Comparative System Architecture for Large, Government-sponsored Space Systems

by

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Abstract

The fundamental issues in any discussion of a proposed system architecture must involve the relative quality of the architecture when compared to other proposals and the architecture's ability to satisfy the needs and abilities of the customer, the system environment and the system developer. While the latter issue can often be easily addressed through standard system architecture methods, the former comparative issue can often be quite difficult due to some of the uncertainty and ambiguity in the relative merit of system architecture factors. In large government-funded space system architectures, which often span years of development/production and cost tens of billions of dollars, this difficulty is especially apparent and highlights the need for an effective method for comparative evaluation.

This thesis research has developed a unique tool by which comparisons of system architectures can be made. This technique, which is a fuzzy set extension of the Axiomatic Design method, has the ability to incorporate and capture both technical and non-technical parameters that are vital to the comparison process. This tool is effectively applied to architectural proposals for the human exploration of Mars. As supporting objectives, the research examines the structure of advanced technology developments, explores the affects of the government budgetary process and comments on the government/contractor managerial relationship as they pertain to space system architectures.

Thesis Supervisor: Edward Crawley
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My advisor, Ed Crawley, deserves special recognition and thanks for making the System Design and Management Program a reality and for his leadership in making it a success.

I would also like to thank the members of the Exploration Office at NASA Johnson Space Center for their discussions of and enthusiasm for the human exploration of Mars. I am confident that we will all be present for that very exciting day when humans, again, step onto the surface of a New World.

Finally, I would like to thank my wife. Roxane has given up time from her own career, taken on more household duties, and been very supportive through the entire process. The completion of the SDM program literally would not have been possible without her.

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Chapter 1

Introduction

The space age was introduced with some important words from the U. S. Senate:

> Space is presented at this junction, as a frontier. It is a dimension, not a force, a dimension enlarging the sweep and scope of all our established activities to the measurement of infinity – as the frontier of the American West enlarged the potential of the colonies to the limits of a continent.
>
> For any frontier, as Americans know from their national history, the imperative is exploration, not control. Only by exploration – by pioneering the unknown, by venturing the uncertain – can the promise of any frontier be realized. This must now be our imperative for the space frontier.

"Venturing the uncertain" is a phrase that best captures the role of the space systems architect. The space frontier has presented engineers and scientists alike with new challenges to conventional ideas. While most design is actually redesign, the space systems that have been developed to date and that will be developed in the future innovate on the architectural level. Space systems are somewhat unique in this regard. Yet, their uniqueness is not limited to their technical nature. The way in which the technological process interacts with society and the way macro-engineering tasks have revolutionized the management of engineering developments is a marvel in itself.

At the core of these multi-billion dollar efforts, an architecture – a structure – of a system can often be the determining factor as to the program's success or failure. Space Station Freedom, the Strategic Defense Initiative (SDI) and the Space Exploration Initiative (SEI) are just a few high profile examples where architectural decisions resulted in a program not even reaching initial deployment. These and other examples illustrate the consequences of selecting poor architectures. Yet, it is essential to recognize that the fundamental character of both successes and failures of space system architectures do not lie solely within the technical parameters of the endeavor. Management of these very large and complex systems demands special and constant attention. Government-sponsored space systems have unique aspects in that the procuring entity is not the design or manufacturing organization. The government-contractor relationship, the public perception of the program and the Congressional view of the program also play integral, if not fundamental, parts in the system architecture. All of these technical and non-technical parameters must be considered when system architectures are created, or more importantly, when they are evaluated.

1.1 Background on System Architecture

System architecture, as an academic pursuit, is relatively new activity, yet system architects and their principles have existed since engineering projects have been around [Alexander 1964]. The great wonders of the ancient world had system architects who answered a customer's needs while effectively structuring his/her project to deal with changing environmental conditions and the engineering/management challenges [Hauck 1989, Ortloff 1988, Reid 1997]. These system architects arose from the tutelage of previous masters and who were schooled in their "arts." That system of apprenticeship lasted for generations and, to a lesser extent, still exists today when engineers of exceptional talent train their subordinates in a particular field. This method of producing good system architectures has faded due to the rapid expansion of technologies that have generated specialized disciplines, a utilitarian culture that produces a more mobile workforce, and a fast-moving social environment that has produced an ever-increasing need for better product architectures. Additional methods of system architecture have arisen over the years. In Eberhardt Rechtin's book "System Architecting: Creating and Building Complex Systems [Rechtin 1991]," the author introduces four broad categories of system architecting. These methods are presented so that a case can be made that one of the methods, the so-called heuristic method, is a particularly effective one. The four system architecture processes presented in Rechtin's book include:

Normative or *Pronouncement* - This technique is based on the "school" of ideas that a recognized expert developed over the course of his/her career. It is a judgmental, experiential approach to system architecting and leads to a evaluation of the "goodness" of an architecture based on some set of rules. The pronouncement method is generally best applied by immediate subordinates of the founder of the school of thought. It can be an efficient method, but often is not easily generalized or accurately carried out by someone other than an immediate successor of the recognized expert.

