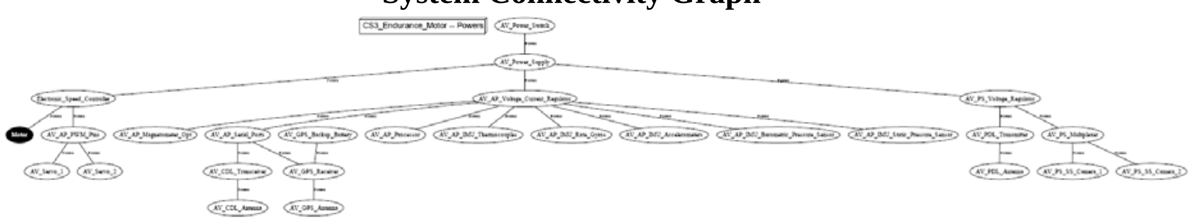


CEE Matrix

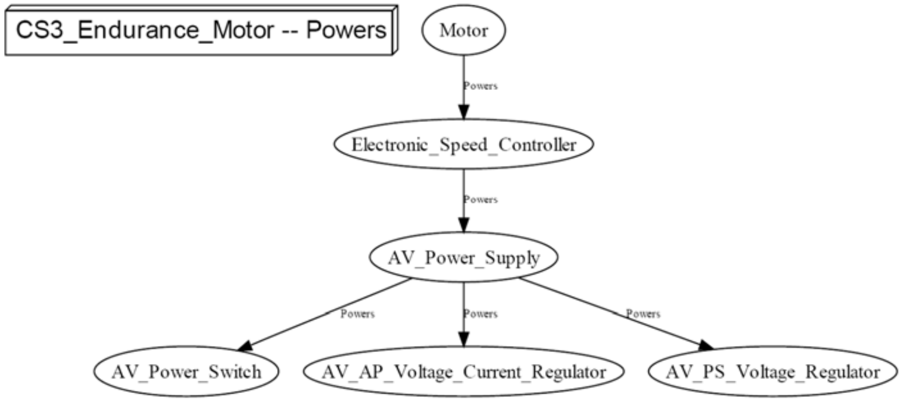
	Pc	Cost	CEE	CEE*
Motor	1	100	2100	1680
Fuselage	0.8	2500	2000	1600

Change Initiator: Motor
Relationship Type: Powers

System Connectivity Graph



CIRT Change Graph

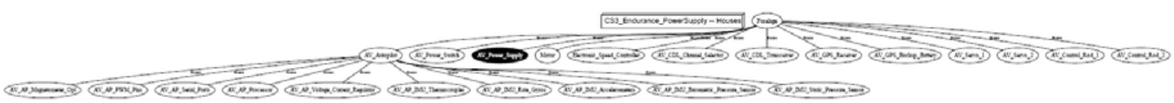


CEE Matrix

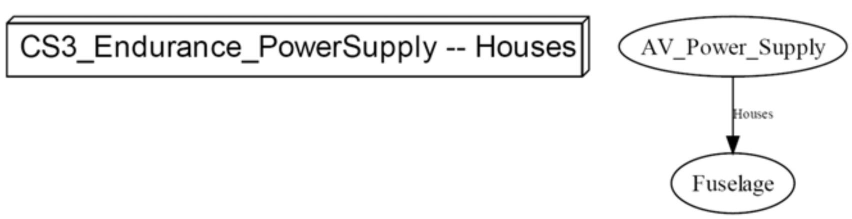
	Pc	Cost	CEE	CEE*
Motor	1	100	410	328
Electronic_Speed_Controller	0.8	150	310	248
AV_Power_Supply	0.8	200	190	152
AV_Power_Switch	0.2	50	10	8
AV_AP_Voltage_Current_Regulator	0.2	50	10	8
AV_PS_Voltage_Regulator	0.2	50	10	8

