

Understanding and Managing Uncertainty in Lean Aerospace Product Development

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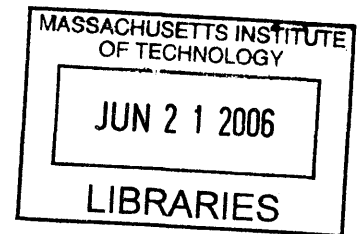
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Abstract

Aspects of aircraft product uncertainty during system development are examined. Generation of stakeholder value in lean aerospace product development is linked to the reduction or elimination of project risks and uncertainties in areas such as customer requirements, product performance, and issues that may arise later in the product's life cycle.

A commercial aircraft system project is explored as a case study. The system is comprised a numerous subsystems developed by separately managed teams. Teams had different approaches to risk identification and mitigation. The relative success of each team is summarized.

A framework for creating value by efficiently and effectively managing uncertainty and mitigating risks during aerospace system development is presented.

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Acronyms and Abbreviations

CDR	Critical Design Review
Cert	Subsystem Certification
CPM	Composite Performance Measures
DFX	Design for "X" (a generic term that collectively refers to Design for Manufacturability (DFM), Design for Reliability (DFR), etc.
ERP	Enterprise Resource Planning
IPD	Integrated Product Development
LAI	Lean Aerospace Initiative
LEM	Lean Enterprise Model
MFA	Market Feedback Analysis
MRP	Material Resource Planning
Qual	Qualification Testing
PDR	Preliminary Design Review
TPM	Technical Performance Measures
TPS	Toyota Production System

1 Introduction

1.1 Motivation

The Toyota Production System (TPS) has been widely studied and emulated for its ability to efficiently provide customers with high quality products. Translating these lean manufacturing concepts to product development activities has proven to be difficult and there are still many unresolved issues with the measurement and classification of “value” that is created by various development tasks.

In product development, the stakeholders not only want a product delivered on time and within budget - they also seek assurance that the system will meet their full expectations. The aerospace industry has a keen need to produce tangible evidence that quality and performance uncertainties have been eliminated. Therefore, one cannot discuss value creation in aircraft system development without an understanding of product uncertainty encountered on a typical program and the methods utilized to eliminate any associated risks so that the customer has total confidence in the product’s abilities.

1.2 Objectives

The objective of this paper is to explore the relationship between principles of lean product development with an emphasis on the effect of uncertainty and risk in this arena. The intent is to demonstrate a relationship between risk mitigation activities and the generation of customer value in the design and development process, and to provide guidelines for completing these activities in a manner that reduces cycle time, assures quality, and makes the most efficient use of company resources.

1.3 Scope

The term risk is used in a variety of ways in engineering and business environments. For a thorough discussion of the different uses of the word, please see Oehman (2005) which explores the link between risk management and crisis management and the ability of high performance teams to avoid crisis situations that can destroy a program's value.

The focus of this report is product risks (typically technical risks) that can affect planned program execution in aerospace system development, thus causing budget and schedule overruns, or failure to meet required product performance targets. The end result of these problems could be low customer satisfaction, failure to achieve profit goals, loss of market share, etc. This report is not intended to address risk in the same sense as a system safety analysis that looks at potential hazards attributed to an aerospace product in service.

2 Applying Lean to Product Development

2.1 Fundamental Lean Concepts

There are five basic principles in the application of lean thinking (Womack and Jones, 2003). They are:

1. Specifying value – The specification of value typically begins with the identification of customers. One must develop an understanding of their needs and desires in terms of specific products and services. The customer defines value.
2. Identify the value stream – This step maps the organization's tasks in a manner that allows people to visualize the end-to-end process including activities that are efficient and those that are wasteful. Lean analysis groups activities into 3

categories: value added (type I), non-value added but necessary due to other constraints (type II), and unnecessary non-value added.

3. Make the flow continuous – After the wasteful activities have been identified, the remaining activities are coordinated so that inputs and outputs flow between process steps unencumbered. This step requires a focus on the product's needs and should not be influenced by existing organizations or infrastructure.
4. Let customers pull value – An organization should not make anything until it is needed. Then it should be made without significant excess lead time.
5. Pursue Perfection – Practice continuous improvement and strive for a stream of perfect value creating processes. There is no end to this pursuit.

2.2 Lean in Manufacturing

The five steps described above have successfully been applied to many manufacturing organizations. Value is typically defined by customers as a manufactured product delivered at the right time, at the right price, and with sufficient quality.

Value stream mapping in manufacturing primarily traces the path of the physical product or products throughout the process. Waste that is identified in manufacturing processes has been loosely grouped into seven categories(Murman, et al, 2002):

- Rework (Defects)
- Overproduction
- Transportation
- Movement (motion)
- Waiting time
- Inventory
- Processing

Instituting flow in manufacturing involves discarding the batch-and-queue mentality prevalent in mass production and installing small-lot production, reducing inventory, by minimizing handoffs, queues, work-in-progress, etc. (LAI EVSMA, 2005)

It may also involve implementing MRP/ERP solutions for information management (Womack and Jones, 2003).

Inventory reduction and MRP/ERP systems are also involved in the implementation of pull in manufacturing systems. In addition, there is an analysis of takt times and lead times, and there is an attempt to level the production of products to the extent possible. Process measurement and control are keys to the pursuit of perfection in manufacturing (Hsu and Skevington, 1987).

2.3 Lean in Aerospace Product Development

Although Toyota's model can provide a valuable template, there are numerous differences between the aerospace and automotive industries that may influence the suitability of certain methodologies. The aerospace industry is characterized by (Murman, et al, 2002):

- Low volumes
- Cyclical business
- Product complexity
- Year-to-year variations

In addition, the author has personally encountered other factors that may present special consideration in aerospace products:

- More rigorous certification requirements (automotive is also high, but less so)
- Limited opportunities for new products
- Enormous development costs

Given these factors, aerospace systems often present a tremendously high risk to companies. In extreme cases, new product launches are sometimes referred to as “bet the company” projects. Risk management becomes a critical skill in these situations.

The translation of lean manufacturing methods to the product development environment is an active area of study and many open issues remain. Most of the differences are driven by the fundamental uncertainty in the product development process (PDVSM Guide, McManus 2004). It is less repetitive than manufacturing and uncertainty cannot easily be trimmed from the process by repetition of identical steps from iteration to iteration. Product development works on information about a product rather than the physical product itself, and all of the information is rarely available at the onset of a program. And finally, people engaged in product development work are more likely to encounter a mix of jobs, with greater and lesser difficulty and complexity.

Despite these differences, it can still be possible to apply the 5 steps of lean manufacturing as practiced by Toyota translate to product development in the aerospace industry. The initial challenge is defining value.

2.4 A definition of Value in Product Development

As stated earlier, the first step in instituting a lean methodology is specifying value. The creation of value in product development is not always intuitive.

Slack (1999) defines value in product development by the following equation:

$$\text{Value} = N * A * f(t) / C$$

Where N is the need for the product or service, A is the ability of the product or service to accomplish the customer need, f(t) is the time dependency (availability) on the value of the product, and C is the cost of ownership. The challenge becomes derivation of quantifiable metrics to apply to each of these terms. The quantities A and C suggest that development of a product only generates value if it can be shown to be compliant to the

stated and unstated needs of the stakeholders, and if the product development schedule matches the customer needs.

Browning (2002) simplifies Stack's equation by stating that product value is proportional to product performance divided by cost and lead time, where product performance can be equated to the elimination of product risk. Browning's analysis illustrates an important co-dependence in the product development value creation process: the ability to unambiguously demonstrate the quantity $f(t)$ is yet another element of N. In other words, proof that the customer needs have been met prior to entry into service is itself another customer need. Browning proposes a risk-value model to measure value through the reduction of risk since risk reduction can equate to product capability demonstration. Development of a product only generates value if it can be shown to be compliant to the stated and unstated needs of the stakeholders.

A common error in the management of product development programs is direct association of value with the creation of program artifacts or predefined schedule milestones. These may include completion of design drawings, electrical schematics or software code, test reports, and manufacturing facilities. However, the value of these artifacts can be minimal if the design and verification activities that preceded the artifact leave the product's capability uncertain. Too often, programs strive to achieve hollow milestones at the expense of true value adding activities that ensure the quality of the product.

There is a growing body of literature suggesting that product development is fundamentally not about creation. Rather, the ultimate goal of the process is elimination of any uncertainty related to the success of the final system (For example: Browning, Deyst, Eppinger, and Whitney, 2002). In many ways this perspective simplifies the application of lean principles to a product development environment. Risk and uncertainty are related principles. Risk management is about handling the unknown and achieving product robustness. (Bernstein 1996). "Risk denotes a combination of the likelihood and consequence of an undesired event." (NASA Systems Engineering

Handbook). If we can measure risk, we can measure the creation of value as the risks and the associated uncertainties are eliminated.

This is not an entirely new concept. One definition of value proposed by Deyst (2001) states “value is the amount by which risk is reduced per resource expended.” Utilizing this concept, risk mitigation activities are significant sources of value in the product development cycle. Chase (2002) takes a more balanced perspective on value, but still includes risk abatement in his definition. “Value encompasses the elements of performance, cost, schedule, and risk.”

Shaikh (1998) recommends that managers incorporate an expected value of the impact from identifiable risk issues in a development program’s cost and schedule tracking metrics.

Browning, Eppinger, Deyst, and Whitney (2002) propose Composite Performance Measures (CPM) based largely on the tracking of Technical Performance Measures (TPM) of the product. Examples of TPM’s include reliability and range of an aircraft compared to stated requirements. So once again, it is proposing that value is created when uncertainties are conclusively eliminated. Quantitative approaches to reducing product variability such as six sigma and robust design techniques (Thorton 2004) can be considered forms of risk reduction.

Browning discusses risk related to program schedule (1998) as well as product performance (1999). The two are interrelated. Sources of schedule risk include the number of intentional and unintentional iterations, activity (sequencing) (in)flexibility, availability of resources, and “unknown unknowns”. Sources of performance risk include the quality of the design concept, product complexity, requirement stability, and technology uncertainty. Clearly, schedule and performance compliance are both important to the success of a product.

The notion of value created by risk reduction exposes some basic differences in the application of lean to product development and manufacturing processes. When lean is applied in a manufacturing environment, iteration and non-linear process steps are almost always viewed as wasteful. There is an attempt to minimize process variations to maximize repeatability. At some level, product development processes are repetitive and present opportunities for lasting continuous improvement (Murman. et. al., 2002).

However, the level of uncertainty during the development phase of a program is far greater than in manufacturing. Each new product design differs from its predecessors in some way or else there would be no need to create it. "Iteration is not always a waste in PD processes, in fact managed iterations may be more desirable than a slower 'right the first time' process especially early in PD." (McManus, PDTTL Roadmap, 2005).

The elimination of uncertainty is seldom a straight forward process. Depending on the complexity of the design task, a development team may find it necessary to chip away at unknown qualities in a gradual manner.

2.5 Waste in Product Development

Bauch (2004) categorizes types of waste in product development and suggests methods for making the presence of waste transparent. He translated and expanded the seven manufacturing wastes to the collection summarized in the following table.

Table 1 – Product Development Wastes

Waiting	<ul style="list-style-type: none"> • People waiting for data, approvals, or other events • Information waiting for people • People waiting for capacity to become available
Transport/Handoffs	<ul style="list-style-type: none"> • Excessive data traffic • Handoffs • Stop and go tasks / task switching • Ineffective communication
Movement	<ul style="list-style-type: none"> • Lack of direct access • Information hunting • Remote locations
Overprocessing	<ul style="list-style-type: none"> • Unnecessary features and processes • Unnecessary detail and accuracy • Excessive approvals • Excessive transactions • Inappropriate use of competency • Inappropriate use of tools / methods
Inventory	<ul style="list-style-type: none"> • Unnecessary testing equipment and prototypes • Excessive data storage • Critical path related queues • High system variability • Exceeding capacity utilization • Large batch sizes
Overproduction / Unsynchronized processes	<ul style="list-style-type: none"> • Poor synchronization (contents) • Poor synchronization (time and capacity) • Over dissemination of information • Redundant tasks
Defects	<ul style="list-style-type: none"> • Deficiencies in IQ attributes • Erroneous data and information • Poor testing and verification
Re-invention	<ul style="list-style-type: none"> • Poor design re-use • Poor knowledge reuse
Lack of system discipline	<ul style="list-style-type: none"> • Unclear goals and objectives • Unclear roles responsibilities and rights • Unclear rules • Poor schedule discipline • Insufficient readiness to cooperate • Incompetence/training
Limited IT resources	<ul style="list-style-type: none"> • Poor compatibility • Poor capability • Low capacity (availability)

Many of the wastes described by Bauch are due to lack of coordination and communication. These include unavailable resources, redundant performance of tasks, excessive transactions, and poor synchronization of tasks resulting in unnecessary waiting. But there are also multiple categories related to program or product uncertainty and the impact of these unknowns. Examples are high system variability, erroneous data and information, rework, poor design and knowledge reuse (reuse is an elementary risk aversion strategy), and unclear goals and responsibilities. Kato (2005) ranked the most significant forms of waste and found that the top three are over-processing, rework, and incorrect information. It could be argued that both rework and erroneous information are byproducts of uncertainty in development. And at least one aspect of over-processing, unnecessary features, is also an indication of uncertainty in customer needs. So besides the earlier argument that elimination of uncertainty creates value by providing customers with requisite confidence in the product, it would also appear that uncertainty is a key topic in the elimination of waste.

Risk management is an effective approach to prevent “firefighting” further on in the development process (Smith et al. 2002). Firefighting is a term used to describe an unstructured and inefficient approach to project management focused on short-term accomplishments. Smith addresses a unified approach to risk management at the project level as a way to avoid this type of waste.

3 A framework for Understanding Uncertainty and Risk Mitigation

The purpose of this section is to broadly define a common set of definitions for:

- Categorizing the types of uncertainty that are typically encountered in aerospace product development,
- The management steps in identifying, tracking, and resolving the associated risks
- The most prevalent activities that can be used to reduce the amount of uncertainty and risk.

3.1 Classifying Uncertainty

If we are contending that value creation and waste elimination in product development hinges on uncertainty and risk, then a framework for describing and categorizing uncertainty is important. McManus and Hastings (McManus 2005) provide a framework for understanding uncertainty in complex systems. They note that uncertainties may provide opportunities as well as risk. In simple terms, they state **Uncertainties** lead to **Risks or Opportunities**, which are handled technically by **Mitigations or Exploitations**, which hopefully lead to desired **Outcomes**.

In their taxonomy, uncertainties are segregated into lack of knowledge and lack of definition. Herbert Simon wrote that man has bounds on his cognitive ability. These bounds are both internal and external, i.e. his mind and the availability of information in his environment. A person's working memory is claimed to be 7 +/- 2 "chunks". (Simon 1969). Furthermore, people do not typically utilize their full cognitive ability when making rational decisions. Decisions need to be made with limited time, knowledge, and other resources, and in a world that is uncertain and changing (Gigerenzer, 2001).

Figure 1 - Knowledge Classification illustrates one manner in which we might think about bounded rationality and uncertainty in a product development environment. There are facts that are unknown by anyone and others that will never be known. These are not worth addressing. There exists a more relevant space of facts that are known – at least by somebody. For those facts to be useful in product development, they must reach the person who needs them in a manner that is within his or her cognitive limits.

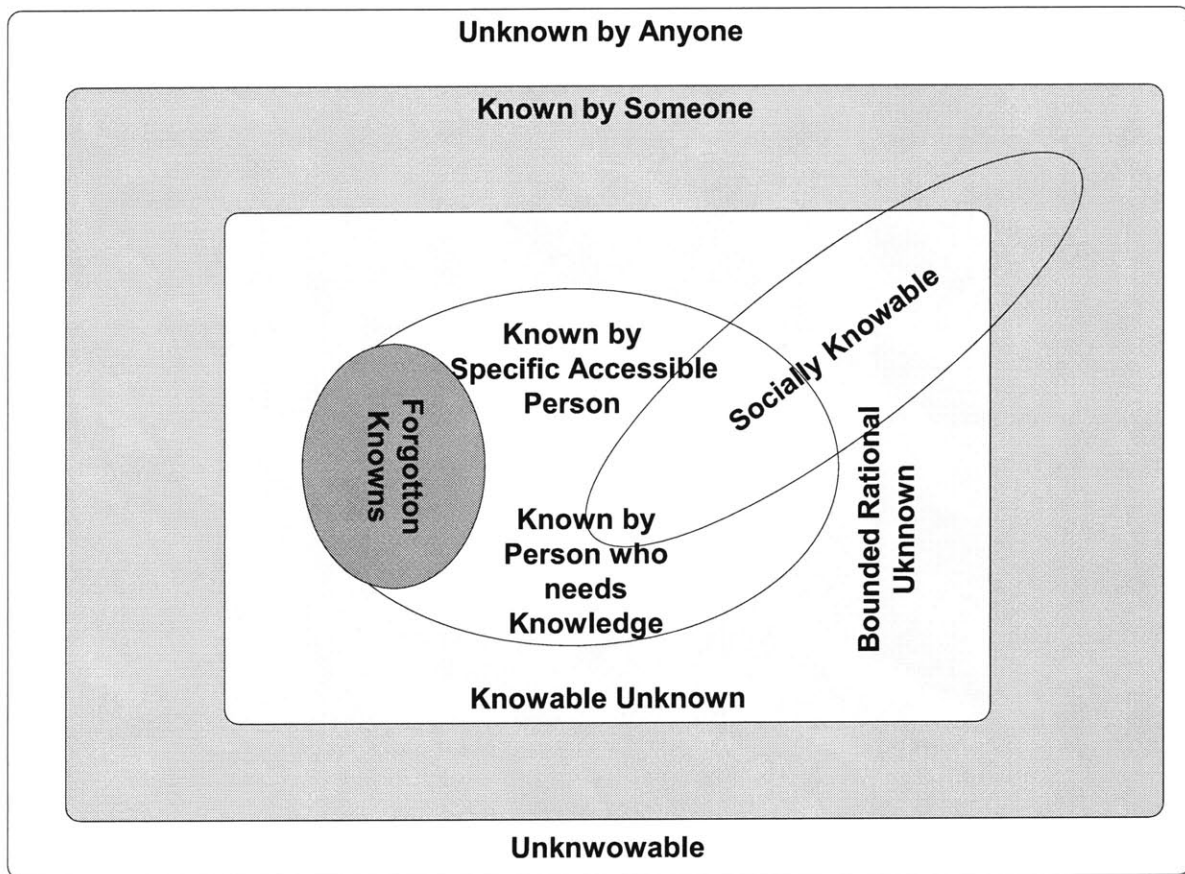


Figure 1 - Knowledge Classification

Rather than using Simon's concept of bounded rationality, McManus simply subdivides his classes of uncertainty into statistical phenomena, known unknowns, and unknown unknowns. The risks associated with these uncertainties include degradation (performance shortfalls) and funding/cost/schedule variations as well as others that are

beyond the scope of this paper (disaster/harm). Outcomes are defined in terms of product attributes such as reliability, robustness, versatility, flexibility, evolvability, and interoperability.

Another way to classify uncertainty has been proposed by the software engineering community. A 1993 paper by Carnegie Mellon's Software Engineering Institute proposed grouping product uncertainties into three basic categories. Uncertainties can be known, unknown or unknowable. "Known risks are those that one or more project personnel are aware of – if not explicitly as risks, at least as concerns. The unknown risks are those that would be surfaced (i.e. become known) if the project personnel were given the right opportunity, cues, and information. The unknowable risks are those that, even in principle, none could foresee." (SEI-93-TR-6, 1993). This is the uncertainty taxonomy that was utilized to conduct the research for this paper.

Classical project risk management techniques consist of methods to identify and mitigate known risk or concerns and certain tasks that have historically been proven to uncover unknown unknowns.