Rational or *Procedural* - The pronouncement method's problem with generalization is not found in the procedural method. In fact, the procedural method's central tenet is the rational abstraction of a system architecture problem. Procedural methods aim to develop a general framework that is comprehensive enough for easy mapping of specific problems and, then, to use that abstraction to mechanically solve the system architecture problem. The forward and backward chaining of logic is one of the method's strengths, yet this positive feature can also be one of its weaknesses. The procedural approach can occasionally be faced with a logical situation that does not fully close. In this case, the procedural method breaks down due to its lack of direction on how to creatively bridge this logical gap.

Argumentative - The argumentative process is the system architecting approach that engineers have probably experienced most often. This method relies on intuition and brainstorming to generate a set of ideas that will eventually coalesce into a preferred system architecture. Clearly, this method can be very creative, but its critics would argue that it does not ensure a complete coverage of the trade space, nor does it methodically evaluate the value of one solution versus another.

Heuristics - A heuristic approach to system architecting is Rechtin's method of choice. Heuristics rely on the shared wisdom of a field and the use of contextual facts. An example of a common designer's heuristic is "keep it simple, stupid." This example illustrates the prescriptive form of heuristics. Descriptive heuristics, such as "a model is not reality," also have a place in this approach. While this generalized lessons learned approach has powerful application to certain fields, the truths that they promote as fact may not be valid outside a particular context. Furthermore, much like the argumentative method, heuristics often may not have the analytical underpinning that one would like to see in a system architecting approach.

Since each of these architecting methods have certain weaknesses, it may be possible to improve upon them to produce a new method of system architecting. However, before this can be attempted, the features of a system architect's process need to be clearly identified. A list of properties associated with the system architecting process is provided below along with their definitions and a citation. (It should be noted that numerous citations are available, but only one is given per property for reasons of clarity).

A system architect needs to able to abstract[1] his/her problem. A good system architecting process should give direction on how to manipulate a problem in a functional space. This movement may be accomplished,

[1] "Architecting generally begins with generating an abstract or paper description - a model - of the system and its environment." pg. 4 of Rechtin's text.

for example, through the use of specifications, projections or statements about assumptions.

System architecting processes should also be capable of reducing[2] a problem to a manageable size. A system architect's role is to deal with complexity. In that role, a method is needed to reduce the number of variables and partition/aggregate the problem.

Synthesis[3] is also a property needed in a system architecting method. It requires that a combination of variables be brought together into some harmony. A synthetic process may also permit the prioritization of problem variables.

An intuitive, creative[4], aspect is also a valued property of a system architecting process. This option-seeking character of a good system architect may be one of his/her most powerful capabilities and is often mentioned as the "genius" quality of renowned architects.

The most visible role of the system architect is his/her interaction[5] with the development community. A good architecting process should provide some guidelines on how one should interact with all the technical and non-technical interfaces that exist throughout a program's lifetime.

An often overlooked characteristic of the architect is the way one maintains[6] or "keeps the faith" during a project. Any system architecture method should be able to direct the activities of a system architect in the process of sustaining the integrity of a project's structure through its full completion.

---

[2] "The architect's problem is to reduce this complexity to a manageable degree..." pg. 13 of Rechtin's text.

[3] "More recently, architects began to appreciate that still better architectures might be based on complete submission of the individual parts to the purpose or function of the whole." pg. 12 of Rechtin's text.

[4] "Without question, the architect's greatest impact comes during concept formulation and preliminary design. It is a time of great creativity." pg. 14 of Rechtin's text.

[5] "Architecting is working for a client and with a builder..." pg. 13 of Rechtin's text.

[6] "Toward the end of the project, architecting is also certifying completion and satisfactory operation of the system." pg. 13 of Rechtin's text.

Property/Method	N	R	A	H	R+A	R+H	N+H	A+H
abstract	-	+	+	S	+	+	-	+
reduce	+	S	-	+	-	+	+	S
synthesize	+	+	-	+	S	+	+	S
create	-	S	+	S	+	S	-	+
interact	S	S	+	+	+	+	+	+
maintain	S	+	S	+	S	+	+	+

Table 1.1: Pugh Analysis of Architecting Methods

These properties have been identified so that innovations associated with the basic four system architecting methods could be evaluated using Pugh's method.

A table illustrating the results of analysis is found in Table 1.1. The notation in the table is as follows: N = normative (pronouncement), R = rational (procedural), A = argumentative, and H = heuristic. The titles of columns the pluses indicate a combination of approaches. For example, R+H represents a technique that combines both rational and heuristic approaches. In the evaluation of each system architecting process, a "+" sign was used to indicate that this process added value in this category, "S" represents that the process was neutral or the "same" on this factor, and a "-" sign indicates that the process actually hindered the best performance in that factor. For this analysis, most of the combinations including the normative method were explicitly omitted due to the lack of representative system architectures that copy well for space systems. The real power of the normative method is when it is used for an evolutionary development. In this case, it inherently contains a procedural aspect (since a similar system has been developed before) and also contains the other features of reduction, abstraction, interfacing and maintenance. Its true shortfall is that it does not provide any option-seeking guidance nor does it effectively result in a synthetic realization of the system architecting process. While all of these attributes are clearly valuable, the evolutionary approach, again, requires a very similar predecessor project which, in the general case, is not readily available.