Change Initiator: Power Supply
Relationship Type: Houses

System Connectivity Graph



CIRT Change Graph

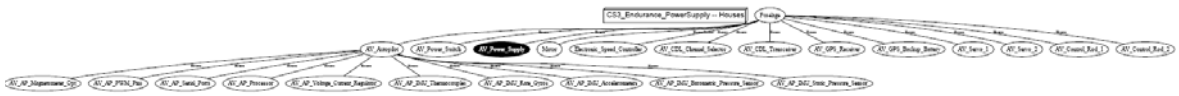


CEE Matrix

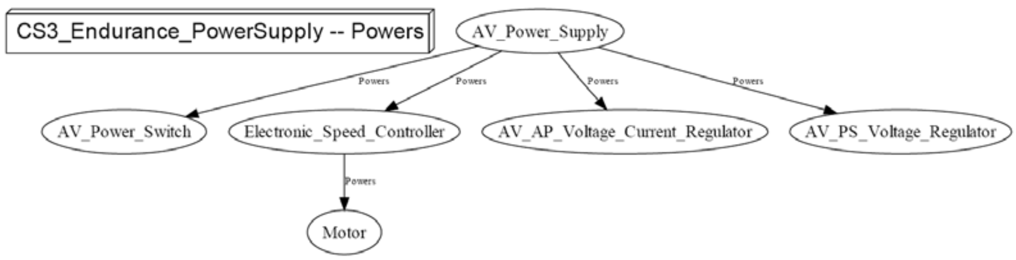
	Pc	Cost	CEE	CEE*
AV_Power_Supply	1	200	2200	1760
Fuselage	0.8	2500	2000	1600