General categories of uncertainty and risk might include the issues listed below. This list is a generalized version of a list utilized by the engineering organization of a large aerospace company that will be discussed as a case study later in this paper.

- Component Variability - sample to sample variation in the elements that comprise a system. Often these variations can be described statistically
- Technology – technology without a proven history of performance
- Enterprise Capability – the organization's skills, expertise, or adequate facilities.
- Customer uncertainties – unknown customer needs or expectations.
- Interactions with other subsystems
- Design errors – performance failures brought about by flaws introduced inadvertently in the design process

- Life Cycle uncertainties – Uncertainty about the future and the ability to meet stakeholder needs after the completion of the design and development process.

Issues arising from unmanaged risks may include but are not limited to the list contained below. These risk outcomes were also extracted from the risk management process of the company explored in the case study.

- Schedule and budget overruns
- Unreliable systems
- Unsafe systems
- Performance shortfalls
- Poor performance in the market
- Systems that are difficult/costly to maintain
- Systems that are difficult/costly to test
- Systems that are inefficient to manufacture
- Installation problems / Interface incompatibility
- Poor aesthetics
- Failure to achieve certification with regulatory agencies
- Loss of commonality
- Part procurement problems

3.2 Risk and Uncertainty Management

Most large aerospace companies practice some form of program risk identification and management on major development programs. Specific procedures vary from company to company, but the core concepts are similar. The following section summarizes the recommended practices documented in A Guide to Project Management Body of Knowledge (PMBOK, 2004) published by the Project Management Institute.

The PMBOK document defines risk management as “the systematic process of identifying, analyzing, and responding to risk” and segregates it into six major processes:

1. Risk Management Planning

2. Risk Identification
3. Qualitative Risk Assessment
4. Quantitative Risk Assessment
5. Risk Response Planning
6. Risk Monitoring and Control

Risk management planning is simply the act of establishing the guidelines and procedures that product development teams are expected to follow when addressing the topic of risk and uncertainty. Items that will be contained in a risk management plan include team membership, roles and responsibilities, guidelines for budgeting of risk management activities, risk scoring standards, reporting formats, and tracking requirements. A lean organization will likely write a common risk management plan/procedure that governs all programs. Not only will this reduce the overall effort, it will ensure common practices across projects and facilitate continuous process improvement within the enterprise.

Risk identification attempts to ascertain the threats to a project's success. The PMBOK guide suggests numerous techniques for information gathering. These include brainstorming, Delphi technique (anonymous polling of domain experts and iterative recirculation to extract further comment until consensus is reached), interviewing of experienced personnel, and Strength-Weakness-Opportunity-Threat (SWOT) analysis. Diagramming techniques that are also recommended include cause and effect diagrams, system or process flow charts, and influence diagrams. Brainstorming appears to be the dominant technique in most US aerospace companies.

Qualitative risk analysis is an assessment of likelihood and impact of each risk issue. Some form of scoring method is utilized to prioritize the various issues. Both probability and potential impact are graded using qualitative terms such as very high, high, medium, low, and very low. The evaluation team is generally given guidelines for determining these thresholds. Risks with a very high probability and impact need to be addressed most aggressively. The results of the qualitative risk analysis are loaded into a probability/impact risk rating matrix. The probability and impact rating are often

combined into a single score. The combination of the scores may be linear, but the team may choose a non-linear scale to reflect their own risk tolerance biases (for example, wishing to avoid very high impact risks regardless of probability).

Quantitative risk assessment attempts to utilize methods such as Monte Carlo simulation, sensitivity analysis, or formal decision tree models when conditions exist for more precise analysis. Many projects are unable to perform quantitative analyses due to high levels of uncertainty and lack of tangible data. Carefully chosen continuous probability can often be applied in lieu of concrete data. When quantitative risk assessment is possible, it can be a highly effective tool for setting realistic, cost, schedule, or scope targets. Quantitative risk assessment for project management is not as prevalent as qualitative risk assessment in current aerospace industry practice.

Risk response planning is the process of developing alternative options and determining opportunities to reduce threats. According to the PMBOK guide, risk response planning activities “must be appropriate for the severity of the risk, effective in meeting the challenge, timely to be successful, realistic within the project context, agreed by all parties involved, and owned by a responsible person. Risk response planning strategies are often grouped into four categories:

- Risk avoidance – changing the project plan to bypass the risk entirely
- Risk Transference – Seeking to shift the consequences of the risk to a third party (for example, obtaining insurance)
- Risk Mitigation – reducing the probability and/or consequence of an uncertainty
- Risk acceptance – when the team determines that the risk level is negligible or when they can not identify any suitable response

Mitigation techniques are the primary focus of this report. Many of the most widely used activities for risk mitigation in today’s aerospace industry are detailed in the following section, Popular Risk Mitigation Activities in Aerospace Product Development.

Risk monitoring and control attempts to assign metrics to the risk issues to allow effective management over time. Individual risks are tracked, new risks are identified

over time, effectiveness of risk response methods are evaluated, and risk management plan progress is measured. Failures of risk response methods result in planning of new activities. Numerous software tools are commercially available to assist with project risk management.

3.3 Risk Mitigation Activities in Product Development

With the exception of the advanced techniques described at the end, this section contains a set of common risk mitigation activities that the author has observed in practice at numerous large aerospace firms.

3.3.1 Simulation

Simulation is the application of computer-based analytical models to aid design and predict product performance. The system models try to mimic the operation of the real system. . Aerospace companies use aerodynamic simulations, thermal simulations, structural simulations, and electronic circuit simulations, as well as many others. Advantages of computer models include the fact that simulations can usually be performed relatively early in the program, thus providing early feedback on feasibility and potential problems. Also there is a relatively low cost of repeating the experiment many times with input or design variations. Thomke describes simulation as one important aspect of “enlightened experimentation” (Thomke, 2001).

A drawback of simulations is that they are limited by the quality of the knowledge used to define them. So they are not as effective for discovering unknown unknowns.

3.3.2 Supplier Integration

Supplier integration is the practice of supplier and subcontractor involvement in system design decisions. Companies are increasingly trying to improve their competitive edge by integrating suppliers for designing products, for manufacturing product, and supplying them (Davis and Speckman, 2003 and Liker, Sobek, Ward, Cristiano 1996). When suppliers are integrated in the design process they become part of the design team. They may be asked to supply a simple component or a complex module or subsystem. Suppliers may be asked to take part in the early concept stages to assess feasibility and offer suggestions for utilizing their components in new and innovative ways. When suppliers are involved in later design stages, they can provide feedback that will allow more efficient methods of manufacturing, greater reliability, lower cost, and many other potential benefits.

3.3.3 Customer Integration and Market Feedback Analysis

At the other end of the supply chain, companies can practice customer integration by asking their customers to become members of the design teams (Daetz, Barnard, and Norman, 1995). A related practice is sometimes referred to as market feedback analysis (MFA). MFA actively solicits feedback from customer to gauge their satisfaction with a product or line of products. Customer integration and market feedback analysis can be effective solving customer requirements issues and gaining a better understanding of customer needs.

3.3.4 Prototyping

Ulrich and Eppinger (2004) define a prototype as “an approximation of the product along one or more dimensions. Prototyping is the act of developing such a prototype. In this report, the term prototype is used to refer to physical entities or functional software – analysis and simulation are not included in the definition of prototype in this document. Prototypes can be comprehensive or focused. Comprehensive prototypes exhibit more of the attributes of the final system. In contrast, focused prototypes implement one or only a

few attributes. Comprehensive prototypes are more costly, complex, and may not be feasible as early in the program.

3.3.5 Design Reviews

Design reviews are meetings to evaluate important design decisions, parameters, and processes by peers and enterprise experts. Reviews often also include customers and suppliers.

3.3.6 Set-based design

Set-based design or set-based concurrent engineering is the simultaneous pursuit of multiple design alternatives until a preferred option becomes evident. This approach may seem contrary to lean thinking, yet Toyota's product development teams practice this system of delaying decisions, providing only partial information to suppliers initially, and pursuing multiple prototypes (Ward, 1995). This contrasts with the more popular design approach of iteration. An advantage of set based design is that alternatives can be explored in parallel rather than in a serial fashion, thereby potentially reducing product development cycle time. Disadvantages often include increased cost and resource requirements if the product is immature or requires significant effort to prototype and/or test.

3.3.7 Reuse

Design is the repeated exploitation of existing designs in new applications. It typically involves the inclusion of previously designed components in hardware and software. Design reuse makes it faster and cheaper to design and build a new product since the

reused components will not only already be designed but also analyzed and tested. Note that aircraft certification standards may require retest of the component if the application changes, even if the component has not been modified. Reuse is an effective risk mitigation tool since so many of the problems encountered during product development are simple errors that are made in design and not detected until testing late in the project.

3.3.8 Best Practices or Standard Work

So called “best practices” or “standard work” describe a concept similar to reuse. However, it involved the reuse of design processes and methodologies rather than reusing the designs themselves. The repeated utilization and refinement of existing processes on multiple designs allows for stabilizing the design environment and pursuing perfection as part of the lean paradigm.

3.3.9 Upgradeable Architecture

Upgradeable or extensible architectures allow simplified modification of the product in anticipation of new requirements or opportunities. An upgrade is simply a new version of the same feature extensibility provides new features that did not exist when the product was originally entered into service (Maier and Rechtin, 2002). Both of these situations have benefits to product developers for managing risks such as changing customer requirements or the supply chain’s inability to procure the necessary components at a future date.

3.3.10 Design Margin

Design margin provides additional allowances for error beyond the limits of the system requirements. The allowance is specifically chosen to compensate for a recognized uncertainty; rather it is a general-purpose allotment that allows the system to function properly in the event of unforeseen circumstances. (Parkins, 1999)

3.3.11 System Integration Test

System integration test is the unified testing of a set of interfacing components or subsystems that might not otherwise be verified together prior to customer delivery. The testing collects multiple elements of a system in a single facility to demonstrate performance at a system level. It is largely a test of interfaces and functional coupling.

3.3.12 Tolerance Analysis and Control

Tolerance analysis and control is provides error budgets to components, calculates the effect at a system level, and strives for repeatability in product realizations. An example of tolerance control is the six sigma process practiced at numerous manufacturing companies. Unlike design margin, tolerance analysis examines and attempts to compensate for known variations caused by manufacturing deviations from nominal, thermal effects, wear, aging, variation in system inputs, etc (Harry and Lawson, 1992).

3.3.13 Industry Standards

Industry standards can be leveraged to incorporate well-known multi-purpose interfaces or architectures into a specific system. Use of industry standards can greatly aid in coordination and communication between multiple individuals or design teams by providing a common point of reference. They may also allow for the purchase of

commercial off the shelf components that would eliminate the need for additional development effort to produce a custom design.

3.3.14 Design for “X” (DFX)

Design for X or DFX creates integrated sub-teams to address aspects and ramifications of the design. Examples include design to cost (a.k.a. design for affordability), design for manufacturability, design for maintainability, design for testability, etc. Each of these methodologies may have its own dedicated team. The most common of these methodologies is design for manufacturability (DFM) (Ulrich and Eppinger, 2004). Manufacturing efficiency and quality is critical to the ultimate success of most products. Companies will usually establish guidelines to match products characteristics with the capability of the manufacturing facility to allow efficient production.

3.3.15 Sensitivity Analysis

This report defines sensitivity analysis in terms of product performance. The analysis estimates the level of dynamic response of the system to input perturbations or stimuli. How sensitive are the results to possible variations of uncertain input factors (Blanchard and Fabrycky, 1998). The analysis may be conducted analytically or as set of a simulation experiment. A designer may find that his or her product can be made to perform unacceptably if operating conditions vary by a relatively small amount in a certain way. A robust system will not be sensitive to small changes in operating conditions.

3.3.16 Organizational Mitigations

Include attempts to restructure the design participants and resources to address shortcomings in execution. It may be done to improve communication, increase oversight/independence, focus on particular enterprise goals, etc.

3.3.17 Advanced Techniques

McManus described more recent developments for dealing with uncertainties that are not yet widely used in practice.

Multi-Attribute Tradespace Exploration (MATE) is one such approach. It is a conceptual design tool. It is a technique for analyzing system architectures and trading various attributes rather than establishing rigid requirements. Uncertainty may be one of the attributes directly analyzed using MATE, or sometimes the tool will reveal potential shortcomings without the explicit inclusion of uncertainty in the analysis. Multiple analyses may be performed using numerical models to simulate various uncertainties and produce the associated level of risk.

The framework also includes methodologies derived from the financial industry such as portfolio or real options methods. These techniques are most effective for managing external uncertainty influences such as market and need shifts, budget mandates (Weigel 2004a), or policy mandates (Weigel 2004b).

The framework maps the mature quantitative methods in the upper left corner of a matrix, qualitative methods for less well-characterized risks fall in the middle, and new evolving tools like tradespace exploration and real options occupy the lower right.

4 Research Methods and Goals

The intent of this section is to describe the methods utilized for collecting and analyzing independent data to support this thesis, the rationale for choosing those methods, and the anticipated outcomes.

As stated in the introduction of this report, the primary goals of the research is to explore the role of uncertainty in lean product development, demonstrate a relationship between risk mitigation activities and the generation of customer value in the design and development process, and to provide guidelines for completing these activities in a manner that reduces cycle time, assures quality, and makes the most efficient use of company resources. To fulfill these goals, two different types of data are required. The first set of data comes from a case study of a group of completed projects at an aerospace system developer. Four related programs have been selected because of their combination of similarities and differences. All four projects were executed at the same company (albeit at two different locations in the United States), all were performed for the same customer, staffed by teams with comparable skill and experience levels, spanned the same 3 year period (approximately), and the four programs shared common progress reporting and cost tracking schemes. Yet, all of the programs were led by different individuals who had dissimilar priorities and approaches to the product development cycle. The similarities in the programs make their relative results comparable. Their differences provide an opportunity for study in the form of correlation analysis between each program's risk management efforts and their eventual success in minimizing waste and delivering value.

In addition to budget and schedule performance data, reports citing problems and discrepancies for each of the products were generated over the course of the projects. These problem reports provide valuable insight into the root cause of errors and

inefficiencies the teams encountered. These reports were often highly technical and understanding their content required some expertise in the particular product domain. Between one hundred and four hundred reports for each product were generated at the time of analysis. The majority of problems were minor and required little effort to correct. 75% to 90% of the reports fell into this category. More serious problems that necessitated significant rework were extracted, their root causes isolated, and traced back to program risk that either weren't identified or were identified and not sufficiently retired.

Lastly, the projects' manpower accounting did not segregate expenditures that were specific to risk management and reduction. Therefore, interviews with one team member per product were performed to assess the relative effort expended on risk and uncertainty reduction activities.

The second element of independent research is intended to provide insight into the proper risk management strategies to minimize waste and maximize value. A survey was distributed to a select group of expert engineers and managers working in a product development environment at the same company analyzed in the case study. Not all of the engineers work for the same business unit or the same product lines as the case study sample programs. In total, eight engineers or engineering managers with between 18 and 35 years of experience responded to the survey. The intent was to collect expert opinions on the benefits of uncertainty reduction activities on an array of products at the same major aerospace subsystem supplier. Data includes not only the survey results, but also post-survey interviews with the participants to gain additional insight into their responses. Four post-survey interviews were conducted, each lasting about two hours.

Rather than sample a large group of engineers with varied levels of experience, a small group of top engineers and managers were chosen since each had participated in multiple projects over their long careers and were better able to provide a broad, time-tested opinion. Organizational titles of the survey participants include Chief Engineer, Technical Fellow, Systems Engineering Manager, and Program Manager. Their

products often contain a mix of mechanical hardware, electrical or electronic elements, and (in the majority of cases) embedded software.

5 Aerospace System Development Case Study

To better understand risk management principles in practice, an analysis was performed on documentation from a completed aerospace system development program to assess the difficulties and potential benefits of well executed risk and uncertainty management. In addition to reviewing historical documents, interviews were conducted with lead engineers. Areas of interest include indications of superior or inferior performance by teams with aggressive risk management strategies, evidence of a team's ability to effectively identify known unknowns prior to task execution, and the final impact of unknown unknowns on the project.

5.1 Program Description

The aerospace program studied was a commercial aircraft development project at a second-tier subsystem supplier (i.e. a supplier to the company responsible for acquiring a certificate of airworthiness from the government regulating authorities). The development cost of the subsystem was on the order of tens of millions of US dollars at the time of execution around 2001-2004. This analysis will focus on the development of four of the major components that were elements in the subsystem. Two of the components were mechanical devices (a fluid pump and a fluid metering unit), another was electronic, and another major component was the software embedded in the electronic unit.

Integrated Product Development (IPD) teams were formed to design, validate, and prepare each of the components for production. The IPD teams were cross-functional groups that met on a regular basis to share information and coordinate activities among the various engineering and management disciplines needed to develop the product. Each component had its own dedicated team, although there was also an integration team

comprised of system engineers representing each of the components. A single Program Manager had responsibility for the overall subsystem, but delegated much of the day-to-day management and coordination duties to individuals known as the Project Engineers for each component. Theoretically, each of the IPD teams was working to the same set of company product development procedures and program management guidelines. In practice however, the teams employed dissimilar management styles and emphasized different priorities. Each team's approach to program risk identification and mitigation was one of the areas where management variation was most evident.

Engineers developing a mechanical pump clearly face different challenges than the engineers developing embedded avionic software. However, there were enough similarities in scope and technical difficulty to allow the argument that the relative success of each of the teams was due in large part to management proficiency. All of the components were deemed to be safety critical for the aircraft, thus requiring stringent development quality control and comprehensive testing to demonstrate compliance to requirements. All of the components contained design elements that represented unproven technology for the company. Initial manpower and schedule estimates produced by each of the teams were on the same order of magnitude. All of the teams served the same customer. And finally, in addition to risks inherent in the design of the product, all of the IPD teams faced program risks such as management of suppliers and internal staffing issues. In summary, four comparable case studies will be examined to determine whether variations in risk management produce discernable differences in the success of the projects.

5.2 Procedures for Management of Risk and Uncertainty

The organization appeared to have a mature and well-defined process for identifying and mitigating risk (known unknowns) similar to the industry recommended practices described in the earlier section of this document. Company procedures required risk management activities as part of standard operating procedure. If the component IPD

team followed the procedures as their managers presumed, they would have followed the process described hereafter.

The risk management process began during the concept generation phase of the program. Each IPD team held a meeting or set of meetings to review the proposed concepts. Besides the team representatives from the engineering disciplines, the reviews also often (?) include higher level managers, senior engineering experts, and other stakeholders including manufacturing, aftermarket support personnel, and customers. After the product concepts and program plans were described and debated, the review meeting concluded with a risk identification exercise to generate a list of potential issues and uncertainties that threatened the success of the program.

Risks were typically identified using brainstorming techniques where each of the meeting attendees was asked to state an item to be added the list. The meeting coordinator would solicit ideas from the participants until all of the issues from every person were captured. No ideas were rejected during this part of the exercise.

After the risk list was created, the items would be described, classified, and ranked. Ambiguous or incomplete descriptions of issues were clarified and expanded to permit accurate debate. Items were often classified into a fixed set of categories as a means of simplifying management and reporting. Technical risk/uncertainty categories might include: performance, physical installation, suitability to the operating environment, manufacturability, maintainability, reliability, safety, testability, open requirements issues, impact on weight, impact on cost (profitability), and others.

Ranking of risks involved assessments of both probability of occurrence and severity of the potential consequences. Although guidelines were stated to permit quantitative rankings, these judgments were usually more qualitative. The guideline for probability of occurrence called for a five-point scale where the lowest rating represented likelihood in the very low single digits and the highest rank represented a likelihood of about 70% or higher. The participants were provided with additional instruction on assessing

probability of occurrence based on the need for new technology development, existence of similar products within the company's portfolio, prior development of technical skills within the organization, etc.