In returning to the Pugh analysis, it can be seen that the combination of the rational approach and the heuristic methods results in the best system architecting technique. Higher order combinations of methods do not produce better approaches. This latter conclusion is beneficial since it is not exactly clear how and when these combinations would be implemented. It is not very surprising, based on experience, that no single method is the clear winner. This outcome may be the result of a couple of factors. Rational methods, by definition, do not have contextual information embedded in them. This deficiency strips away the years of experience and the strides of some of the experts of the field from contributing to a system architecture. Furthermore, the ability to provide much direction on the interaction of the system architect with his/her specific environment also appears to be a significant shortcoming of the rational method. It is felt that rational methods may be most valuable when a problem is well understood and does not require a major new examination. Heuristics, on the other hand, are almost orthogonal in their capabilities. Heuristics provide the architect with the collected wisdom of the industry and offer descriptive and prescriptive commentary on a given architecture. In a combination, the rational methods make up in quantitative and evaluative abilities for the deficiencies in those areas experienced in the more qualitative ideas of the heuristics method.

In summary, each of the architecting processes have their merits and weakness. However, for large, government-sponsored space systems, some methods stand out. Normative methods are not applicable to comparative system architectures because, too often in large space systems, the environment and the technology move faster than the standards. Participative methods are also not applicable because the stakeholders are inaccessible (e.g., Congress, taxpayers) and are not knowledgeable in the technical areas. Heuristics are applicable, but are generally, due to their largely descriptive nature, more valuable in the development of the architecture rather than making an equitable comparison. The remaining technique, the rational approach, is valuable and applicable in comparative system architecture for one essential reason: the ability to make unambiguous, fair comparisons on a set of agreed-to factors in a rapid and iterative fashion. A combined method of an established rational method and industry-specific prescriptive heuristics could prove to be an important tool for system architecture studies.

1.2 Previous Work in Rational Methods

The problem of a comparative system architecture analysis, when examined from within a rational context, is essentially the evaluation of a multivariate objective function. Previous work in this area has mostly focused on attempts to automate the basic design process, and has paid less attention to the higher order problems of system architecture. Yet, the progress that has been made in system design can be applied to comparative system architecture studies.

The simplest method for evaluating a multivariate design problem is to simply enumerate all the possibilities and evaluate each one. In this scenario, which is similar to a grid search in optimization theory, a set of combinations of attributes is defined which span the trade space. Zwicky's morphological problem solving method is a good example of this technique [Zwicky 1948]. A derivative of Zwicky's basic approach is found in Pugh's method [Pugh 1991] that develops a series of variants by combining the most attractive design combinations found through a simple rating system. Quality Functional Deployment (QFD) can be seen in the same light as these other two scoring methods [Portanova 1990, Hauser 1988, Hill 1991]. QFD develops a relationship matrix and correlation matrix that relates, typically, customer needs to technical requirements. A ranking of customer needs and some benchmarking against known similar products permits the evaluation of various designs which satisfy technical requirements in dissimilar ways. Additional features and applications of QFD permit its use in process design, quality control and even in the definition of Statements of Work for contractor execution of government-sponsored efforts.

A step above the brute force methods of exploring the entirety of the trade space is a more systematic use of discrete function evaluation using a select set of points. The Taguchi method of Design of Experiments utilizes orthogonal arrays to discover the effect of a particular variable on the overall design when all the other variables are changed [Taguchi 1984, Taguchi 1987, Brown 1992]. Through the careful application of the Taguchi method, one can examine the effects of all the variables in the problem while minimizing the number of analyses. Discrete optimization algorithms also selectively move through a multi-dimensional space through the use of search directions. The simplex method [Ellis 1962] is the most common of these methods. It develops its search directions through the evaluation of a set of N+1 vertices (where N is the number of variables in the problem), calculates the centroid of the figure formed by joining those vertices and then evaluates points that lie on a line orthogonal to the centroidal plane. The simplex method's next search continues by evaluating a new set of vertices about that new, more optimal point. The simplex method, like other discrete optimization algorithms, can often be fooled by the location of local minima or by the lack of clear search directions in very flat multi-dimensional surfaces.

While the above methods have dealt largely in the realm of engineering variables, two other methods, Multiattribute Utility Theory (MAUT) and Analytic Hierarchy Process (AHP), function largely on the perception and evaluations made by either the customer or a set of experts that evaluate the design choices that are presented during each step of the analysis. MAUT [Shtub 1994, Dyer 1976, Feinberg 1985, Keeney 1976] bases its analysis on the assessment of an individual or set of individuals evaluations ("utility") of a situation with a fixed set of attributes. After a utility function has been determined, then a probability tree is constructed to examine all the possible outcomes that are available to the decision maker. By searching the tree for the path of maximum utility, one can find the best design solution. AHP [Shtub 1994, Bard 1986, Belton 1984, Saaty 1986] also begins with a hierarchy of objectives similar to the decision tree seen in MAUT. Yet, in AHP, priority weights and pairwise comparisons of objectives using a 9-point scale of relative importance are made at one level of the hierarchy and are then flowed up to the next level. This process continues until a clear design alternative is produced at the highest level of the hierarchy. Obviously, each of these methods is only as good as the utility function that is derived, the priority weights established and the pairwise comparisons that are solicited.