Change Initiator: Power Supply
Relationship Type: Powers

System Connectivity Graph



CIRT Change Graph

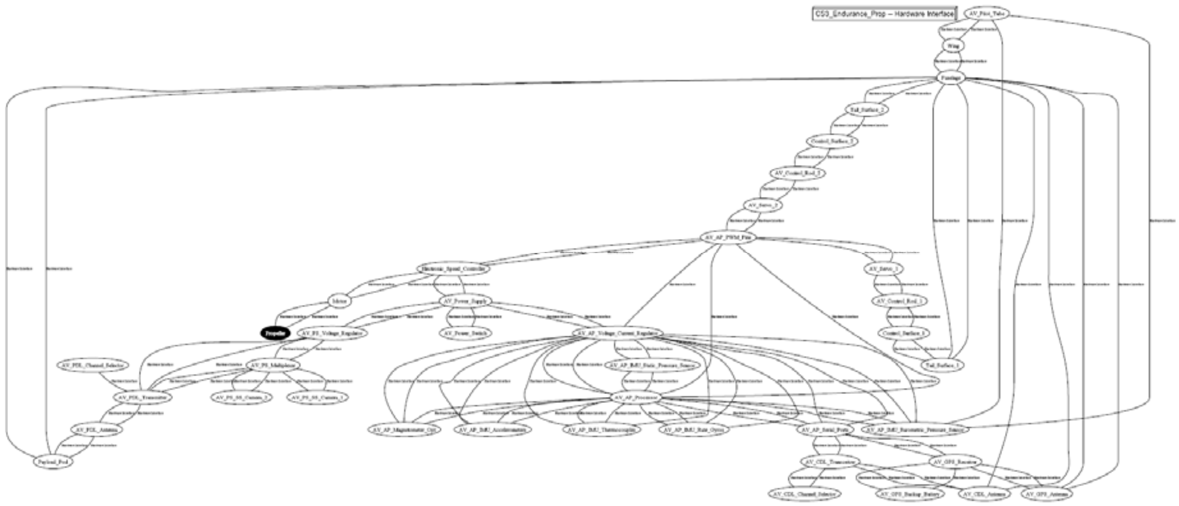


CEE Matrix

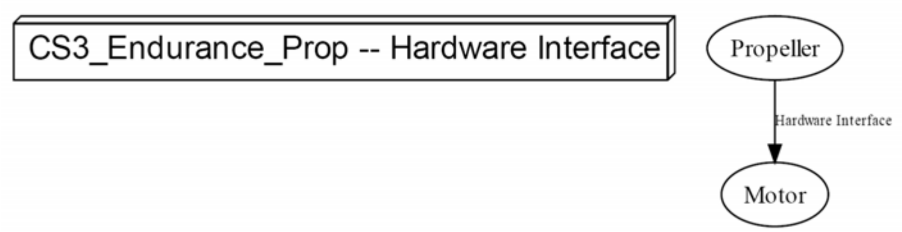
	Pc	Cost	CEE	CEE*
AV_Power_Supply	1	200	370	370
AV_Power_Switch	0.2	50	10	10
Electronic_Speed_Controller	0.8	150	140	140
Motor	0.2	100	20	20
AV_AP_Voltage_Current_Regulator	0.2	50	10	10
AV_PS_Voltage_Regulator	0.2	50	10	10

Change Initiator: Propeller
Relationship Type: Hardware Interface

System Connectivity Graph



CIRT Change Graph

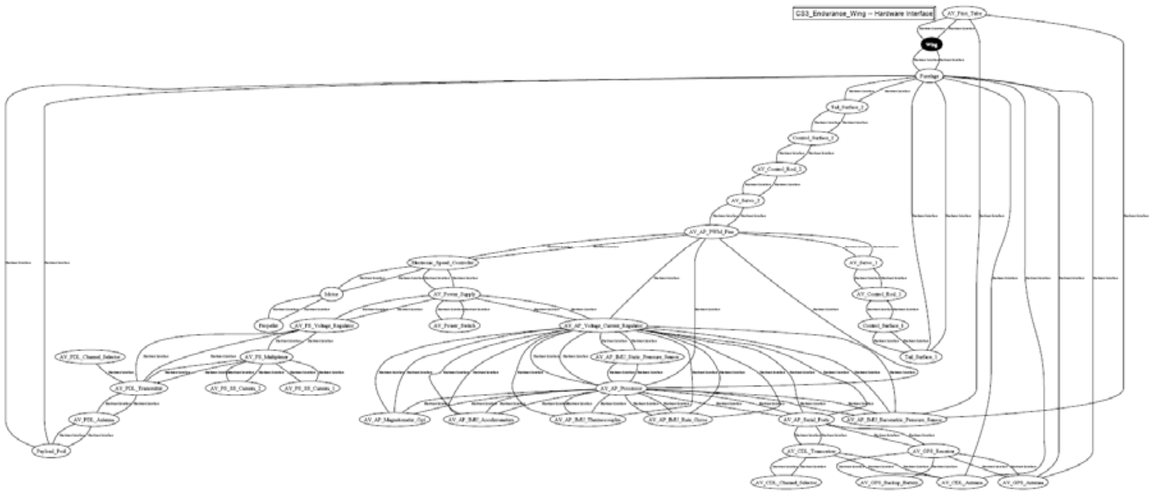


CEE Matrix

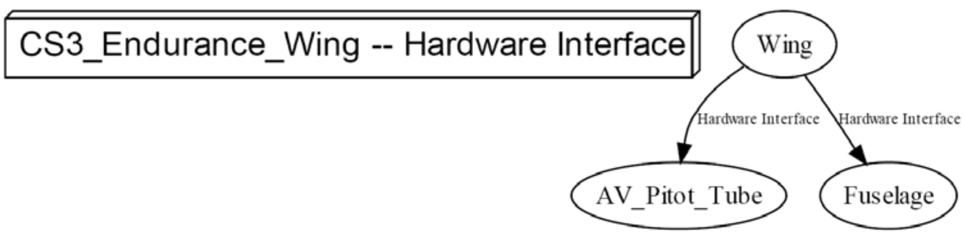
	Pc	Cost	CEE	CEE*
Propeller	1	50	70	14
Motor	0.2	100	20	4

Change Initiator: Wing
Relationship Type: Hardware Interface

System Connectivity Graph



CIRT Change Graph



CEE Matrix

	Pc	Cost	CEE	CEE*
Wing	1	3000	5016	4012.8
AV_Pitot_Tube	0.8	20	16	12.8
Fuselage	0.8	2500	2000	1600