Consequence severity was also rated on a five point scale. Areas of potential impact included weight increases, recurring cost increases, development cost increases, schedule slips, reliability degradation, and others. The threshold values used to judge potential impacts were customized for each component by the Program Manager in accordance with his perception of each team's capability to compensate for non-ideal execution. For example, a potential three week schedule slip might have been deemed a severity level 2 on one component but a severity level of three on another because of the perception of a more aggressive baseline schedule on the second component.

For any risk item, after the probability and severity were graded, the two values were combined into a single composite score. All of the risks items could then be sorted from most critical (high probability of occurrence, high severity of impact) to the least critical (low probability of occurrence, low severity of impact).

Follow-on meetings of the core product development team members were held to construct action plans for the most critical risk issues. A software tool was utilized to document planned activities to address each risk, the anticipated date of completion, and revisions to the perceived risk level as the mitigation activities demonstrated successful results. An individual team member would be assigned responsibility for coordinating the risk item's action plan and reporting the status back to the team. The tool produced risk status for any item in the form of a "waterfall chart" that showed the perceived risk level falling in discrete steps as the risk mitigation plan was carried out. Failure of a risk mitigation activity to achieve its desired purpose would require a replan.

New risk items could be added and evaluated anytime the team felt that circumstances warranted it. New items were often added at later design reviews when relevant

stakeholders were gathered. Examples of these reviews are Preliminary Design Review (PDR) and Critical Design Review (CDR).

Product risk summaries were reviewed by high-level management during program stage gate reviews. These management reviews would be held at key schedule transition points when the project was stepping from one program phase to the next (e.g. prior to starting environmental qualification test). The organization had guidelines for the highest level risk that was tolerable at any particular program phase. However, there was no limit on the cumulative risk of all open issues. In other words, an item identified as a risk level four might be scrutinized by management if it had not been reduced by a particular phase of the project, but twenty items all having risk level three would not draw the same attention even though that situation is potentially more dangerous.

5.3 Execution by the Product Teams

Examination of program documentation for each of the product teams and follow-on interviews with the participants revealed significant differences in the way that the risk management procedures were executed. At one end of the spectrum, the mechanical fluid metering unit team thoroughly identified and aggressively mitigated issues of risk and uncertainty. At the other extreme, the software team failed to perform many of the up front activities to identify risk at the early program stages, thereby spoiling their opportunity to actively manage foreseeable problems. Despite the wide variation in the level of rigor practiced by the four teams that were analyzed, all were able to present status information during early and mid stage gate reviews that satisfied upper management. By the later stage gate reviews, signs of problems were readily evident in the program's standard cost and schedule metrics.

In the end, all teams were able to meet their required schedule deadlines. However, some of the components required a significant assignment of additional manpower during the later project stages in order to avoid delays. Also, the software team negotiated a reduced

set of performance requirements for initial deliveries to achieve the customer deadlines. Analysis of the financial expenditures needed to produce the product on time provides a reasonable gauge of the management proficiency of each of the teams.

The program expenditures vs. plan for the fluid metering unit are summarized in the figure below.

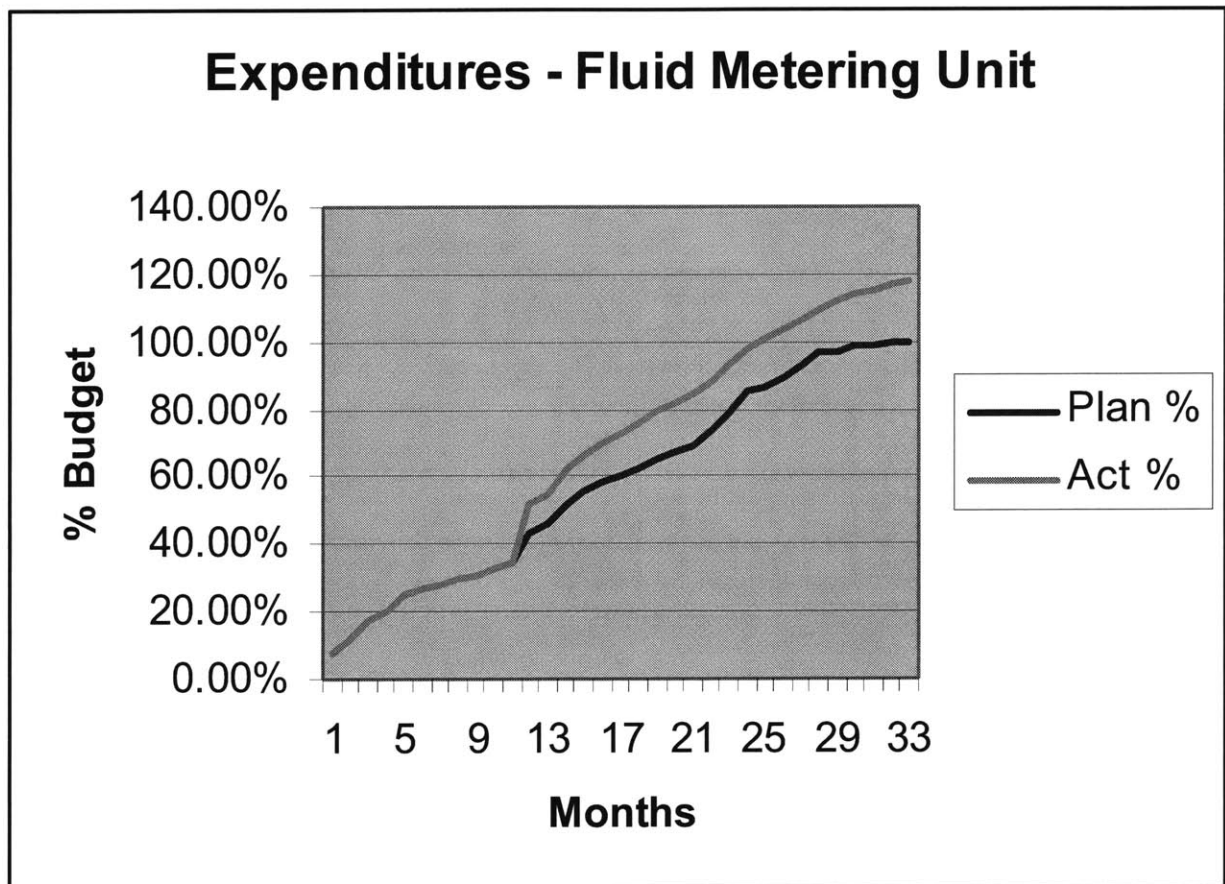


Figure 2 – Budget Performance, Mechanical Unit

Although there was nearly a 20% overrun in development of this component, analysis of problem reports and interviews with engineers and managers revealed that most of the problems were non-technical in nature. Based on the reports and interviews, a fishbone chart depicting the primary causes of cost overrun was constructed. See Figure 3 below.

Fluid Metering Unit Root Cause Analysis

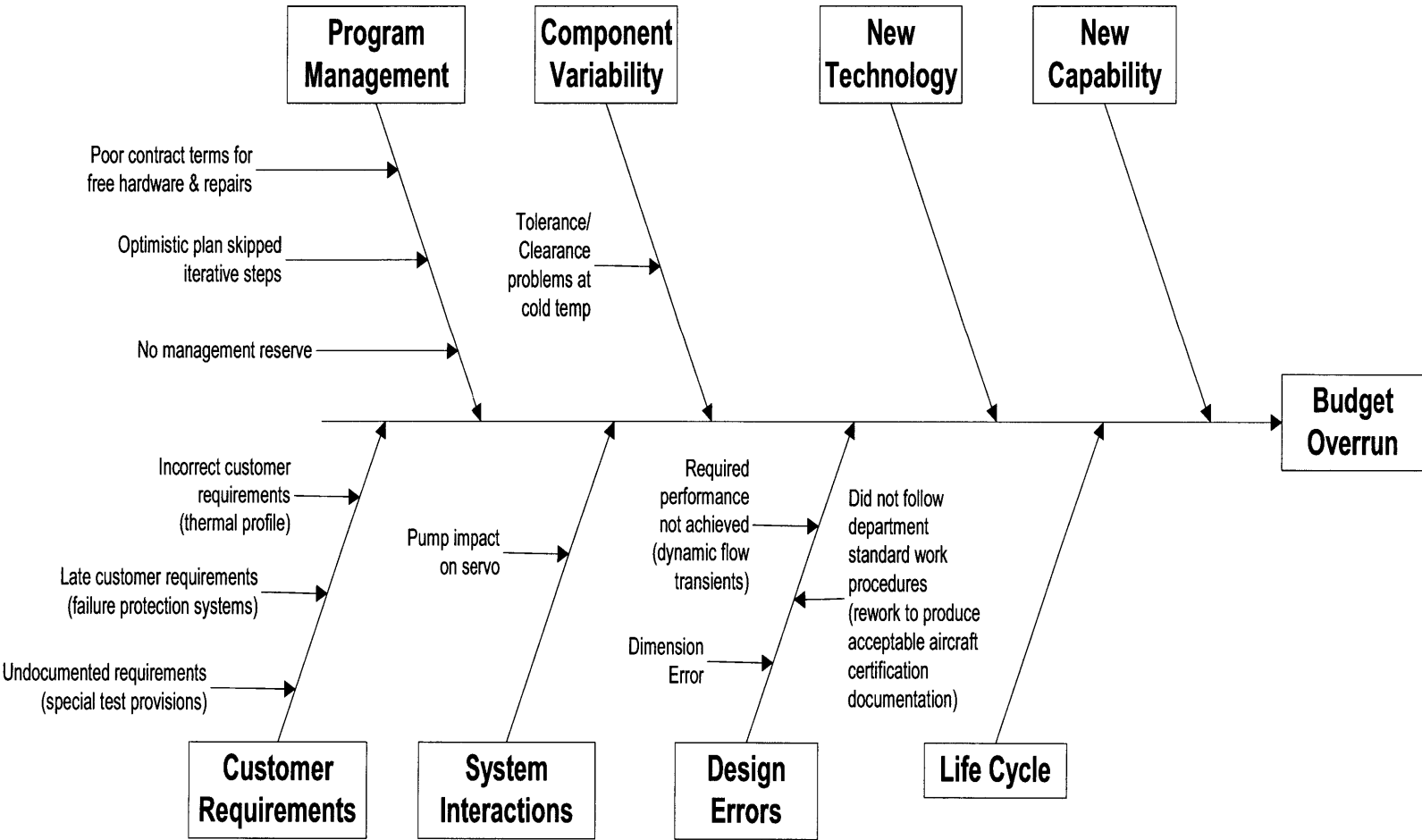


Figure 3 – Fishbone Chart, Mechanical Unit

Detailed analysis of financial records indicated that the majority of the budget overrun was not due to technical pitfalls. Rather, program planning and poor contract negotiation were the primary culprits. Much of the excess expense was for free hardware and hardware upgrades that were promised to the customer. In addition, overly aggressive project planning resulted in projections that provided no management reserve and did not reflect iterative steps that had become common practice on prior programs.

The most significant problems that resulted from known unknowns or knowable unknowns was a component tolerance problem that became evident when testing the unit at extreme low temperatures and an interaction problem with the output of the fluid pump. The cold temperature was never identified and tracked as part of the risk management process. During interviews, engineers claimed that the issue was not identified as a separate risk item because there was a feeling that the department's standard work procedures were rigorous and robust enough to handle any special circumstances inherent in the design. The standard work procedures later turned out to be inadequate. Likewise, the pump interaction problem was a failure by the team to identify a knowable risk during the review and brainstorming process.

Other causes of extra expenditures included customer requirements issues and basic design mistakes. To some extent, the customer issues were known in advance and identified as a potential area of risk. However, the team was unable to resolve the issues in a timely and efficient manner. The moderately high overrun on the fluid metering unit demonstrates that a project that proficiently manages technical product risk is still susceptible to non-technical program risks and external issues such as customer requirements problems.

The software spending profile is illustrated in Figure 4.

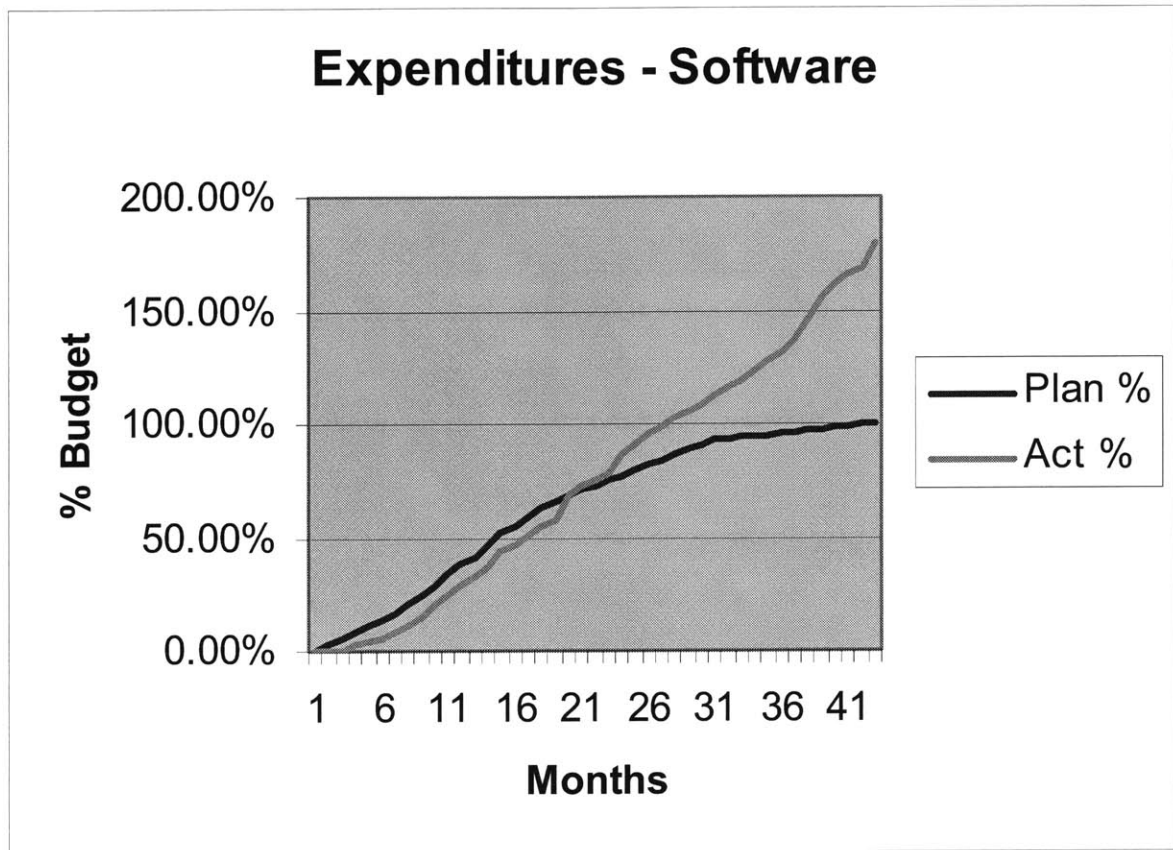


Figure 4 – Budget Performance, Software

The software spending profile initially under spent and then appeared to be on target one and a half years into the program. However, accomplishments were not accumulating at the required rate and significant uncertainties were not being addressed. As the problems evolved, a large deviation to plan developed, software engineering staffing more than doubled, and as stated earlier, performance requirements for deliverable software versions were negotiated to reduced levels with the customer. The 87% cost overrun shown in the spending curve understates the overrun because additional functionality still had to be delivered at a later date.

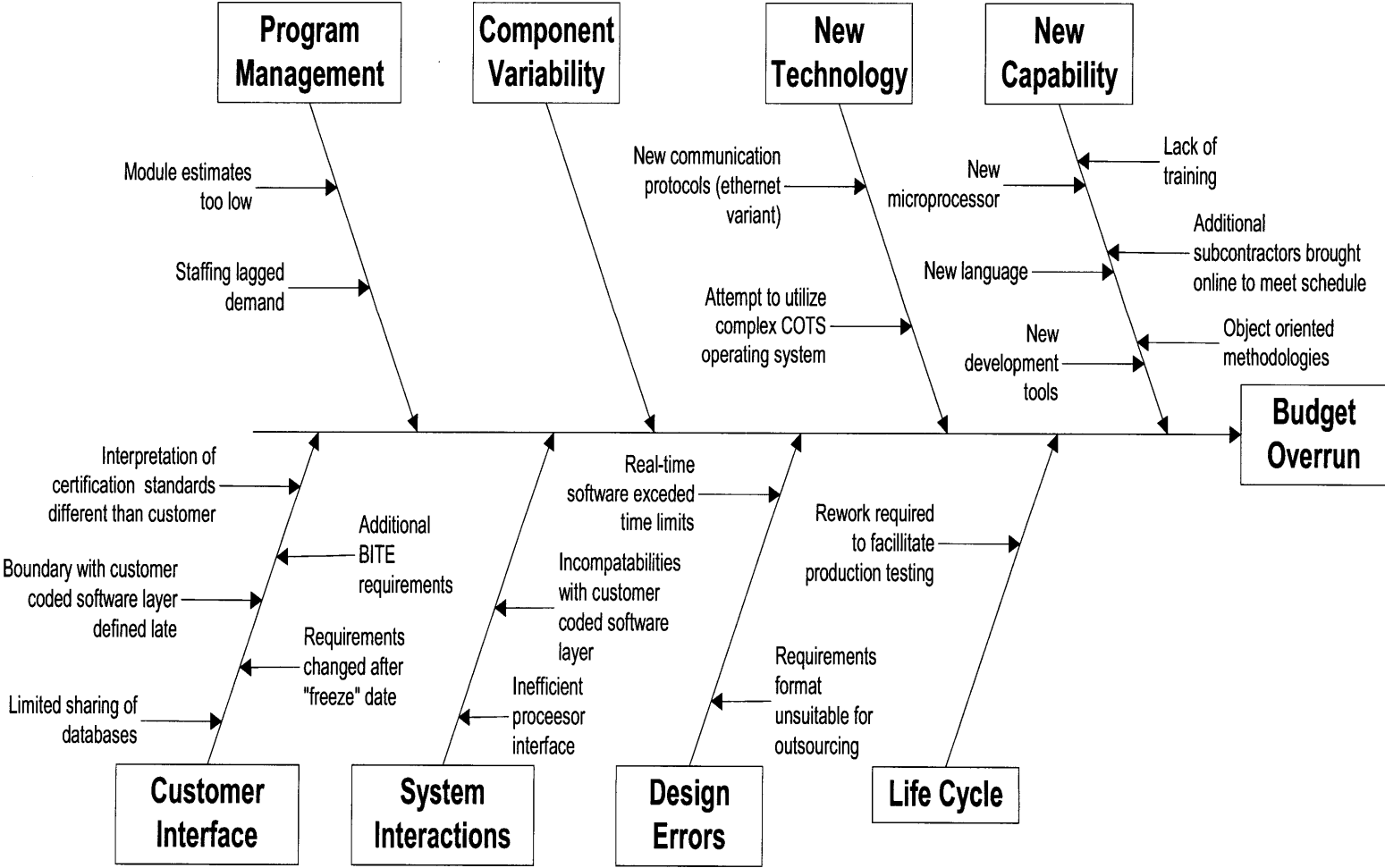
Analysis of software problem reports and interviews with managers and engineers produced the root cause diagram shown in Figure 5. Unlike the fluid metering component, the most significant causes of additional expenditures on the software

product were technical in nature. Furthermore, the engineering team felt that many of these issues were apparent in the earliest stages of the program but were not collected or actively addressed. Technical issues included the application of new technology, attempts to implement design practices that were beyond the organization's prior experience and skill sets, and interactions with interfacing subsystems. If the uncertainties and risks had been identified earlier, obvious mitigation strategies likely would have emerged. Potential risk mitigation steps were:

- Team members noted lack of training in new tools and technologies as something that would have benefited them greatly.
- Other engineers within the company had skills that were more closely aligned with the needs of the program, but they were not included on the team.
- In hindsight, there were opportunities to greatly reduce the in-house manpower by purchasing relatively inexpensive software intellectual property in the form of pre-coded software libraries.
- The team squandered opportunities to develop and test early prototype software versions on hardware that adequately represented the final system.