Suh's Axiomatic Design [Suh 1990] stands apart from the other rational (or "procedural") methods of design. It begins simply with two axioms (i.e., the independence of functional requirements must be maintained and the information content must be minimized) and proceeds to develop a set of theorems that cover the design process from its inception in a set of customer needs to product delivery through the proper selection of process variables. Axiomatic Design not only provides a method by which designs can be evaluated, but also prescribes (through its axioms and theorems) directions for possible design solutions. Furthermore, through its use of functional requirements and design parameters, it has proven to be sufficiently general as to be able to design organizations and human systems as well as the more tangible and analytic engineering problems. Recent work [Suh 1995] has seen this method applied to large and complex systems with some success.

1.3 Organization of the Thesis

Immanuel Kant, the great 18th century philosopher, theorized that the mind is not designed to give us uninterpreted knowledge of the world, but always examines the world through a certain perspective or bias. In the system architecting process, this view of thinking is useful in that it highlights the pattern recognition aspects of architecting (i.e., structuring). In Rechtin's view, heuristics are the collected wisdom of experts who have recognized patterns for success or failure in the architecting process. However, the above analysis of an architect's abilities demonstrates the dangers of a given perspective producing a certain tunnel vision. Hence, there is a need for structured approaches to apply these collected pieces of wisdom. Axiomatic Design (AD) is structured application of heuristics. In its most basic form, AD applies two heuristics in the form of its axioms. (It should be noted that Suh's axioms can be found in several of Rechtin's heuristics, and, in this sense, show the intersection of the two approaches). When applied to non-technical functions, a wider application of heuristics can also be brought to bear.

This thesis will extend the application of the principles of Suh's Axiomatic Design to the specific problem of comparative system architecture analysis for large, government-sponsored space systems. These types of engineering programs have some special characteristics that can and should be addressed. Specifically, this thesis will cover:

Chapter 2 - Axiomatic Design and Its Fuzzy Set Extension

Axiomatic Design is a deceptively simple design tool that uses a structuring step and a measurement of uncertainty to evaluate a proposed design. In the case of system architecture, the linguistic uncertainty in defining system structure and the uncertainty in design parameters require a possibilistic approach to the definition of architectural variables. Fuzzy set theory is introduced to provide a rigorous mathematical basis for the inclusion of these types of variables and to handle uncertainty types that are more general than is currently encompassed in the Axiomatic Design framework.

Chapter 3 - Factors in Space System Architectures

This chapter develops conjectures that large, government-sponsored space systems have architectures that are determined solely by their political, managerial and technical factors. To understand these factors from within the technique developed in Chapter 2, a set of guidelines are developed for architectural comparisons in the areas of government funding cycle effects, government/contractor interactions, management structure best practices and technology selection (the latter being a natural outcome of Axiom 2).

Chapter 4 - Architectures for Human Exploration of Mars

This generic framework is applied to a specific problem facing the Exploration Office at NASA's Johnson Space Center. This architectural problem is whether a lunar mission is necessary to support human exploration of Mars or whether the best architecture focuses all of its resources on a mission exclusively designed for Mars. This problem can be traced back to the von Braun designs of the late 1960s, through the

Space Exploration Initiative, and to the current discussions concerning the Draft Reference Mission iterations. With the supporting information from Chapters 2 and 3, several conclusions can be offered concerning the relative merits of these very different architectures.

Chapter 2

Axiomatic Design and a Fuzzy Set Extension

The architecting process, as previously mentioned, is a form of design that involves a number of technical and non-technical parameters. Axiomatic Design is capable of handling both of these types of parameters. However, in its current form, some types of design decisions are not adequately addressed by the AD process. An extension of this process can be achieved through the application of fuzzy set theory.

This chapter will review the basics of axiomatic design and its applicability to system architecture, thoroughly discuss the fuzzy set extension of axiomatic design and examine this extension in terms of the system architecture problem.

2.1 Axiomatic Design

Design techniques are centered around methods of how the implementation of a design concept satisfies the prescribed requirements for the design. Suh [Suh 1990] describes this process as allocating the "how we want to achieve something" to the "what we want to achieve." In order to evaluate designs, Suh introduces axioms that provide the designer with design direction and a measure of preferences between competiting

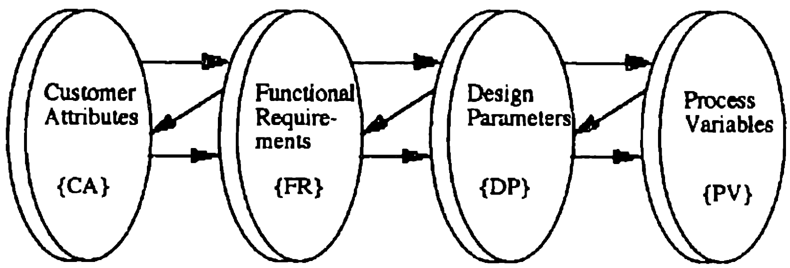

Figure 2-1: Axiomatic Design Domains

designs. Essentially, the Axiomatic Design (AD) process is a two-step process that corresponds to the two axioms. The first axiom details the "proper" relationship in domain mappings. The second axiom describes the characteristic of a design that makes it preferred to other design solutions. These axioms and their implementation are described in detail in the discussion below.

2.1.1 Basic Description of Axiomatic Design

In very specific terms, the AD process specifies four domains: the customer domain, the functional domain, the physical domain and the process domain. Each one of the adjacent domains represent a "what/how" pair. For example, a hierarchy of functional requirements ("what"), under decomposition, has a correspondence to a set of design parameters ("how") that describe the design. This mapping between domains is illustrated in Figure 2-1.

It should be noted that the mapping is conducted between hierarchical trees. These trees are successively formed through a "zig-zagging" process by which the designer moves from function to form and back again. This movement, between so-called "characteristic vectors" represented by the letters CA, FR, DP and PV, reflect the tension between form and function that is universally found in all design methods. The general nature of these domains can be seen by the entries in Table 2.1 [Suh 1997]. Furthermore, the domains are described below:

Customer Domain: The customer domain contains the description of the customer

Domain / Character Vectors	**Customer** *CAs*	**Functional** *FRs*	**Physical** *DPs*	**Process** *PVs*
Materials	Desired performance	Required properties	Micro-structure	Processes
Software	Attributes of the software	Output spec. of the program codes	Input variables, algorithms, modules or code	Subroutines, machine code, compilers, modules
Organization	Customer satisfaction	Functions of the organization	Programs or offices	People and other resources that can support the programs
Systems	Attributes desired of the overall system	Functional requirements of the system	Machines, components or sub-components	Resources (human, financial, materials, etc.)

Table 2.1: Contents of Domains for Various Applications

needs and the environment that surrounds the design process. Conjoint analyses, market surveys, discussions with the stakeholders, and popular accounts of technology visionaries may all be sources for this type of information. Additional information from government regulations, social trend analyses and reviews of competing products are also needed to fully understand the environment in which the customer are deriving their needs. These attributes, however, must be hierarchically arranged and suitable for mapping to their functional counterparts.

Functional Domain: In order to fully capture customer attributes in a design, they must be converted into functional requirements that can be imposed upon a design (FRs). These functional requirements need to contain specific metrics that describe the performance objectives of the design. Furthermore, by definition, a function must contain an action verb which indicates the required form of operation. Unlike the CA domain, FRs don't reside solely in the functional domain. No design is free of constraints (C), and the *FRs* and the design constraints are tightly bound together.

Constraints describe the boundaries for the domain of acceptable solutions. "Input" constraints are created as part of the design specifications. "System" constraints are those boundaries that are imposed by the system in which the design must function. An example of an input constraint might be the total weight of the design. Likewise, an example of a system constraint might be a volume constraint on a part that is required for the operation of a larger machine. The distinction between a functional requirement and a constraint is subtle, but an important part of the functional domain.

Functional requirements also have three very important characteristics. First, they are the minimum set of requirements that are needed to satisfy the objectives of the design process. Excess requirements will result in unnecessary redundancy or overly complicated designs that waste resources. Secondly, the functional requirements must be independent. This condition is actually definitional, but should be explicitly stated so that the designer can be rigorous in the pursuit of accurate and sufficient functional requirements. Finally, functional requirements must be defined in a *solution neutral environment.* This last characteristic is often the hardest one for a designer to produce due to his/her background in the design field. However, if a solution neutral set of functional requirements are created, the designer's creativity will not be hampered by known and common design solutions.

Physical Domain: The AD process continues by developing the most common mapping: the correspondence between functions and physical realizations of those functions. In this instance, the "design equation" is stated in the form:

$$\{FR\} = [A]\{DP\} \tag{2.1}$$

where,

$$A_{ij} = \partial(FR_i)/\partial(DP_j)$$

This equation provides a mathematical insight into the coupling that may or may not exist in the design. By coupling, it is meant that one functional requirement is satisfied in the design by more than one design, or mathematically,

$$A_{ij} \neq 0 \qquad \text{for } i \neq j \text{ and not triangular.}$$

Suh also introduces the term "decoupled" to describe the condition where the design matrix, A, can be made lower triangular.

A simple example of a functional requirement/design parameter pair might be:

FR_1 =Deliver liquid at a flow rate of $Q = 5$ ml/s,

DP_1 = The pump speed on the fluid pump W.

By going through all the functional requirements and relating design parameters to them according to some conceptual or detailed design, one can apply the subsequently described axioms of AD to find a better design or evaluate competiting designs.

Process Domain: The final domain, the process domain, describes the manufacturing or production methods needed to develop the design. Clearly, one can not produce a design without considering its ramifications on production methods. The framework in the process domain is similar to the design equation:

$$\{DP\} = [B]\{PV\} \tag{2.2}$$

where,

$$B_{ij} = \partial(DP_i)/\partial(PV_j)$$

Again, the concepts of uncoupled (i.e., a diagonal matrix), decoupled and coupled designs becomes important when evaluating the design of a manufacturing process.

An example of a design parameter/process variable pair might be:

DP_1 =Density of plastic cylinder, ρ,

PV_1 = Pressure applied during formation P.

It should be noted that the design matrix A and the process matrix B can be multiplied to produce a relationship between the functional requirements and the process variables. While each equation can and should be developed separately, it is valuable to note this relationship since the structure of the resultant matrix, C, as a coupled, decoupled or uncoupled matrix has important implications.

With the definitions of design domains complete, the explicit definition of the design axioms can now be stated.

> **Axiom 1** - *The Independence Axiom*
> "Maintain the independence of FRs.
> **Axiom 2** - *The Information Axiom*
> "Minimize the information content of the design."

Axioms, by definition, are fundamental truths upon which logical constructs can be formed. Axioms are also without counterexamples or exceptions. So, Suh's axioms require no derivation or proof. However, they do require some explanation and discussion.