Embedded Software Root Cause Analysis

Figure 5 – Fishbone Chart, Software



- Software Engineers did not get involved to the extent necessary with the design of the hardware elements that directly interface with the software. Inefficiencies, performances shortfalls, and incompatibilities resulted.

Most if not all of the problems encountered by the software team were potentially knowable unknowns that could have been identified with sufficient foresight.

A number of the Software Engineers stated that any one of the individual uncertainties could have been handled by the team within the planned budget, but the combination of so many separate issues overwhelmed the design and development personnel. Because nobody took the time at the start of the program to compile the list of potential issues and summarize the aggregate risk profile, the intensity and scope of the self-imposed challenges were never understood. So, another potential risk mitigation action would have been to encourage a greater amount of reuse from prior products instead of pushing the limits of the organizations technology and skills along so many boundaries.

It should be noted that the software team encountered similar non-technical program risks and errors that were observed in the analysis of the mechanical fluid metering unit. Problems with estimates and program planning, staffing delays, customer requirements issues, subcontractor management difficulties, and simple design errors all occurred in the development of the embedded software. If the team had encountered only these issues and perhaps a small subset of the technical problems that were overlooked, the cost overrun almost certainly would have been more moderate.

The mechanical pump and the electronic unit are the most interesting components to analyze because the two teams invested significantly in the identification of technical uncertainties and risks at the onset of the program, but they failed to follow up with most of the risk reduction strategies due to schedule and budget pressures combined with staffing limitations. A detailed comparison of the problem reports recorded by the IPD teams with the initial list of perceived risk items identified by the team throughout the course of the program showed significant overlap between the problems that were

predicted to occur and the ones that actually did occur if they were not aggressively reduced per the organization's operating procedures.

The percentage of budget overrun for both the pump and the electronic unit were above the percentage for the metering unit and below the amount on the software development effort.

The mechanical pump team spending profile is shown in Figure 6. The middle region of the chart is informative because it shows the attempts of the team leaders to maintain program expenditures according with the plan and actually shows a period of under spending. Unfortunately, the intermediate success was achieved by reducing the investment in important activities that may have been able to prevent the rapid excursion from the plan in the late stages when numerous problems were identified in final verification testing, system integration testing, and environmental qualification testing.

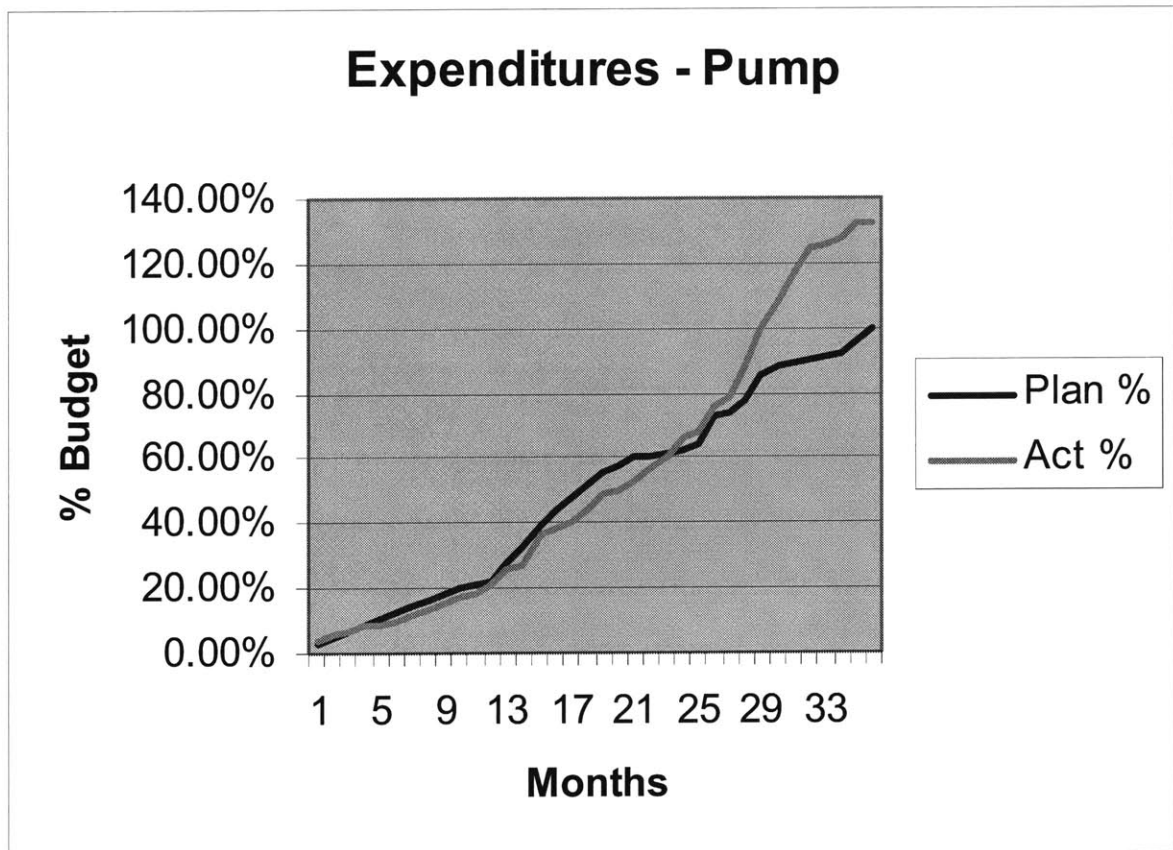


Figure 6 – Budget Performance, Pump

The vast majority of issues that led to the cost overrun on the pump were known concerns that were not followed up by rigorous mitigation plans. The introduction of new technology and capabilities beyond prior design experience were flagged as risks during initial review of customer requirements and product concept generation. After the risks were identified and documented, insufficient effort was made to take additional steps to ensure that the problems were prevented prior to testing late in the program. Once again, this team also encountered difficulties with non-technical programmatic issues, but these were not the worst contributors to the overrun. A summary of the root cause analysis of the events that led to excess manpower expenditures on the pump is shown in Figure 7.

Pump Root Cause Analysis

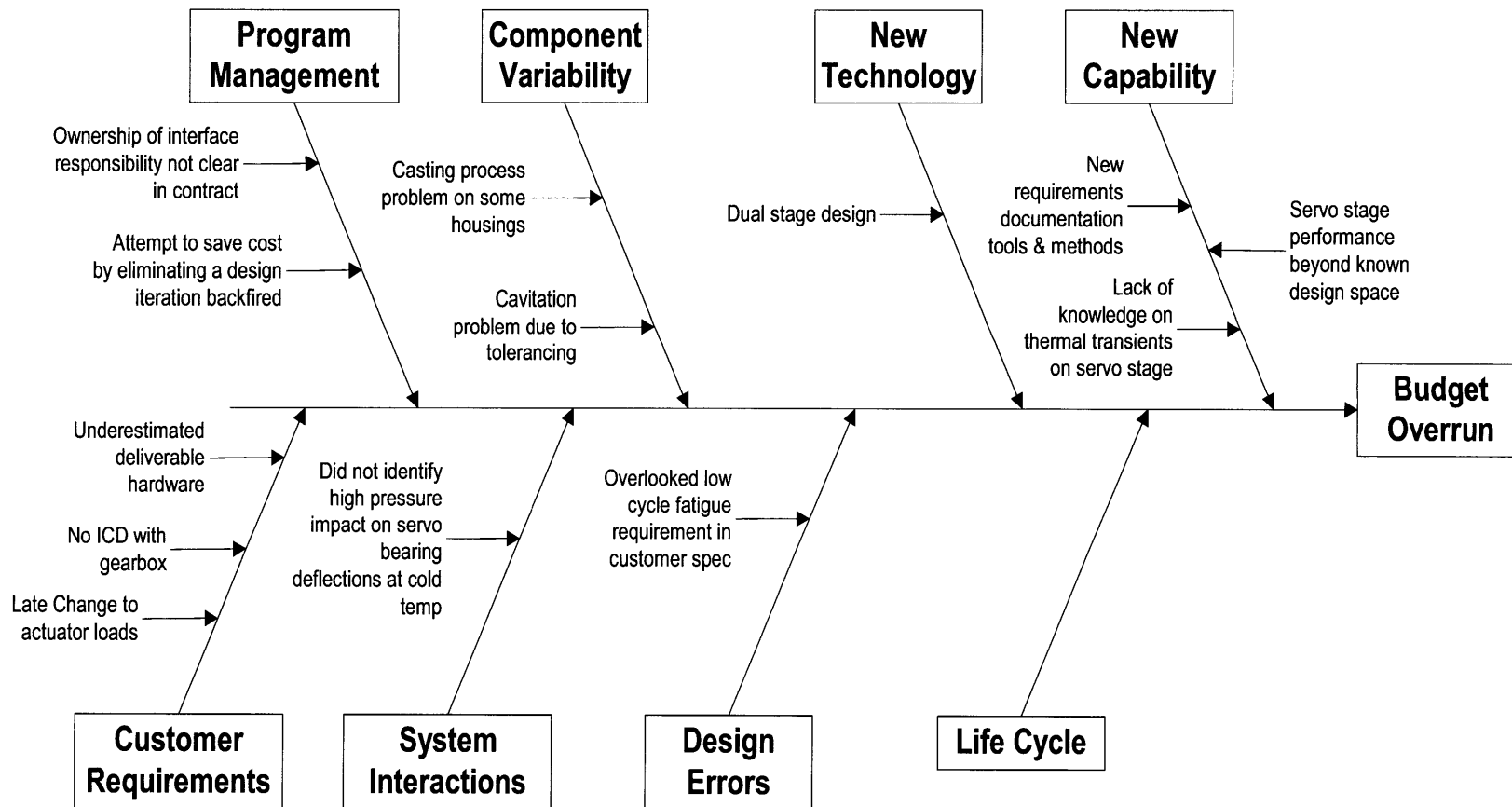


Figure 7 – Fishbone Chart, Pump

The spending profile for the electronic component is shown below. In many ways, it is similar to the curve for the mechanical pump. There are obvious periods of under spending and on-target spending that would have been viewed favorably by management. But once again, a large number of issues went unresolved until the final testing phases and a dramatic excursion from the plan was irreversible.

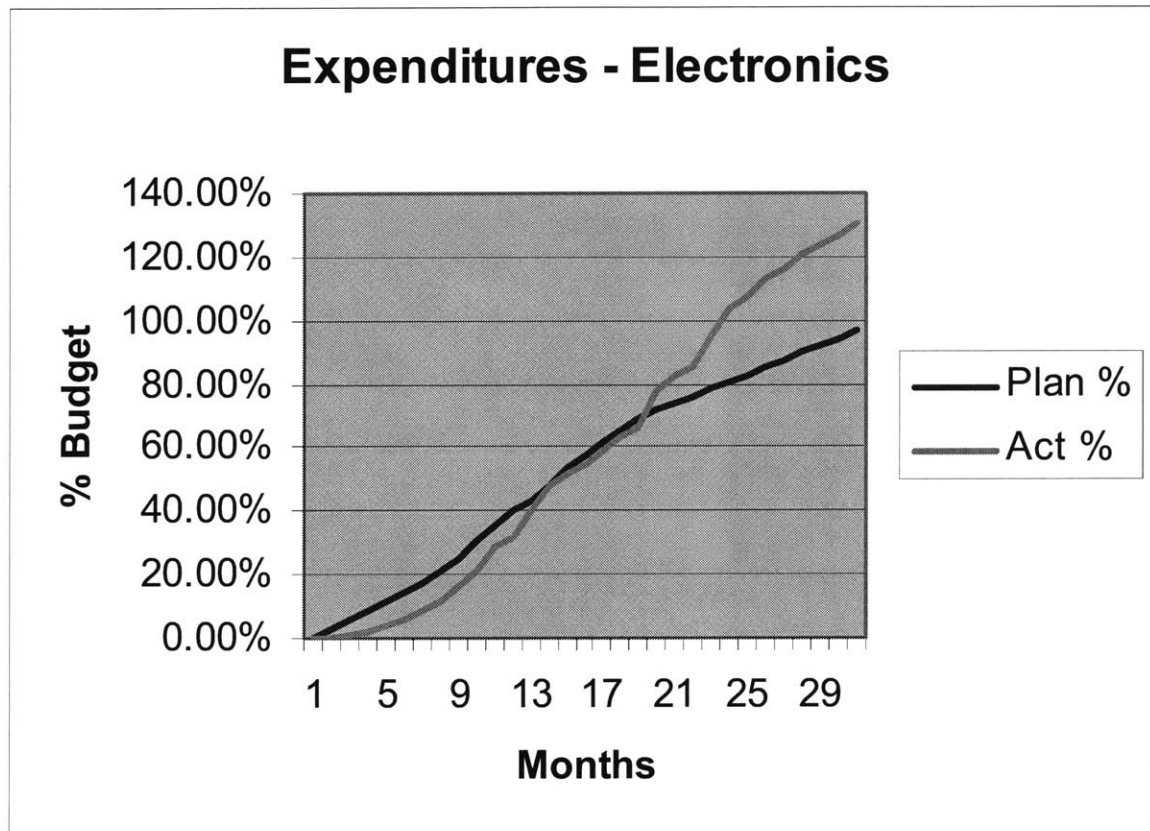
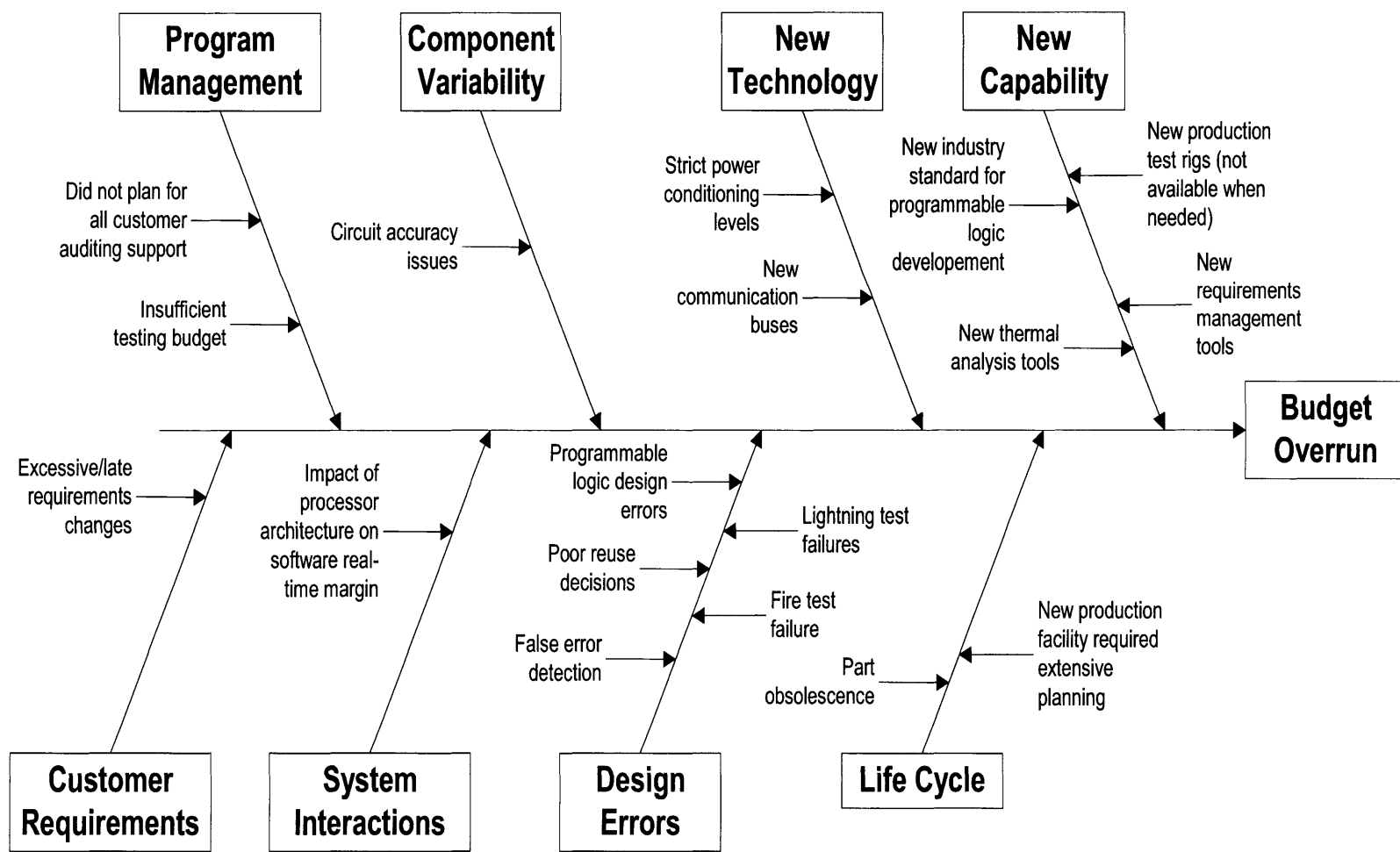


Figure 8- Budget Performance, Electronics

The findings of the root cause analysis for the electronic unit are shown in Figure 9. A significant number of these issues can also be traced back to the risks assessments that were performed by the design team long before any of the problems surfaced.

Electronic Unit Root Cause Analysis

Figure 9 – Fishbone Chart, Electronics



The team had identified most of the technology and enterprise capability uncertainties very early in the program. Numerous engineers stated that part of the problem was that too many risks, many of them insignificant, were assessed and tracked in the early stages of the program. After PDR, there are over a hundred individual risk items that were assigned to owners on the IPD team. The method of rating and ranking the concerns did not accomplish the goal of prioritizing the risks because participants were unwilling to discard information. The risk management process defined in the department procedures became burdensome and eventually collapsed.

5.4 Case Study Summary

This case study demonstrates the capability of a product team to improve program performance through a thorough and diligent risk assessment and mitigation process. Teams showed consistent ability to identify many of the areas of uncertainty that would later lead to eventual testing failures and redesigns. Because no firm quantifiable data was available to depict the amount of effort spent on the risk activities for each of programs, discussions with participants from each of the programs were used to gain a gross qualitative assessment of the product development teams' commitment to different forms of risk mitigation activity over the course of development. One participant from each of the four programs was interviewed for approximately 30 minutes. Table 2 -Risk Mitigation Commitment by Program shows the relative investment (for activities where additional resources were required like prototypes or extra tests) or level of rigor (for activities that sometimes have minimal cost impact like reuse or allocation of design margin). A "Low" indication designates that minimal or no effort/rigor was applied. "Mid" indicates that the effort/rigor was applied in an incomplete fashion. And "High" indicates that the activity was a program priority that received satisfactory attention.

Table 2 -Risk Mitigation Commitment by Program

	Fluid Metering Unit	Software	Pump	Electronics
Simulation	High	Low	High	Low
Supplier Integration	High	Low	Low	Mid
Customer Integration	Mid	Mid	Mid	High
Prototyping	High	Low	Mid	Mid
Design Reviews	Mid	Low	Mid	Mid
Set-Based Design	Low	Low	Mid	Mid
Reuse	Mid	Low	Mid	Low
Standard Work	Mid	Mid	High	Mid
Upgradeable Architectures	Low	Low	Low	Low
Design Margin	High	Low	Mid	Low
Integration Test	High	Mid	Mid	High
Tolerance Control	High	Low	High	Low
Industry Standards	Low	Mid	Low	Low
DFX	High	Low	Mid	Mid
Sensitivity Analysis	Mid	Low	Mid	Low
Organizational Mitigation	Low	Low	Low	Low

One can see that the Fluid Unit showed the highest level of commitment to risk reduction activities and software the lowest. The commitment of the other two teams was spotty.