The first axiom's implications have been alluded to in the discussion of the design and process equations. The independence of the FRs is achieved when an uncoupled design matrix can be found. It is also achieved when a decoupled design is found due to the fact that one can set one functional requirement for one design parameter and then work through the rest of the functional requirements by individually establishing their settings as well. A common misconception about this functional independence is that physical integration is forbidden by this axiom. This is not the case. If both functional requirements can be met by individual and distinct physical parameters, then a physically integrated design might be a preferred design when examined under the information axiom, a set of constraints or the process equation.

In short, in order for a design to be considered "good" under the Independence Axiom, the design must be decoupled or uncoupled. Coupled designs are not appropriate designs in the AD framework.

Once the implications of the Independence Axiom are understood, the question

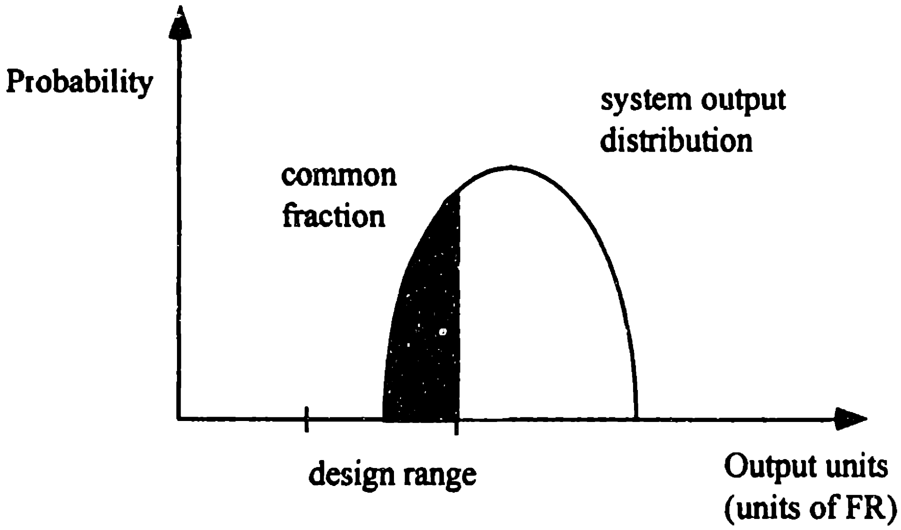

Figure 2-2: Graphical Depiction of Information Content

immediately arises as to how decoupled and uncoupled designs can be selected. The Information Axiom is the answer to this question. The "minimization" of the "information content" is an abstract definition, but a powerful one. Suh goes on to explain this concept in terms of design tolerances, system ranges and the probability of achieving the FR. The mathematical descriptions are generally the most clear:

$$\text{Information} = I = \log_2(1/p) \tag{2.3}$$

where p is the probability of achieving the functional requirement. Alternatively, p can be defined as

$$p = \text{tolerance/range}$$

or,

$$p = \text{common fraction/system output distribution}$$

where the "common fraction" and "system output distribution" can be seen in Figure 2-2.

The common fraction represents the likelihood of achieving the desired output using the proposed system. A larger common fraction would increase the probability of success of meeting each individual FR. From this definition, some intuitively obvious methods of choosing a better design become clear. A better design can be found by either choosing a system which increases the overlap with our design range or expand the design range (i.e., specify a larger tolerance).

The Information Axiom applies to the entire design. In other words, the information content of the entire design must be lower than any competiting design.

$$I_{total} = \sum_{i=1}^{n} \log_2(1/p) \tag{2.4}$$

The information content of the design should not be confused with the complexity of the design, but rather the probability of the design achieving its performance objectives. Designs with higher probabilities of success will have lower information contents.

2.1.2 Usage of Axiomatic Design for Systems

For AD to be useful in constructing system architectures, one must understand, in a very specific sense, what a system is. AD, up to this point, has been discussed solely in terms of its application to the design of discrete, "small" items. Unfortunately, the space industry does not deploy "small" items. It deploys "systems."

> *A system is a collection of a number of parts that interact to perform a function or functions.*

Systems also come in several different types. An **open** system is one in which the environment is sufficiently fluid to cause regular changes in the constituents of the system. A **flexible** system is a system that must respond to changing functional requirements. A **large** system, according to Suh, is one that has a large number of functional requirements at the highest level of its hierarchy. It should be noted that large systems are not necessarily physically large or complex in terms of the number of parts it contains. Large, in this definition, simply means that it must do a great many different functions. Examples of these systems are found in Table 2.2. For

Types of Systems	Examples
Open	The Internet, high employee-turnover companies, personal computer industry
Closed	Project teams, disposable cameras, calculators
Fixed	Power converters, beverage cans, review teams
Flexible	Phone switching systems, public education systems, hospitals
Small	Microwave ovens, photocopiers, maid services
Large	The Space Shuttle system, the Dept. of Defense

Table 2.2: Examples of System Types

this discussion, the space systems of interest are large, flexible, closed systems. The class of flexible systems that are most commonly found in aerospace systems are those that have *mission modes.* These systems are represented, in AD context, by the set of equations (for example):

$$\begin{aligned} t = 0, \qquad & \{FRs\}_0 = \{FR1, FR3, FR5, FR7\} \\ t = t_1, \qquad & \{FRs\}_1 = \{FR2, FR4, FR5, FR7\} \\ t = t_2, \qquad & \{FRs\}_2 = \{FR3, FR7, FR8, FR9\} \end{aligned} \tag{2.5}$$

As in the design of small systems, a set of DPs must be found for each set of FRs and their subsequent hierarchies. For a flexible system, however, DPs need to be found for each of the FRs found in each mission mode. The same AD process applies here and Axiom 1 must be satisfied through the judicious selection of DPs. A knowledge base of DPs is always implied in the design process and certain design options are available to the designer via experience, research, analogy or sheer creativity. This knowledge base or database can be notated as:

$$\begin{aligned} FR1 \;\; & \$ \;\; (DP1a, DP1b, \ldots, DP1m) \\ FR2 \;\; & \$ \;\; (DP2a, DP2b, \ldots, DP2n) \\ \ldots \;\; & \$ \;\; \ldots \end{aligned} \tag{2.6}$$

$$FRn \ \$ \ (DPna, DPnb, \ldots, DP2p)$$

where the \$ denotes the satisfaction of an FR by a DP.

What are the implications of the selection of DPs on the flexibility and physical integration of the system? A system that is very flexible contains a sufficient variety of DPs that allow it to respond to a large set of different mission modes. Object-oriented programming (OOP) has this concept of flexibility at its center. OOP develops a set of DPs (objects) that can be used whenever a new functional requirement enters the system. Yet, a separate set of DPs for each set of FRs in each mission mode becomes prohibitively large and expensive for most systems. In fact, the Information Axiom demands some "physical integration" of these DPs *while retaining the independence required by the Independence Axiom.* By physical integration, it is meant that the system (whether hardware or software) has multiple functions satisfied in the same physical location. The software world, again, contains a good example. A subroutine that has many of the same algorithms may satisfy many functions through the use of different input flags. It is said to be physically integrated and functionally independent since one "chunk" of the design satisfies many functions.

A series of design matrices does not provide the designer the type of visual insight that is often the most valuable. Visualization of data in data rich environments is a common tool of system architecture (e.g design structure matrices, N^2 diagrams, etc.). Axiomatic Design's version of the visualization of an architecture is the module-junction diagrams. A module is defined as the row of the design matrix that yields an FR when the appropriate DPs are selected. A junction is the type of combinations of DPs required to achieve an FR. As previously discussed, there are 3 types of combinations: uncoupled, decoupled and coupled. Figure 2-3 shows the corresponding graphical representations of these combinations.

To illustrate this flow diagram method, the following design equations are offered.

$$\begin{bmatrix} FR1 \\ FR2 \end{bmatrix} = \begin{bmatrix} X & C \\ 0 & X \end{bmatrix} \begin{bmatrix} DP1 \\ DP2 \end{bmatrix}$$

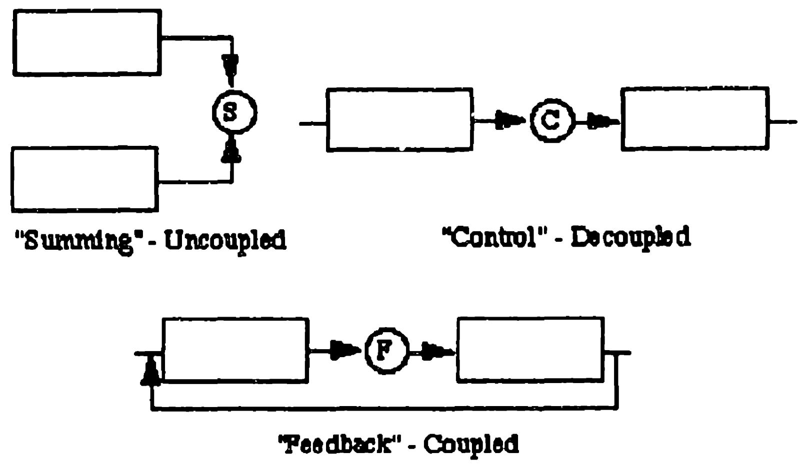

Figure 2-3: Types of junctions

$$\begin{bmatrix} FR11 \\ FR12 \\ FR13 \\ FR14 \end{bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 \\ X & X & 0 & 0 \\ 0 & X & X & 0 \\ 0 & 0 & 0 & X \end{bmatrix} \begin{bmatrix} DP11 \\ DP12 \\ DP13 \\ DP14 \end{bmatrix}$$

$$\begin{bmatrix} FR21 \\ FR22 \end{bmatrix} = \begin{bmatrix} X & 0 \\ 0 & X \end{bmatrix} \begin{bmatrix} DP21 \\ DP22 \end{bmatrix}$$

The design equations indicate that the design satisfies the Independence Axiom due to its selection of *DPs* that only provide decoupled or uncoupled solutions. Figure 2-4 shows how easily it is to see the difference in the decoupled and uncoupled relationships between modules. This quick visual representation serves many purposes. The lowest level modules (often called "leaves") can be readily traced to their impact on higher level functions. This capability is useful for providing insight into the effect of engineering change orders on higher level functions (see [Nordlund 1996] and for understanding the potential location of failures when performing a detailed failure analysis. The diagrams are also very useful in understanding the interactions within the architecture and the potential for organizational or technical problems within the system. Finally, the module-junction diagrams provide the system architect a visual understanding into the level of decomposition that was needed to represent the system. As specified by Suh, a system does not require further decomposition when the lowest level FR requires no further decomposition. In a top-level system architecture, that lowest level may be a system itself. For example, an interplanetary spacecraft may end its top-level architecture discussion with a FR of "provide spacecraft communication and tracking at X data rate and for Y periods" by merely specifying the DP of "the Deep Space Network allocation to this spacecraft" due to its rich and successful history of supporting interplanetary vehicles.