Table 3 - Major Problem Reports by Program summarizes the significant problem reports from the fishbone diagrams in a matrix format. The numbers in the table indicate the total number of major problems identified by program in a particular category of negative outcomes.

Table 3 - Major Problem Reports by Program

	Fluid Metering Unit	Software	Pump	Electronics
Program Management	3	2	2	2
Component Variability	1	0	2	1
New Technology	0	2	1	2
New Capability	0	6	3	4
Customer Requirements	3	5	3	1
System Interactions	1	2	1	1
Design Errors	3	2	1	5
Life Cycle	0	1	0	2
TOTAL	11	20	13	18

Each of the product examples experienced problems that were beyond the typical scope of product technical risk management – so predicting and understanding known unknowns in the technical realm is only part of the challenge. Non-technical setbacks and unknown unknowns are also uncommon occurrences that must be anticipated and properly managed.

It appears that the Fluid Metering Unit outperformed the other programs largely due to its ability to avoid issues with new technology, new enterprise capability, and problems planning for the later life cycle phases of the product. The worst performing programs both in terms of problem reports and budget overrun were the software and electronic unit. The software teams had significant difficulty dealing with new skills or enterprise capabilities that they needed to support their program. The electronic unit had the most problems with fundamental design errors. It should be noted that although no firm financial data is available to calculate a return on investment for the program, the fluid

metering team leader proclaimed that his expenditures for risk mitigation activities were at least an order of magnitude below the budget overruns on the other programs.

A correlation analysis of Table 2 -Risk Mitigation Commitment by Program and Table 3 - Major Problem Reports by Program confirms the observation that increased effort spent on risk mitigation activities produces fewer problems. The correlation coefficient calculated was -0.9767^1 (the more effort expended on risk mitigation, the fewer problems). Likewise, there is a strong negative correlation (-0.8777) between risk effort expended and the amount of budget overrun discussed in section 5.3 Execution by the Product Teams. And as one would expect, there was a strong positive correlation (0.7551) between the number of significant problems and the amount of cost overrun. The strength of the correlation is very compelling, especially given the small number of data points. It clearly illustrates the relationship between minimizing risk and reducing waste in a lean product development environment.

The following section of this report will use survey data from product development experts to produce generalized risk and uncertainty management recommendations so that a manager might hope to duplicate or improve on the performance of the best project in the case study and avoid many of the pitfalls encountered by all of the projects..

¹ Correlation analysis was performed by replacing the high, medium, and low indicators with the values 3 through 1 respectively. The columns were then summed to calculate a value representing the total effort expended on risk activities for each of the programs. The effort values were cross correlated with the numbers of problems per program and the percentages of cost overrun.

6 Recommendations for Uncertainty Elimination and Risk Management in a Lean PD Environment

6.1 Management Survey

In order to develop a strategy for effective mitigation of product development uncertainty, a survey was created. Rather than solicit responses from a large random sample of engineers, the goal was to poll highly experienced experts with broad system development responsibilities in aerospace products or similar industries such as naval and industrial equipment. None of the engineers and managers responding to the survey is employed by an airframe manufacturer, so their responses were from the perspective of sub-tier suppliers who typically are one or two levels removed from the top-level aircraft design.

The survey was based on classical risk mitigation activities that have been practiced in industry for years. These activities were summarized earlier in this report. A copy of the survey is enclosed in appendix A.

The survey was divided into two interspersed sets of questions. First, these questions attempted to ascertain which mitigation activities were most effective for each type of product uncertainty described earlier in this paper. And second, the experts were asked to recommend which of six program phases would be most appropriate for applying the risk mitigation effort.

6.1.1 Effectiveness of Uncertainty and Risk Mitigation Activities

The following table summarizes the mean survey responses to the first set of questions, i.e. effectiveness of each mitigation activity to eliminate an area of product risk. The results have been color coded to highlight the most effective techniques in blue and

slightly less effective methods in yellow. The most effective techniques are considered to be those scoring between 4.0 and 5.0 since this indicates that these activities are effective on most programs and highly effective on at least some. The items highlighted in yellow are at least moderately effective on most programs. The type of uncertainty is listed along the row at the top and the mitigation activity is shown in the column on the left. Scores from the surveys were averaged and placed in the appropriate location in the matrix.

Table 4 – Survey Results: Mean Mitigation Activity Effectiveness Scores (N=8)

	Variability	New Technology	Enterprise Capability	Customer	System Interactions	Design Errors	Life Cycle Concerns
Simulation	3.125	3.125	1.500	2.250	4.000	1.125	0.625
Supplier Integration	3.375	3.500	4.250	2.000	3.250	2.000	4.000
Customer Integration	1.375	2.750	2.875	4.625	3.375	1.000	2.375
Prototyping	3.000	4.125	3.500	3.625	3.625	4.750	1.875
Design Reviews	2.750	2.750	2.500	3.625	3.125	3.000	3.125
Set-Based Design	1.500	3.500	2.625	2.375	2.375	1.250	2.000
Reuse	3.750	2.375	2.375	3.125	3.250	4.500	3.125
Standard Work	3.625	2.625	3.375	2.375	3.875	4.500	2.625
Upgradeable Architectures	2.875	3.250	3.375	4.625	3.500	3.000	4.500
Design Margin	4.500	2.625	2.500	2.875	3.375	2.875	3.250
Integration Test	3.250	3.750	3.625	3.875	5.000	3.750	1.625
Tolerance Control	5.000	2.250	2.250	2.250	3.875	2.250	2.000
Industry Standards	3.750	2.875	3.875	3.375	4.125	3.000	3.250
DFX	3.125	3.000	3.625	3.375	3.250	3.125	4.750
Sensitivity Analysis	3.625	3.625	2.000	2.125	4.625	3.250	3.000
Organizational Mitigation	1.750	2.125	3.625	2.750	2.875	2.250	2.125

Key:

5 = Very beneficial on almost all programs

4 = Moderately beneficial on most, very beneficial on some

3 = Moderately beneficial on almost all programs

2 = Moderately beneficial on most, no benefit on some

1 = No benefit on most, moderate benefit on some

0 = No benefit on almost all programs

Follow-up interviews with many of the respondents provided insight into the rationale for their recommendations. Numerous observations can be drawn from the summary table row by row (i.e. by mitigation activity) and the results of these follow-up interviews:

- Computer simulations are thought to be most effective for reducing issues with interactions between subsystems. Specific tools that provide this benefit include CAD packages that allow physical dimensioning between components to be coordinated. Also, dynamic system modeling tools such as Matlab™ can expose problems with performance interactions and instabilities due to coupling between subsystems.
- Integration of sub-tier suppliers can be a very effective method to fill enterprise capability voids by establishing a subcontracting relationship with another firm that possesses the required skills. Supplier integration is also an important element in preventing troubles later in the product life cycle since many of these issues often stem from supplier quality problems and failures of suppliers to meet delivery commitments.
- Obviously, customer integration is imperative for correcting customer requirements errors, ambiguities, and omissions. It was also noted that customer integration is also a key part of preventing system integration problems since knowledge about other subsystems and the function of the higher level system usually resides with the customer.
- Prototyping was considered a highly effective technique for eliminating most types of uncertainty except for issues that tend to arise later in the product's life cycle. It was considered most effective for proving new technology and reducing design errors. A number of the experts believe that early product prototyping is an underutilized practice. It was also noted that, when dealing with embedded software projects, access to representative processing hardware (and to a lesser extent target simulators) not only reduces errors but also tends to speed development.

- Design reviews were considered to be at least moderately important for reducing all types of uncertainty, but not extremely effective for any one type. The outcomes are not always conclusive. Survey respondents cited many instances of potential problems that were identified and addressed as the result of a review, but also noted problems that were overlooked despite a large audience in the review meeting. Yet all felt that properly conducted design reviews were crucial to the overall success of a program because of their ability to expose issues in a timely and relatively inexpensive manner compared to other methods.
- Set-based design was considered one of the least recommended techniques for managing uncertainty, although most of the experts saw some benefit when the primary design concept involved high risk technology that might not be viable and can not be demonstrated in a suitable timeframe.
- Reuse of prior design was thought to provide great benefits in preventing common design errors if the design elements could be utilized without any modification. It was also noted as a benefit in managing variability because of the pre-existence of design analysis and a history of any issues that might have arisen in prior manufacturing or field usage.
- Implementing “standard work” or “best practices” in design methodologies was cited as one of the most effective ways to reduce common design errors by requiring all members of the design staff to follow established procedures that have been scrutinized and refined over time and are often accompanied by supporting toolsets or design checklists.
- Upgradeable architectures were another approach that the respondents considered effective but underutilized. A frequent issue with customer inputs is late changes to the system requirements and extensible or adaptable architectures can reduce the effort required to adapt to late modifications in definition. Upgradeable architectures also can provide a less costly and labor intensive manner for dealing with component obsolescence that may occur with systems that must be maintained in the field for decades.
- Design margin is considered valuable for coping with uncertainty due to variability in components due to manufacturing variation, effects of the

surrounding environment, and any changes due to aging or wear over a period of time.

- The experts who responded to the survey stressed the need for integration testing that brings together as many of the interfacing components and subsystems as early as feasible. They felt that, regardless of any efforts to manage, design, and simulate the interfaces, testing with representative hardware and software (if any) is the only conclusive procedure for assuring compatibility prior to assembly of the full system and should not be omitted.
- All agreed that tolerance analysis and control is the obvious mitigation for uncertainty due to component variability. Furthermore, it was considered beneficial to the prevention of system interactions since because many problems that cross subsystem boundaries are due to effects like electrical noise, mechanical backlash, or physical interference during installation that can be managed and minimized by lowering variability in the design.
- Industry standards were considered most valuable for coordinating mechanical, electrical, and software interfaces between adjoining subsystems and thereby avoiding potential incompatibilities. It should be noted that use of industry standards was regarded as valuable for lowering essentially all classifications of uncertainty in the survey with mitigation of new technology risk as the area with the least positive influence.
- Design for “X” (DFX) was another mitigation process that is seen as providing wide-ranging benefits. This is due to the breadth of topics covered by the generic term DFX including manufacturability, reliability, affordability (cost), maintainability, usability (human factors), supportability (serviceability), etc. Many of these topics address potential problems that can arise after the product design is complete and the system is being produced for field service, so it is not surprising that respondents to the survey saw the most benefit for DFX in reducing uncertainties in the later product life-cycle.
- Sensitivity analysis was viewed as most beneficial for reducing potential system interactions between coupled subsystems. For example, if a dynamic system is

highly sensitive to small perturbation in its inputs, the overall system is far more likely to exhibit unstable behavior when the subsystem interfaces are connected.

- Finally, organizational changes were not perceived as extremely helpful for abating any type of uncertainty, but the experts felt that management could help to address shortcomings in the enterprises skills and capabilities by dedicating individuals or small teams for training or other forms of skill enhancement.

Additionally, observing the table's columns (i.e. uncertainty categories) we note that no category lacks an effective method of uncertainty reduction. Most categories have more than one activity that was judged very effective and all have numerous activities that were perceived as moderately effective. This is not to say that the redundancy is necessarily wasteful. Due to the high level of uncertainty involved in most complex system development programs, it is unlikely that any single technique can manage all potential problems in a manner that allows sufficient time for correction and recovery. Additional discussion on the timing and efficient application of the mitigation methods will be covered in the remainder of this report.

6.1.2 Timeliness of Uncertainty and Risk Mitigation Activities

The second set of survey questions asked for recommendation on the timing of uncertainty and risk mitigation activities relative to six major phases of a typical aerospace program. The six program phases were customer requirements capture, concept generation, preliminary design, design verification, and qualification testing /system certification (see figure below). Note that although the figure depicts the program phases occurring in series, there is often parallel effort with parts of one development phase beginning before the completion of a prior phase.

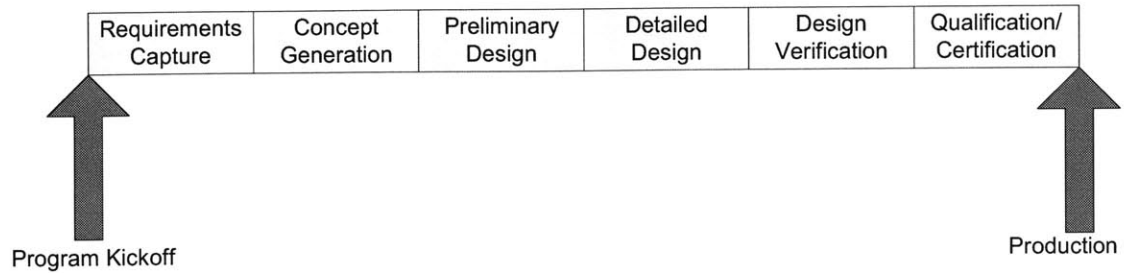


Figure 10 – Typical Program Sequence

Requirements Capture is the period of the program when the design team receives and reviews customer specifications and attempts to understand customer needs. Effort is generally needed to clarify any ambiguous or imprecise requirements and investigate unwritten customer expectations. In addition, the team may derive and document internal requirements such as manufacturing constraints and recurring cost limitations on purchased components to ensure profitability. For sub-tier aerospace suppliers, the requirements capture phase usually begins prior to awarding of the contract and continues after the company had been chosen to supply products.

The concept generation and selection phase begins after the requirements review and capture, but much of the effort may overlap the requirements phase. Concept generation is the creation of approximate system descriptions (form, fit, and function) and general architectures. Typically, more than one concept will be formed and a selection process eliminates the less optimum designs. Related trade studies are usually needed to evaluate the advantages, disadvantages, and risks associated with various concepts.

Preliminary design is a refinement of the product concept into specific requirements for hardware, software, people, facilities, equipment, and any other supporting resources. Higher level system architectures are broken down into individual component or module requirements that are needed to construct the larger system elements. Tight coordination between members of the product team is crucial. On most aerospace programs, it is customary to hold a Preliminary Design Review (PDR) near the conclusion of this phase to review design decisions and supporting analysis. The PDR typically includes customers, members of the design team (sometimes including suppliers), and other

individuals who are there to represent specific interests from non-design segments of the enterprise.

Detailed design is a further extension of preliminary design. Rigorous analysis occurs during this phase and the team is expected to produce definition of the system elements in sufficient detail to allow realization of each component and the system as a whole. Designs are stabilized. A Critical Design Review (CDR) typically occurs near the conclusion of this phase to review the detailed definitions and supporting analysis.

Following detailed design, representative hardware must be fabricated and software compiled to allow the next program phase, design verification. However, verification includes not only component and system-level testing, but also analysis and design reviews. Some of the reviews and analysis may have been performed in parallel with the earlier preliminary and detailed design efforts. The intent of verification is to conclusively demonstrate compliance to specific product design and performance requirements.

Qualification and Certification is the final program phase that will be discussed in this report. The goal of qualification is validation of the system's suitability for the intended application over a range of operating environments and conditions (i.e. to demonstrate system robustness). Examples of qualification tests for aerospace products include temperature and vibration testing of hardware, electromagnetic interference testing of electrical and electronic components, as well as numerous other types of tests. Certification is a term more often used with commercial aviation products than military systems. It is the process of substantiating the design to government agencies responsible for overseeing the airworthiness of a specific system.

The survey results for the second set of questions are illustrated in the graphs that follow. The height of the bars in each chart depicts the number of experts responding with that recommended program phase on their surveys. Note that some charts show fractional

numbers because individuals split their answers between multiple program phases. Again, follow-up interviews with most of the participants were conducted to record the rationale for the responses.

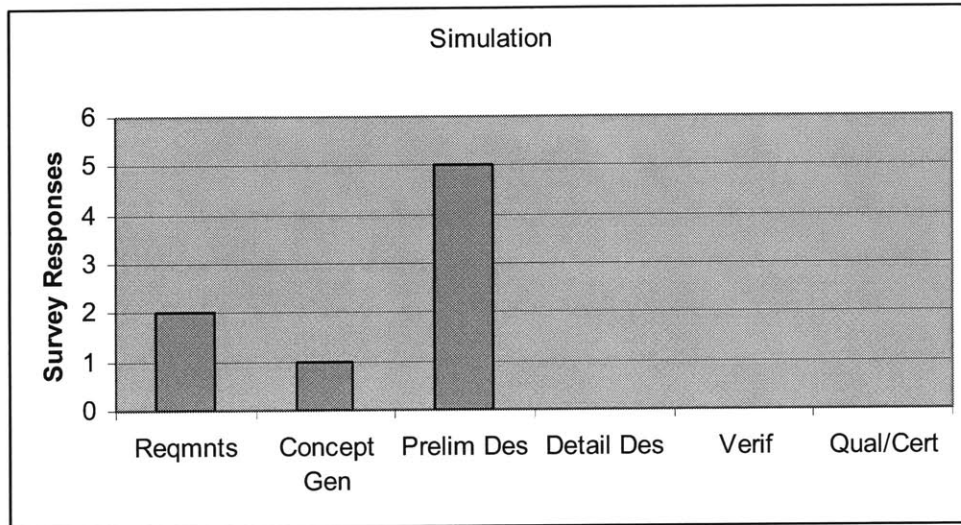


Figure 11 – Simulation Timing

The majority of survey responses indicated that the greatest benefit of simulation is gained in the preliminary design phase after the system definition has evolved to the point that representative models can be created. Individuals noted the benefits of simulation during earlier steps for “validation” of system requirements and for performing concept trade studies. However, most of the experts believed that the greatest percentage of uncertainty reduction occurred when the models included additional fidelity that isn’t possible very early in the project. This may have been related to the fact that the engineers were accustomed to working for a second-tier supplier and perhaps would not see the benefits that could be gained earlier by performing simulations at the platform or higher system level. No responses indicated large benefit during detailed design since engineering development hardware was not far in the future, although during interviews, engineers noted the benefit during detailed design of computer simulations for automating analysis tasks for thermal effects, electronic circuit accuracy, circuit stability, etc.

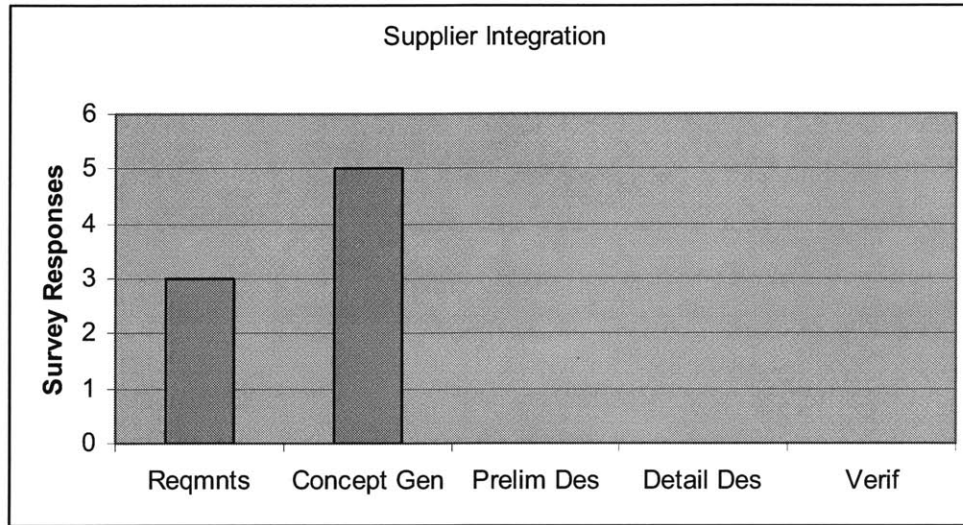


Figure 12 – Supplier Integration Timing

All participants agreed that supplier integration needed to be instituted during the early phases of the program, either during concept generation or perhaps even during requirements capture. At this point in a development project, suppliers can provide feedback on feasibility of concepts as they related to the supplied subcomponents and they may be able to suggest alternative concepts based on subcomponents that the design team had not previously considered. Make/buy decisions can be made to maximize efficiency and minimize risk due to enterprise capability concerns.

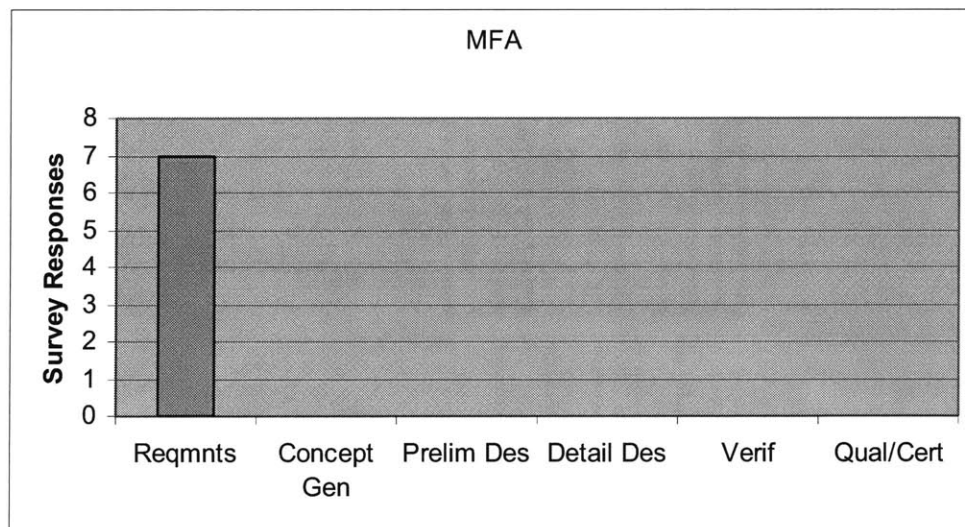


Figure 13 – Customer Integration Timing

There was a unanimous response that customer integration (sometimes called market feedback analysis, MFA) needed to occur during the requirements capture phase. Concept generation should not proceed unless the design team feels that they have a sufficiently complete set of requirements and understanding of customer needs.

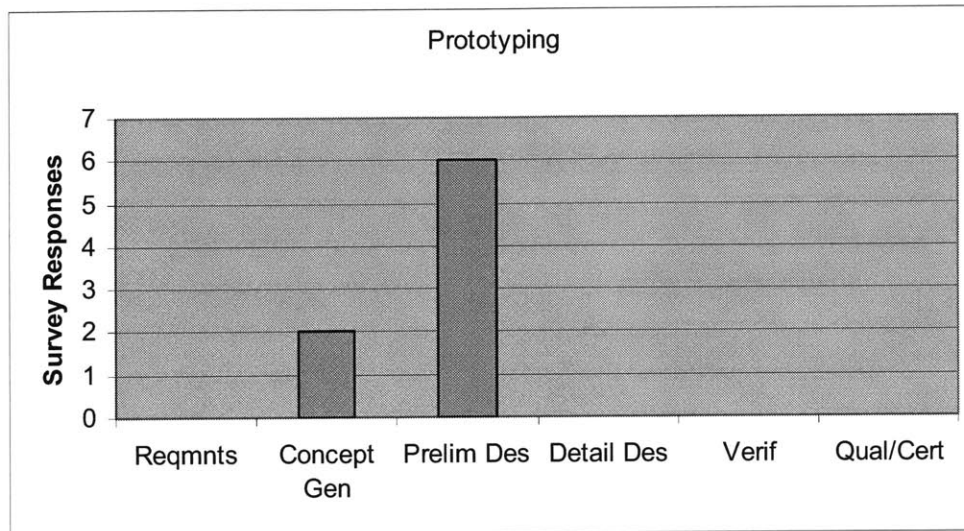


Figure 14 – Prototyping Timing

The profile and rationale for prototyping was similar to the response for simulation. Like simulation, the greatest benefit of prototyping is gained in the preliminary design phase after the system definition has evolved to the point that rough but representative hardware can be created. The benefit diminishes as the project gets closer to having completed development test hardware.

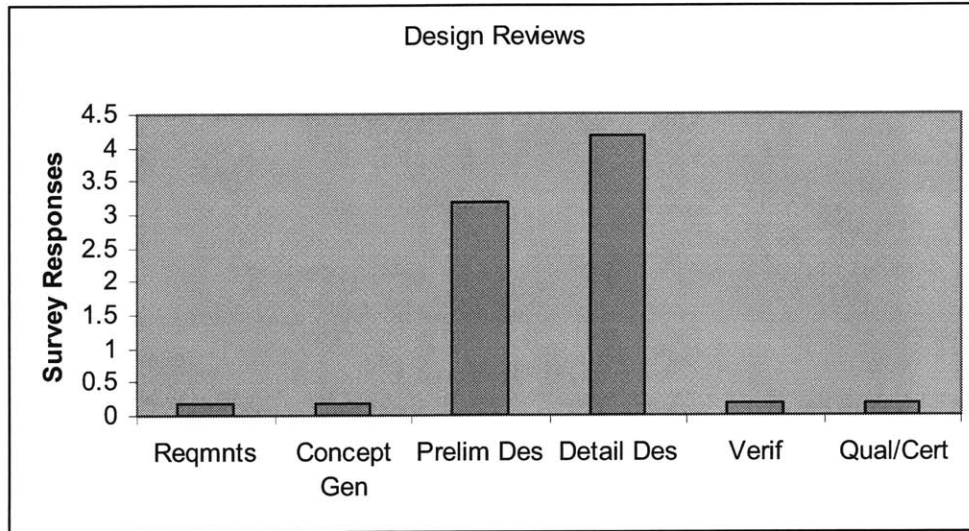


Figure 15 – Design Review Timing

Logically, design reviews were believed to provide the most benefit during preliminary and detailed design when most of the material that is under review is being created.

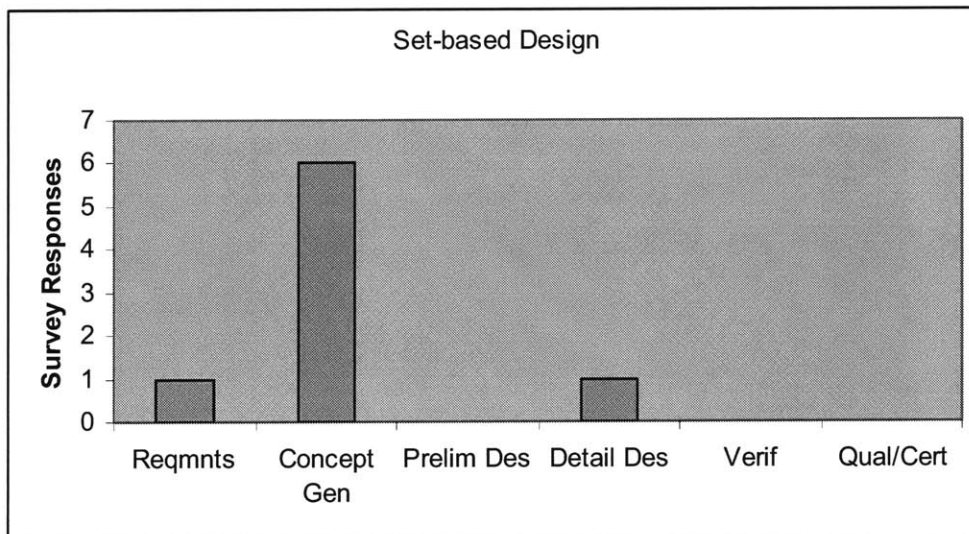


Figure 16 – Set Based Design Timing

It was recommended that set-based design be executed during the concept generation and selection phase. Again, this was considered most beneficial when one or more of the concepts involved technology uncertainties.

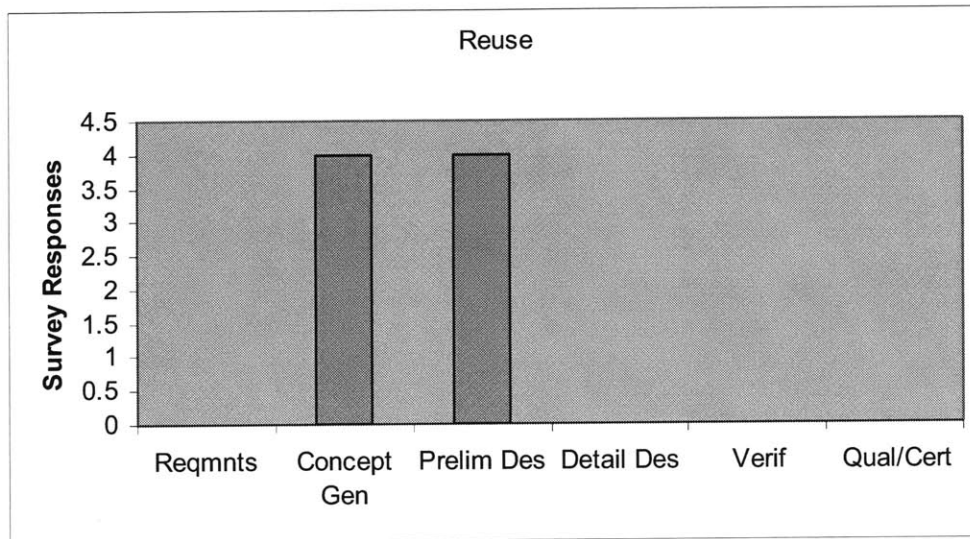


Figure 17 – Reuse Timing

All participants agreed on the need for a plan of reuse early in the program. The optimal program phase appears to depend on the level of subsystem that is intended to be reused. If high level modules are being reused in their entirety, then the decision can be made during concept generation and selection. However, if lower level system elements are being selected for reuse, the team may need to wait until the preliminary design phase to determine with legacy designs are appropriate.

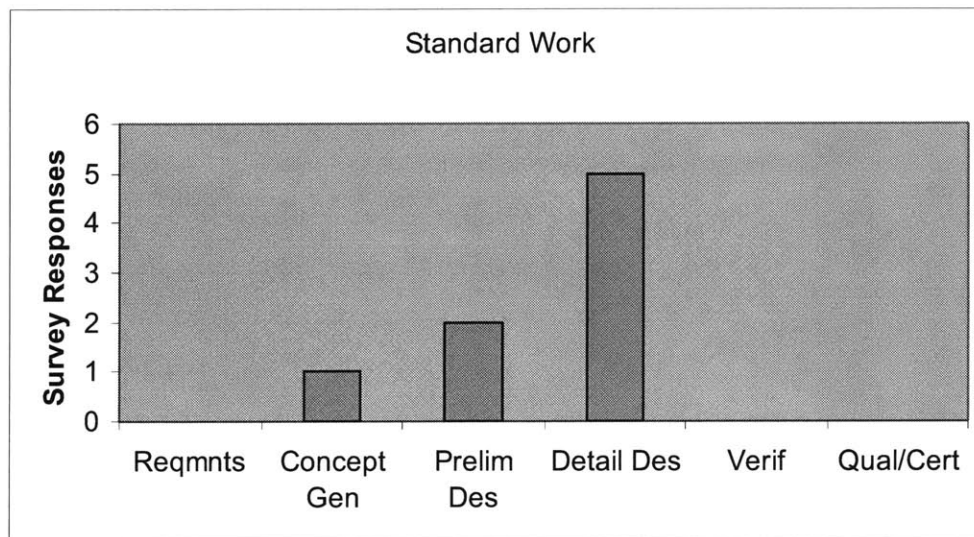


Figure 18 – Standard Work Timing

All of the experts felt that there were engineering procedures that could be standardized for each of the six program phases. But, the majority felt that the greatest opportunities for eliminating errors and improving efficiency existing in the detailed design phase of the program where rigorous and often tedious analyses are performed. It is during this period that many design errors in the low-level product definition are introduced.

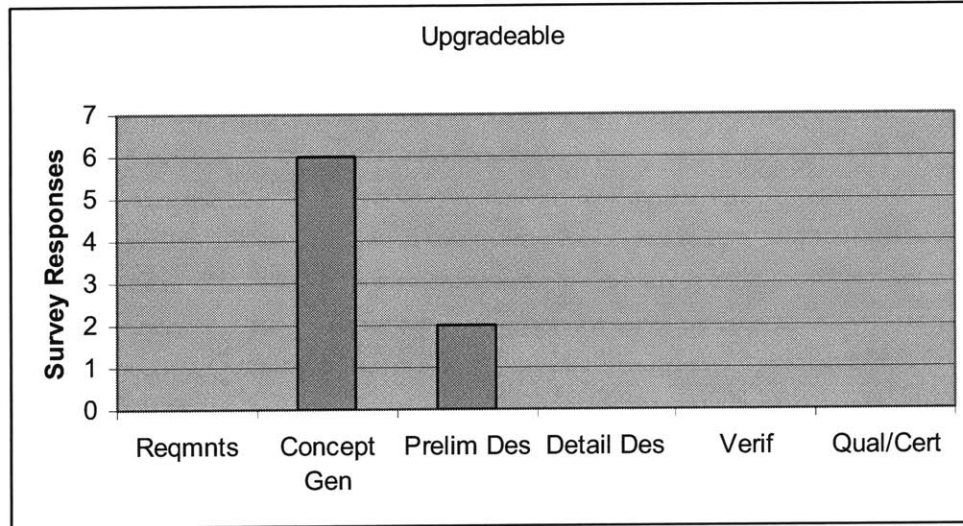


Figure 19 – Upgradeable Architecture Timing

The general consensus was that upgradeable architectures are best conceived and easiest to apply during the concept generation and selection phase, although there may be additional opportunities to implement upgradeable concepts during preliminary design.

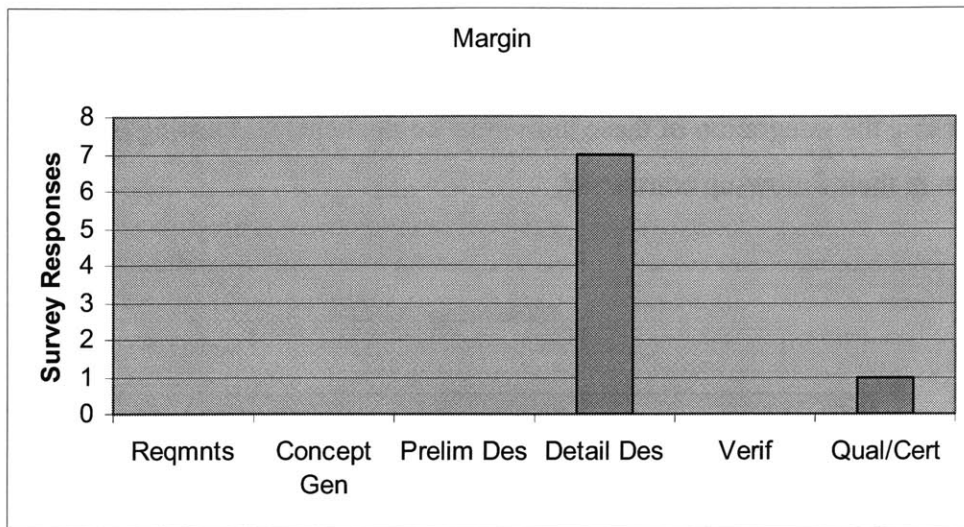


Figure 20 – Design Margin Timing

Design margin is most often inserted into a product during detailed design when product definition is created in sufficient detail to allow component realizations.

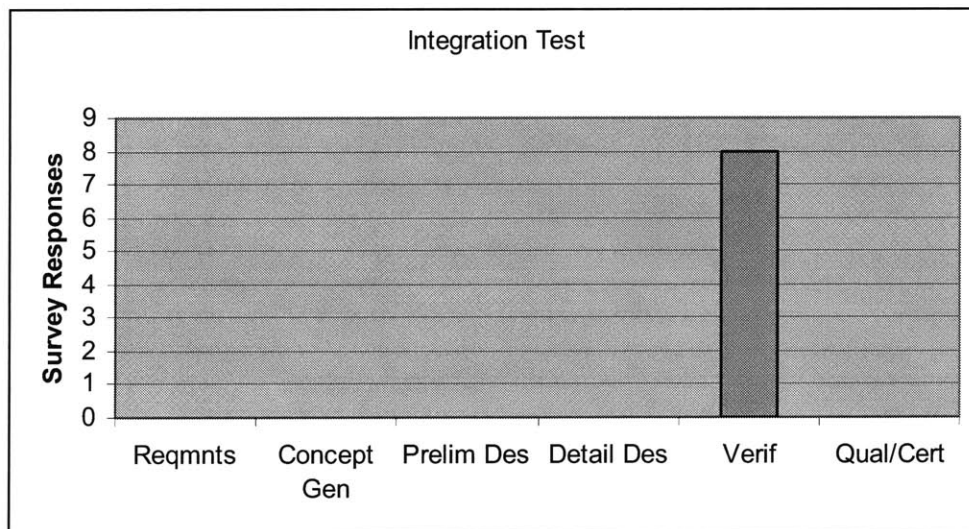


Figure 21 – Integration Test Timing

All respondents to the survey considered integration testing, almost by definition, to be a step in the system verification process. Furthermore, most of the experts emphasized their opinion that no amount of prior interface coordination and system risk reduction

eliminates the need for integration testing. Note that most of these engineers work in an environment where independent development teams produce different components or modules that are later connected to form a subsystem for delivery to a customer. They were stressing the integration of these individual components and testing of the complete subsystem in their follow-up comments.

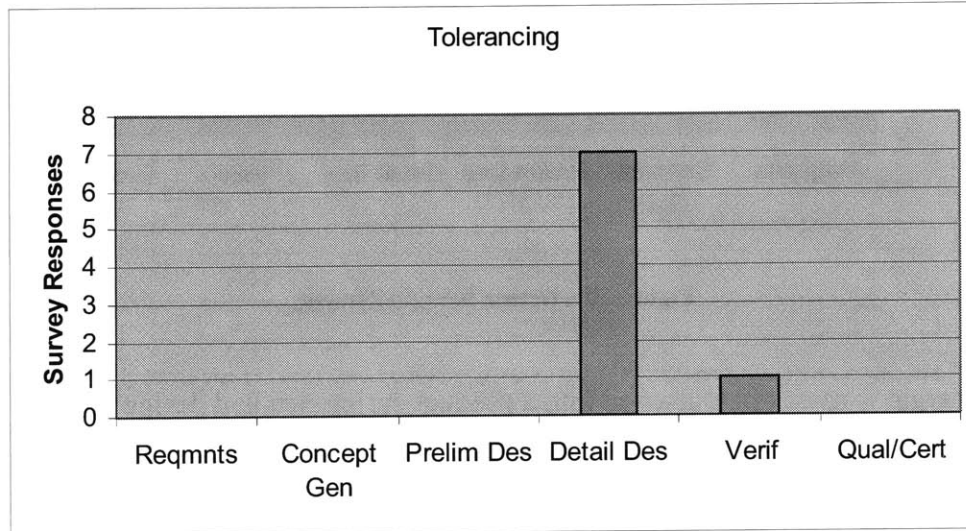


Figure 22 – Tolerance Control Timing

The vast majority of surveys recommended that detailed tolerance analysis be postponed until detailed design. Completing this task earlier would likely result in excessive rework since the design would still be in a fluid and evolving in multiple iterations. If detailed analysis such as tolerance studies were performed too soon, it might be considered an “over-production waste” in the lean product development vernacular. Furthermore, the tolerance analysis requires low-level component definition that is not available at an earlier time.

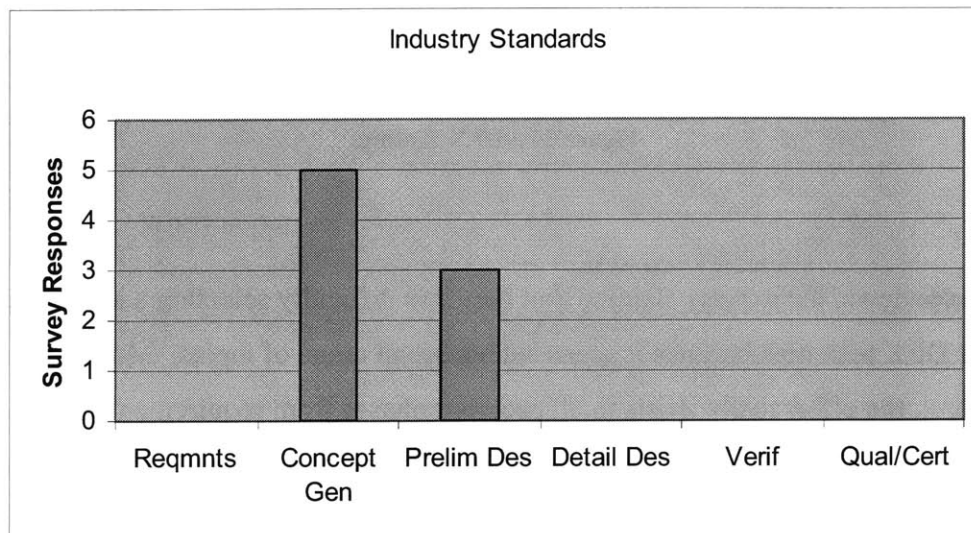


Figure 23 – Industry Standard Timing

Implementation of industry standards becomes very difficult if it is not planned at the concept selection phase or early in the preliminary design phase. Any Attempts to modify a design later in the process results in more excessive rework.

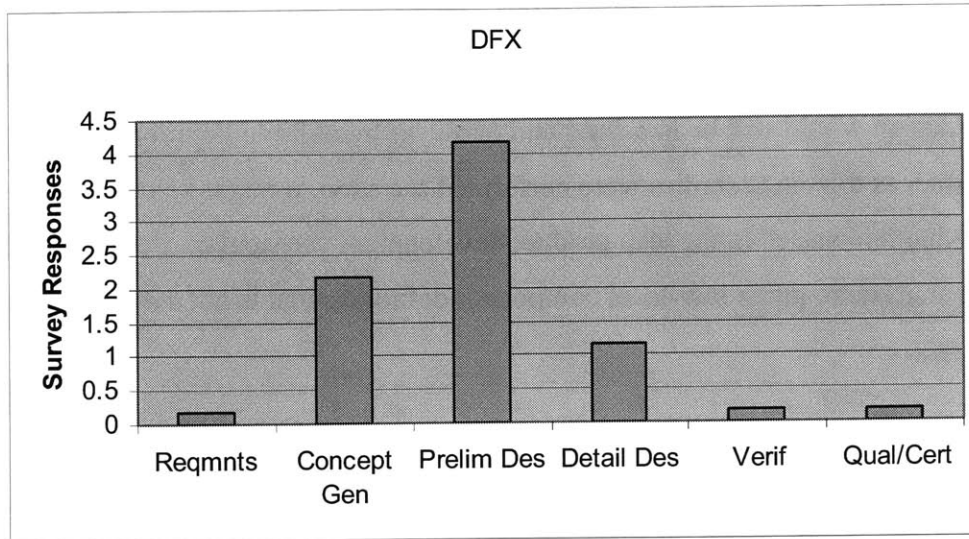


Figure 24 – DFX Timing

During interviews, the experts claimed that they had difficulty selecting a single program phase for DFX activities because it spans such a broad range of topics. Most felt that, to some extent, the effort really exists in all program phases from requirements reviews up to final certification. However, most responses indicated that the greatest benefits were in the first part the preliminary design or concept phases because it is important to consider the needs of the entire enterprise early in a project. Too many development teams spend much of their initial efforts on satisfying performance requirements at the expense of manufacturability, reliability, affordability, and other critical design aspects. Again, excessive rework results when late changes are made to reduce cost, improve predicted reliability, or streamline manufacturing.

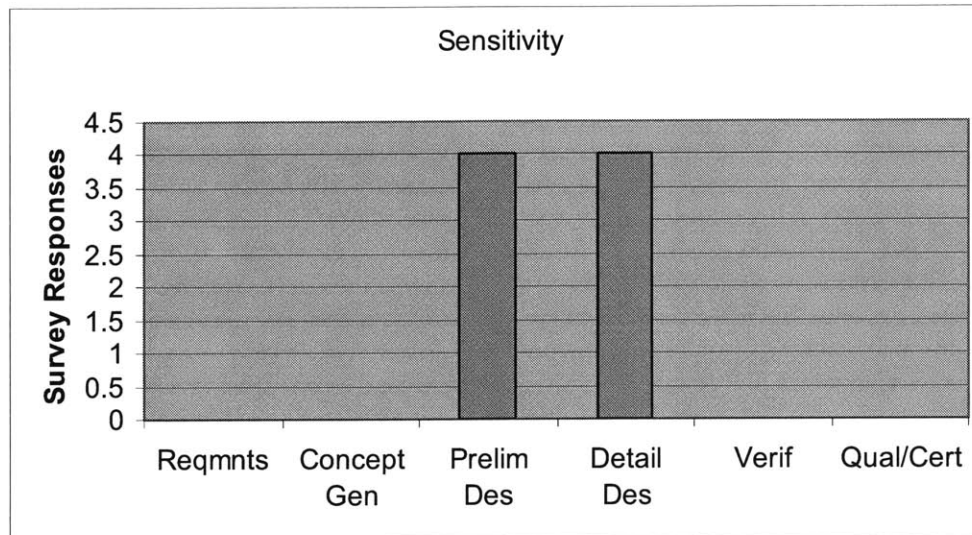


Figure 25 – Sensitivity Analysis Timing

Some experts felt as though the sensitivity analysis task was similar to tolerance calculations, in other words, it should be delayed until detailed design to avoid excessive rework from an evolving architecture and because it is difficult to complete without low-level definition. Others believed that it should be performed during the preliminary design phase because the results were likely to generate system modifications that would be the drivers for additional changes – therefore, postponing the task would result in late stage, inefficient changes to the design. After reconsideration, a number of respondents suggested that the best plan for this analysis will ultimately hinge on the nature of the system and its components. If there is a high degree of reuse from prior products, low technology risk, the enterprise has extensive technical expertise in the area, and design reviews have been completed, then it would be acceptable to delay the analysis until the detailed design phase. However, if there is little reuse or if there is high technology risk, the design team would be wise to perform preliminary calculations or simulations during the earlier phase and then finalize the analysis in the detailed design phase.

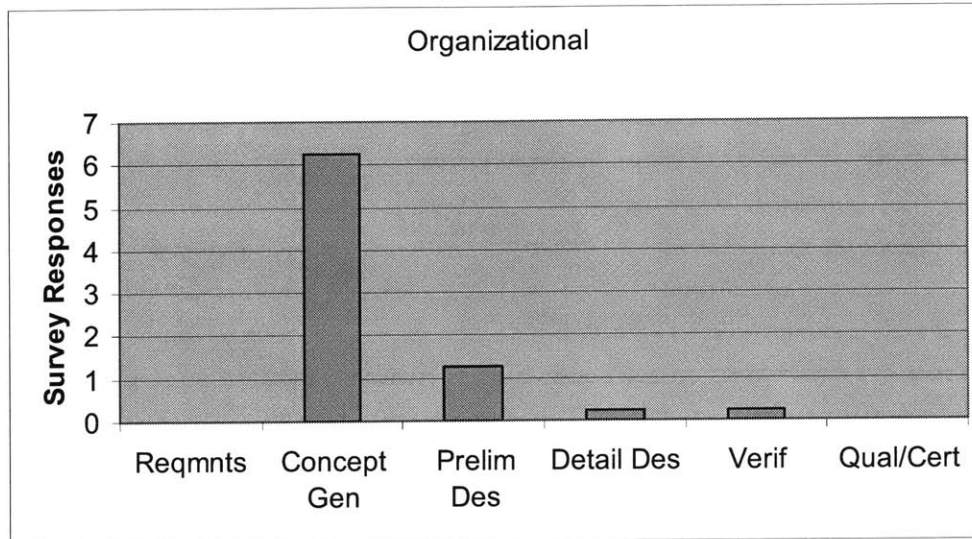


Figure 26 Organizational Change Timing

All of the respondents agreed that late stage organizational changes were counterproductive. Modifications to the organizational structure to address design uncertainty should be assessed very early in the program when the programs challenges can be weighed against the organization's capability and comfort with new technologies.

6.2 Management Recommendations

Based on the results of this survey, it is recommended that managers in a product development environment implement a series of stage gate reviews if their process does not already require such a review between each of the major phases of a program. Ultimately, the optimum strategy for risk management and reduction on any product will be dependent on the nature of the product and the set of known risks identified by the design team. But in cases where a risk cannot be conclusively resolved early in a program, a manager would be wise to require a strong albeit inconclusive form of risk management during the earlier program phases.

Table 5 - Recommended Stage Gate Process for Risk Mitigation (Example) provides one possible set of agendas on the topic of risk management. A manager will need to tailor his process according to the needs of the product and the organization.

Table 5 - Recommended Stage Gate Process for Risk Mitigation (Example)

Review	Recommended Criteria
Stage Gate 1 – After requirements capture and prior to concept generation	<ul style="list-style-type: none"> • Review customer integration activities which should be complete (customer risk) • Establish plans or targets for reuse (design errors, variability), set-based design (new technology), supplier integration (enterprise capability) and/or, upgradeable architectures (life cycle concerns, interactions) for the next phase of the program
Stage Gate 2 – After concept selection and prior to preliminary design	<ul style="list-style-type: none"> • Review results against plans established in stage gate 1 • Establish plans or targets for prototyping (new technology, design errors, enterprise capability, customer), simulation (interactions), sensitivity analysis (variability, interactions) and/or DFX (life cycle concerns).
Stage Gate 3 – After preliminary design and prior to detailed design	<ul style="list-style-type: none"> • Review results against plans established in stage gate 2 • Establish plans or targets for standard work (design errors, interactions, enterprise capability), tolerance control and margin allowances (variability), design reviews (customer, life cycle)
Stage Gate 4 – After detailed design and prior to verification	<ul style="list-style-type: none"> • Review results against plans established in stage gate 3 • Establish plans or targets for integration test (interactions)
Stage Gate 5 – After verification and prior to certification	<ul style="list-style-type: none"> • Review results against plans established in stage gate 4 • All risks should be reduced adequately by this time

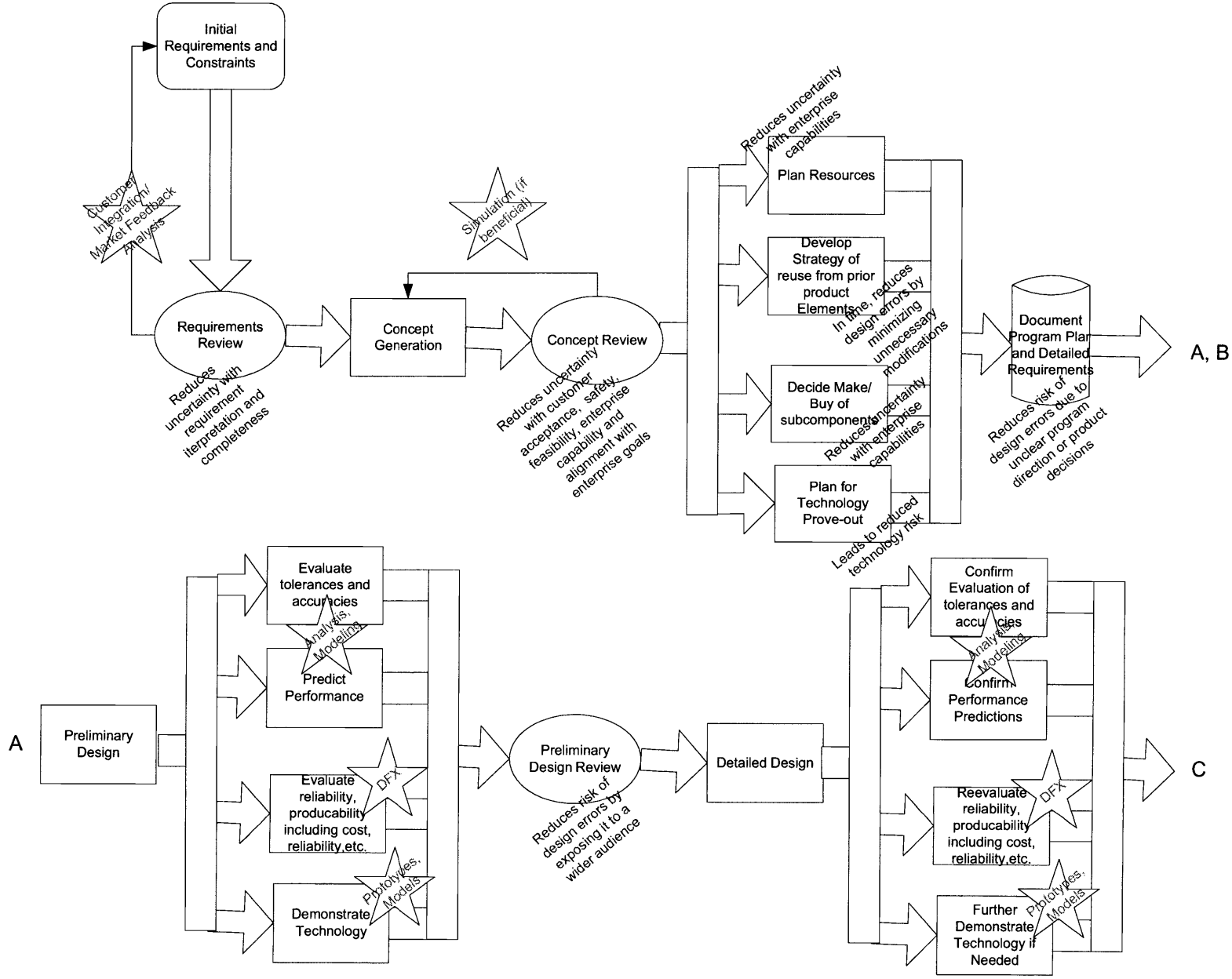
Where the recommended stage gate process calls for establishing plans or targets for execution in the next development phase, ideally these goals should have distinct metrics associated with them to gauge their completeness and effectiveness. To the extent possible, overall program risk metrics, whether quantitative or qualitative, should be

updated as a result of each intermediate step. Consistent uncertainty and risk reduction as a function of program expenditures could be considered a good indication that value is being created. Persistently high levels of risk despite multiple attempts at mitigation could be an indicator of waste in the execution of the program.

The case study clearly illustrated that, careful consideration of product uncertainties and aggressive risk management can greatly improve a project's chances of success. These examples in section 5 showed that just the awareness of potential project risks could benefit a team's performance, although not to the extent when the awareness is combined with effective mitigation strategies. The frequent management error of associating value with the creation of program artifacts or predefined schedule milestones can be avoided if management defines the program tasks by their ability to reduce program uncertainty. For example, figure 27 is a reproduction of a value stream map extracted for the Product Development Value Stream Mapping (PDVSM) Manual. It includes activities like the creation of drawings and manufacturing plans. Figure 28 is a representation of a baseline value stream map from the project described in the case study section of this document. In this VSM, the type of uncertainty that it is meant to address highlights each activity.

Lean practitioners often focus on the elimination of waste in a process. This may lead to debates about the value of tasks that do not lie on the critical path to completion – reviews, inspections, and tests for example. Risk mitigation activities could also fall under this heading. But managers who establish a program's critical path typically do not view the process as one whose goal is the elimination of uncertainty.

Figure 28 - Value Stream Map Including Uncertainty



7 Conclusions and Opportunities for Further Study

7.1 Summary

The stated goals of this paper were to explore the role of uncertainty in lean product development, demonstrate a relationship between risk mitigation activities and the generation of customer value in the design and development process, and to provide guidelines for completing these activities in a manner that reduces cycle time, assures quality, and makes the most efficient use of company resources. These goals were achieved via the case study and survey, although the conclusions were often based on qualitative information such as the opinions of product development team members instead of hard quantifiable measurements.

The detailed analysis supporting the case study provided clear associations that might be obvious to some. Product development teams that undertake aggressive and rigorous activities to identify uncertainties and risk ultimately encounter fewer problems and unplanned rework. These teams complete their project at an overall lower cost than the shortsighted teams who spend less to address uncertainty and risk, but meet greater problems later in the process. Using any measure of value discussed during the introductory sections of this paper, fulfilling customer needs at lower cost and less time equates to increased value.

Table 4 – Survey Results: Mean Mitigation Activity Effectiveness provides a brief overview of many of the most common mitigation activities for each particular class of uncertainty. Depending on the particular uncertainties identified, multiple options are available and a combination of methods will often be required since most of the conclusive techniques are only possible late in a program when efficient recovery is not possible. Section 6.2. provided a concise strategy for the effective management of risk on a lean product development program. An example was provided that used a combination of less conclusive methods performed early and more conclusive methods performed late to resolve issues when the impact would be felt less. The recommendations are practical and consistent with the capabilities of many aerospace product development organizations.

Acceptable levels of uncertainty that may remain at each stage of the program will be highly dependent on the nature of the product and the risk tolerance of the organization. However, in the interest of value creation, managers should expect that quantitatively or qualitatively measured risks levels should decline at a rate over time that approximates the rate of expenditures. If one believes that product development is truly about the elimination of uncertainty that the product will satisfactorily perform its required function, then substantial expenditures without concurrent reductions in the level of uncertainty could be an indicator of wasteful actions.

7.2 Opportunities for additional Research

Efficient methods of visualizing risk reduction as a function of program expenditures represent an opportunity for further research. Although the goals of this thesis were met, additional research is required to provide better quantitative metrics for the measurement of uncertainty, risk, and the relationship to product development value. The risk identification and tracking methodologies used in industry are predominantly based on educated guesses about the likelihood and potential impact of a future event. It is almost certain that different engineering teams and managers would arrive at very different

evaluations of identical sets of scenarios. Current attempts to identify new metrics of uncertainty and risk management and related value equations were briefly discussed at the onset of this paper. These methods are not currently practical or complete. They remain too complex and abstract for application in an industry setting.

Most managers would agree that the elimination of risks provides value. Yet there is a threshold at which the return on investment from risk abatement activities diminishes and over-spending on insignificant sources of risk becomes another form of waste.

Therefore, a quantifiable measure of value provided by risk management is desirable. Proper determination of the correct amount of risk management effort will be imprecise until such a measurement is developed. Once a proper set of risk and value measurements are established, it will be more feasible to conduct research into optimizing the balance of risk management expenditures against the waste that could otherwise be generated.

Finally, the lean risk management recommendations presented in section 6 are still only hypotheses at this point. They represent logical assumptions based on a small sample of aerospace programs and the opinions of experts in that domain. Attempts to apply the recommendations on future design and development programs would yield valuable information about the usefulness of the framework and potential for improvement. The final tenet of lean thinking is the pursuit of perfect. To this end, the risk management framework can be iteratively refined to improve the appropriateness, granularity, and accuracy of value creation through reduction of uncertainty and risk.

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Appendix A - Management Survey

Questionnaire

Uncertainty and Risk Reduction in the Development of Aircraft Systems

We request that you utilize your past experiences in the development of aircraft systems to provide opinions regarding the most effective methods for mitigating areas of uncertainty (risk) in product development programs. In addition, you will be asked to indicate the optimal program phase for executing each mitigation activity.

This questionnaire is concerned with product risks that arise between program kickoff and system certification. It will not address issues that occur after the product has been developed and enters full-scale production. Therefore, manufacturing and service issues occurring later than this time span will be ignored, but we still consider the risk of designing a system that is deemed difficult to manufacture or maintain within the frame of reference. Program management risks such as resource availability and budget stability will not be discussed.

Product uncertainties can be known, unknown or unknowable. “Known risks are those that one or more project personnel are aware of – if not explicitly as risks, at least as concerns. The unknown risks are those that would be surfaced (i.e. become known) if the project personnel were given the right opportunity, cues, and information. The unknowable risks are those that, even in principle, none could foresee.”² This survey addresses known and unknown risks, but does not consider unknowable risks.

² Definitions of known, unknown, and unknowable risks from Software Engineering Institute Technical Report CMU/SEI-93-TR-6, Taxonomy-Based Risk Identification

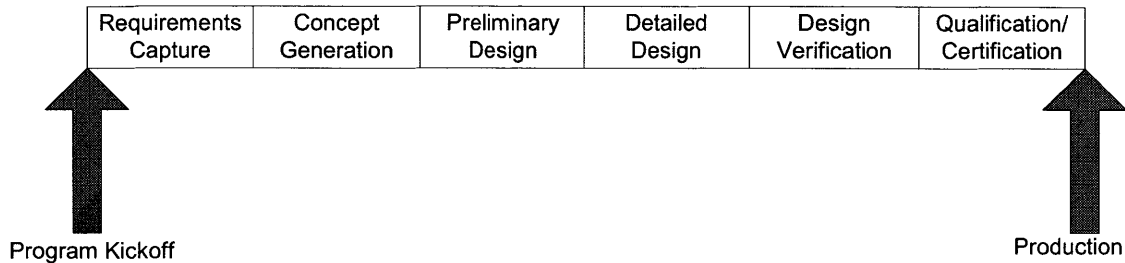
Please review the definitions below before completing the questions that follow.

Categories of Uncertainty

Category	Definition
Component Variability	Sample to sample variation in the elements that comprise a system. Often these variations can be described statistically. Examples include manufacturing tolerances and component drift (due to aging, wear, etc.)
New Technology	Uncertainty caused by the application of unproven technology.
New Enterprise Capability	The pursuit of development tasks beyond the organization's existing expertise. Examples may involve new company facilities or employee skill sets. In other words, technologies or processes that are not necessarily new, but may be new to your enterprise.
Customer Uncertainties	Misjudging customer needs. The system may meet the stated objectives, but the objectives are incorrect in the customer's final appraisal. Issues contributing uncertainty include incomplete, unstable, or ambiguous requirements and inaccurate projections of market demand.
Potential Interactions with Other Subsystems or Within the System/subsystem	Interface problems between system elements. The external environment (temperature, pressure, humidity, etc.) is considered another subsystem that can interact with the system being designed. Installation problems also fall into this category.
Design Errors	The product fails to meet the performance requirements because of one or more mistakes by the members of the design team.
Uncertainty Planning for the Later Life Cycle Stages	Manufacturing, supply chain, and maintainability issues. Examples include designs that can not be produced economically, supplier quality issues, and component obsolescence. Is the design feasible in the long term?

Program Phases

Please consider this general project timeline when evaluating the phases of a program.



- A. Requirements Capture – This phase includes the receipt of customer requirements and any activity required to capture internal or external requirements and unstated customer needs.
- B. Concept Generation – Formulation of product concepts and related trade studies
- C. Preliminary Design – Program activities up to Preliminary Design Review. Often this includes generation of design descriptions and coordination with other functional members of the product team.
- D. Detailed design – Program activities up to Critical Design Review. There is more rigorous analysis and evaluation during this phase. Designs are stabilized.
- E. Design Verification – Includes testing, analysis, and reviews that are performed to demonstrate compliance to specific product design and performance requirements.
- F. Qualification and Certification – validation of the systems suitability for the intended application over a range of operating environments and conditions.

Questions:

Please rate the risk mitigation activities below for their effectiveness in reducing different categories of uncertainty. Effectiveness is judged on the ability to prevent problems that would delay the project schedule, increase the development budget, reduce profitability of the final product, or adversely affect customer satisfaction.

You are also asked to describe the program phase where the activity will likely provide the most benefit on a typical product development project in your enterprise. Assume that all risks identified on this typical product development project have approximately the same impact and probability of occurrence.

1. Simulation is the application of computer-based analytical models to aid design and predict product performance.

How effective is simulation for reducing the following kinds of uncertainty? (Circle one value on each row)

Component Variability	5	4	3	2	1	0
New Technology	5	4	3	2	1	0
New Enterprise Capability	5	4	3	2	1	0
Customer Uncertainties	5	4	3	2	1	0
Potential Interactions with other Systems/subsystems	5	4	3	2	1	0
Design Errors	5	4	3	2	1	0
Uncertainty planning for later Life Cycle stages	5	4	3	2	1	0

5 = Very beneficial on almost all programs
 4 = Moderately beneficial on most, very beneficial on some
 3 = Moderately beneficial on almost all programs
 2 = Moderately beneficial on most, no benefit on some
 1 = No benefit on most, moderate benefit on some
 0 = No benefit on almost all programs

During which stage of a typical program is simulation likely to provide the most benefit? (circle one):

A	B	C	D	E	F
Requirements	Concept Generation	Preliminary Design	Detailed Design	Design Verification	Qualification and Cert

2. Supplier Integration is the practice of supplier and subcontractor involvement in system design decisions

How effective is supplier integration for reducing uncertainty in the following areas? (Circle one value on each row)

Variability	5	4	3	2	1	0
New Technology	5	4	3	2	1	0
Enterprise Capability	5	4	3	2	1	0
Customer	5	4	3	2	1	0
System Interactions	5	4	3	2	1	0
Design Errors	5	4	3	2	1	0
Life Cycle Concerns	5	4	3	2	1	0

5 = Very beneficial on almost all programs
 4 = Moderately beneficial on most, very beneficial on some
 3 = Moderately beneficial on almost all programs
 2 = Moderately beneficial on most, no benefit on some
 1 = No benefit on most, moderate benefit on some
 0 = No benefit on almost all programs

During which stage of a typical program is supplier integration likely to provide the most benefit? (circle one):

A	B	C	D	E	F
Requirements	Concept Generation	Preliminary Design	Detailed Design	Design Verification	Qualification and Cert

3. Customer Integration and Market Feedback Analysis are the practices of customer involvement in system design decisions and the solicitation/analysis of customer satisfaction.

How effective are customer integration and market feedback analysis for reducing uncertainty in the following areas? (Circle one value on each row)

Variability	5	4	3	2	1	0
New Technology	5	4	3	2	1	0
Enterprise Capability	5	4	3	2	1	0
Customer	5	4	3	2	1	0
System Interactions	5	4	3	2	1	0
Design Errors	5	4	3	2	1	0
Life Cycle Concerns	5	4	3	2	1	0

- 5 = Very beneficial on almost all programs
- 4 = Moderately beneficial on most, very beneficial on some
- 3 = Moderately beneficial on almost all programs
- 2 = Moderately beneficial on most, no benefit on some
- 1 = No benefit on most, moderate benefit on some
- 0 = No benefit on almost all programs

During which stage of a typical program is customer integration and market feedback analysis likely to provide the most benefit? (circle one):

A	B	C	D	E	F
Requirements	Concept Generation	Preliminary Design	Detailed Design	Design Verification	Qualification and Cert

4. Prototyping includes the creation and evaluation of physical mockups as well as coarse functional hardware/software

How effective is prototyping for reducing uncertainty in the following areas? (Circle one value on each row)

Variability	5	4	3	2	1	0
New Technology	5	4	3	2	1	0
Enterprise Capability	5	4	3	2	1	0
Customer	5	4	3	2	1	0
System Interactions	5	4	3	2	1	0
Design Errors	5	4	3	2	1	0
Life Cycle Concerns	5	4	3	2	1	0

- 5 = Very beneficial on almost all programs
- 4 = Moderately beneficial on most, very beneficial on some
- 3 = Moderately beneficial on almost all programs
- 2 = Moderately beneficial on most, no benefit on some
- 1 = No benefit on most, moderate benefit on some
- 0 = No benefit on almost all programs

During which stage of a typical program is prototyping likely to provide the most benefit? (circle one):

A	B	C	D	E	F
Requirements	Concept Generation	Preliminary Design	Detailed Design	Design Verification	Qualification and Cert

5. Design Reviews are evaluations of important design decisions, parameters, and processes by peers and enterprise experts. Reviews often also include customers and suppliers.

How effective are design reviews for reducing uncertainty in the following areas? (Circle one value on each row)

Variability	5	4	3	2	1	0
New Technology	5	4	3	2	1	0
Enterprise Capability	5	4	3	2	1	0
Customer	5	4	3	2	1	0
System Interactions	5	4	3	2	1	0
Design Errors	5	4	3	2	1	0
Life Cycle Concerns	5	4	3	2	1	0

5 = Very beneficial on almost all programs
 4 = Moderately beneficial on most, very beneficial on some
 3 = Moderately beneficial on almost all programs
 2 = Moderately beneficial on most, no benefit on some
 1 = No benefit on most, moderate benefit on some
 0 = No benefit on almost all programs

During which stage of a typical program are design reviews likely to provide the most benefit? (circle one):

A	B	C	D	E	F
Requirements	Concept Generation	Preliminary Design	Detailed Design	Design Verification	Qualification and Cert

6. Set-based design is the simultaneous pursuit of multiple design alternatives until a preferred option becomes evident.

How effective is set-based design for reducing uncertainty in the following areas? (Circle one value on each row)

Variability	5	4	3	2	1	0
New Technology	5	4	3	2	1	0
Enterprise Capability	5	4	3	2	1	0
Customer	5	4	3	2	1	0
System Interactions	5	4	3	2	1	0
Design Errors	5	4	3	2	1	0
Life Cycle Concerns	5	4	3	2	1	0

5 = Very beneficial on almost all programs
 4 = Moderately beneficial on most, very beneficial on some
 3 = Moderately beneficial on almost all programs
 2 = Moderately beneficial on most, no benefit on some
 1 = No benefit on most, moderate benefit on some
 0 = No benefit on almost all programs

During which stage of a typical program is set-based design likely to provide the most benefit? (circle one):

A	B	C	D	E	F
Requirements	Concept Generation	Preliminary Design	Detailed Design	Design Verification	Qualification and Cert

7. Reuse is the repeated exploitation of existing designs in new applications.

How effective is reuse for reducing uncertainty in the following areas? (Circle one value on each row)

Variability	5	4	3	2	1	0
New Technology	5	4	3	2	1	0
Enterprise Capability	5	4	3	2	1	0
Customer	5	4	3	2	1	0
System Interactions	5	4	3	2	1	0
Design Errors	5	4	3	2	1	0
Life Cycle Concerns	5	4	3	2	1	0

5 = Very beneficial on almost all programs

4 = Moderately beneficial on most, very beneficial on some

3 = Moderately beneficial on almost all programs

2 = Moderately beneficial on most, no benefit on some

1 = No benefit on most, moderate benefit on some

0 = No benefit on almost all programs

During which stage of a typical program is reuse likely to provide the most benefit? (circle one):

A Requirements	B Concept Generation	C Preliminary Design	D Detailed Design	E Design Verification	F Qualification and Cert
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8. Best Practices or Standard Work is the repeated utilization and refinement of existing processes on multiple designs.

How effective is standard work for reducing uncertainty in the following areas? (Circle one value on each row)

Variability	5	4	3	2	1	0
New Technology	5	4	3	2	1	0
Enterprise Capability	5	4	3	2	1	0
Customer	5	4	3	2	1	0
System Interactions	5	4	3	2	1	0
Design Errors	5	4	3	2	1	0
Life Cycle Concerns	5	4	3	2	1	0

5 = Very beneficial on almost all programs

4 = Moderately beneficial on most, very beneficial on some

3 = Moderately beneficial on almost all programs

2 = Moderately beneficial on most, no benefit on some

1 = No benefit on most, moderate benefit on some

0 = No benefit on almost all programs

During which stage of a typical program is standard work likely to provide the most benefit? (circle one):

A Requirements	B Concept Generation	C Preliminary Design	D Detailed Design	E Design Verification	F Qualification and Cert
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9. Upgradeable Architecture allows simplified modification of the product in anticipation of new requirements or opportunities.

How effective is upgradeability for reducing uncertainty in the following areas? (Circle one value on each row)

Variability	5	4	3	2	1	0
New Technology	5	4	3	2	1	0
Enterprise Capability	5	4	3	2	1	0
Customer	5	4	3	2	1	0
System Interactions	5	4	3	2	1	0
Design Errors	5	4	3	2	1	0
Life Cycle Concerns	5	4	3	2	1	0

- 5 = Very beneficial on almost all programs
- 4 = Moderately beneficial on most, very beneficial on some
- 3 = Moderately beneficial on almost all programs
- 2 = Moderately beneficial on most, no benefit on some
- 1 = No benefit on most, moderate benefit on some
- 0 = No benefit on almost all programs

During which stage of a typical program is upgradeability likely to provide the most benefit? Assume that an upgradeable design already exists and it is being adapted . (circle one):

A	B	C	D	E	F
Requirements	Concept Generation	Preliminary Design	Detailed Design	Design Verification	Qualification and Cert

10. Design Margin provides additional allowances for error beyond the limits of the system requirements

How effective is design margin for reducing uncertainty in the following areas? (Circle one value on each row)

Variability	5	4	3	2	1	0
New Technology	5	4	3	2	1	0
Enterprise Capability	5	4	3	2	1	0
Customer	5	4	3	2	1	0
System Interactions	5	4	3	2	1	0
Design Errors	5	4	3	2	1	0
Life Cycle Concerns	5	4	3	2	1	0

- 5 = Very beneficial on almost all programs
- 4 = Moderately beneficial on most, very beneficial on some
- 3 = Moderately beneficial on almost all programs
- 2 = Moderately beneficial on most, no benefit on some
- 1 = No benefit on most, moderate benefit on some
- 0 = No benefit on almost all programs

During which stage of a typical program is design margin likely to provide the most benefit? (circle one):

A	B	C	D	E	F
Requirements	Concept Generation	Preliminary Design	Detailed Design	Design Verification	Qualification and Cert

11. System Integration Test collects multiple elements of a subsystem in a single facility to demonstrate performance at a system level.

How effective is integration testing for reducing uncertainty in the following areas? (Circle one value on each row)

Variability	5	4	3	2	1	0
New Technology	5	4	3	2	1	0
Enterprise Capability	5	4	3	2	1	0
Customer	5	4	3	2	1	0
System Interactions	5	4	3	2	1	0
Design Errors	5	4	3	2	1	0
Life Cycle Concerns	5	4	3	2	1	0

- 5 = Very beneficial on almost all programs
- 4 = Moderately beneficial on most, very beneficial on some
- 3 = Moderately beneficial on almost all programs
- 2 = Moderately beneficial on most, no benefit on some
- 1 = No benefit on most, moderate benefit on some
- 0 = No benefit on almost all programs

During which stage of a typical program is integration testing likely to provide the most benefit? (circle one):

A	B	C	D	E	F
Requirements	Concept Generation	Preliminary Design	Detailed Design	Design Verification	Qualification and Cert

12. Tolerance Analysis and Control provides error budgets to components, calculates the effect at a system level, and strives for repeatability in product realizations (e.g. six sigma)

How effective is tolerance control for reducing uncertainty in the following areas? (Circle one value on each row)

Variability	5	4	3	2	1	0
New Technology	5	4	3	2	1	0
Enterprise Capability	5	4	3	2	1	0
Customer	5	4	3	2	1	0
System Interactions	5	4	3	2	1	0
Design Errors	5	4	3	2	1	0
Life Cycle Concerns	5	4	3	2	1	0

- 5 = Very beneficial on almost all programs
- 4 = Moderately beneficial on most, very beneficial on some
- 3 = Moderately beneficial on almost all programs
- 2 = Moderately beneficial on most, no benefit on some
- 1 = No benefit on most, moderate benefit on some
- 0 = No benefit on almost all programs

During which stage of a typical program is tolerance control likely to provide the most benefit? (circle one):

A	B	C	D	E	F
Requirements	Concept Generation	Preliminary Design	Detailed Design	Design Verification	Qualification and Cert

13. Industry Standards can be leveraged to incorporate well-known multi-purpose interfaces or architectures into a specific system

How effective are industry standards for reducing uncertainty in the following areas? (Circle one value on each row)

Variability	5	4	3	2	1	0
New Technology	5	4	3	2	1	0
Enterprise Capability	5	4	3	2	1	0
Customer	5	4	3	2	1	0
System Interactions	5	4	3	2	1	0
Design Errors	5	4	3	2	1	0
Life Cycle Concerns	5	4	3	2	1	0

5 = Very beneficial on almost all programs
 4 = Moderately beneficial on most, very beneficial on some
 3 = Moderately beneficial on almost all programs
 2 = Moderately beneficial on most, no benefit on some
 1 = No benefit on most, moderate benefit on some
 0 = No benefit on almost all programs

During which stage of a typical program are industry standards likely to provide the most benefit? (circle one):

A	B	C	D	E	F
Requirements	Concept Generation	Preliminary Design	Detailed Design	Design Verification	Qualification and Cert

14. Design for "X" (DFX) often includes subteams to address aspects and ramifications of the design. Examples include design to cost (a.k.a. design for affordability), design for manufacturability, design for maintainability, design for testability, etc.

How effective is DFX for reducing uncertainty in the following areas? (Circle one value on each row)

Variability	5	4	3	2	1	0
New Technology	5	4	3	2	1	0
Enterprise Capability	5	4	3	2	1	0
Customer	5	4	3	2	1	0
System Interactions	5	4	3	2	1	0
Design Errors	5	4	3	2	1	0
Life Cycle Concerns	5	4	3	2	1	0

5 = Very beneficial on almost all programs
 4 = Moderately beneficial on most, very beneficial on some
 3 = Moderately beneficial on almost all programs
 2 = Moderately beneficial on most, no benefit on some
 1 = No benefit on most, moderate benefit on some
 0 = No benefit on almost all programs

During which stage of a typical program is DFX likely to provide the most benefit? (circle one):

A	B	C	D	E	F
Requirements	Concept Generation	Preliminary Design	Detailed Design	Design Verification	Qualification and Cert

15. Sensitivity Analysis estimates the level of dynamic response of the system to input perturbations or stimuli.

How effective is sensitivity analysis for reducing uncertainty in the following areas? (Circle one value on each row)

Variability	5	4	3	2	1	0
New Technology	5	4	3	2	1	0
Enterprise Capability	5	4	3	2	1	0
Customer	5	4	3	2	1	0
System Interactions	5	4	3	2	1	0
Design Errors	5	4	3	2	1	0
Life Cycle Concerns	5	4	3	2	1	0

- 5 = Very beneficial on almost all programs
- 4 = Moderately beneficial on most, very beneficial on some
- 3 = Moderately beneficial on almost all programs
- 2 = Moderately beneficial on most, no benefit on some
- 1 = No benefit on most, moderate benefit on some
- 0 = No benefit on almost all programs

During which stage of a typical program is sensitivity analysis likely to provide the most benefit? (circle one):

A	B	C	D	E	F
Requirements	Concept Generation	Preliminary Design	Detailed Design	Design Verification	Qualification and Cert

16. Organizational Mitigations include attempts to restructure the design participants and resources to address shortcomings in execution. It may be done to improve communication, increase oversight/independence, focus on particular enterprise goals, etc.

How effective is organizational mitigation for reducing uncertainty in the following areas? (Circle one value on each row)

Variability	5	4	3	2	1	0
New Technology	5	4	3	2	1	0
Enterprise Capability	5	4	3	2	1	0
Customer	5	4	3	2	1	0
System Interactions	5	4	3	2	1	0
Design Errors	5	4	3	2	1	0
Life Cycle Concerns	5	4	3	2	1	0

- 5 = Very beneficial on almost all programs
- 4 = Moderately beneficial on most, very beneficial on some
- 3 = Moderately beneficial on almost all programs
- 2 = Moderately beneficial on most, no benefit on some
- 1 = No benefit on most, moderate benefit on some
- 0 = No benefit on almost all programs

During which stage of a typical program is organizational mitigation likely to provide the most benefit? (circle one):

A	B	C	D	E	F
Requirements	Concept Generation	Preliminary Design	Detailed Design	Design Verification	Qualification and Cert

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