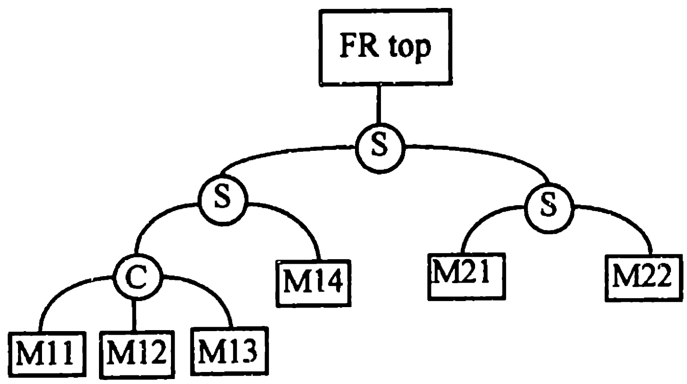

Figure 2-4: Example of a Module-Junction Diagram

2.2 Fuzzy Extension of Axiomatic Design

In Antonsson *et. al.* [Antonsson 1996], the uncertainty present in performing any kind of design is clearly stated:

> "Imprecision and vagueness are intrinsic aspects of engineering design. If (at the start of the design process) a proposed solution was neither imprecise nor vague, its description would be precise and it would therefore be a completed design. While (stochastic) uncertainty typically remains in a completed design description (e.g. dimensional tolerances), the nominal desired dimensions are precise. Engineering design is essentially the process of reducing the *imprecision* in the description of solution concepts."

Anyone who has written technical specifications for a government program, or has tried to design a system based on those requirements, thoroughly understands the uncertainty that remains even after developing very detailed requirements [Hooks 1994]. While any good specification makes every attempt to write requirements that have a specific objectively verifiable metric, it is often the case that imprecise and qualitative phrases have to be used. Handling qualities of aircraft, legibility of display screens, and even the definition of interior volume may be specified by phrases like "sufficient" or "satisfactory" or "appropriate." Most of these instances are merely examples of poor requirements definition. However, there are instances, especially when it comes to defining managerial, political or other human-based factors, when the best terms of reference and metrics can only be explained by linguistic variables. Albert Einstein, in 1921, eloquently stated this idea when he said,

> " So far as laws of mathematics refer to reality, they are not certain. And so far as they are certain, they do not refer to reality."

System architects take their design direction from stakeholders that do not always deal in engineering variables. Furthermore, the types of analyses needed to determine the proper set of engineering variables are often tied to the design alternatives and/or are difficult to fully exercise when working at the top level of a large, complex system. Therefore, it is vital for a system architect to have the tools available that can translate the uncertainty present in the desired system into "knobs and levers" that can be manipulated through a fair comparison of architectures.

With that short motivation, the question immediately arises as to how the Axiomatic Design process handles the uncertainty that is a fundamental part of design. It is clear that Axiom 2 is explicit in its relation to a particular type of uncertainty. For example, a tolerance on a physical dimension will increase the information content as the size of that tolerance decreases. Yet, that type of uncertainty refers only to the imprecision of the design parameter. If the design parameter lacks definition or sharp distinctions, then another type of uncertainty has entered the design process. Furthermore, AD often uses "Xs" or "0s" to indicate a binary membership of a design parameter to the satisfaction of a functional requirement. In instances in which the linguistic uncertainty may be considerable, a more rigorous definition of set membership may be required to understand the degree of functional independence and the associated information content.

It is proposed that Axiomatic Design could better deal with different types of uncertainty and better handle uncertainty as a whole by being extended using some of the ideas developed in fuzzy set theory. Specifically, AD can benefit from fuzzy set concepts in three ways. First, the linguistic ambiguity that exists when trying to design organizations and other qualitative systems can be more precisely evaluated when removed from a binary decision and placed in a fuzzy context. Secondly, the degree of coupling or decoupling in a system can be more mathematically defined for uncertain parameters using fuzzy variables. Finally, and most importantly, the measures of information and the application of constraints required by Axiom 2 of AD can be elegantly handled when fuzzy measures are used and optimization (minimization) is performed using fuzzy constraints. A short introduction to fuzzy set concepts is provided to give the reader sufficient background to understand the extension to AD that are detailed later in this document.

2.2.1 Basic Definitions of Fuzzy Sets

Fuzzy set theory and other forms of fuzzy mathematics arose out the common experience of trying to place an object in a particular category. In 1874, a German mathematician named Cantor made formal these ideas by stating the comprehension principle:

$$A = \{a|p(a)\}$$

where A is a set, a is an object in that set, and p is the property that defines membership. This definition has wide utility and accurately represents the vast majority of sets used in science, engineering and mathematics. However, its utility becomes limited in the presence of increasing levels of uncertainty. Cantor's claim requires that objects that form a set are distinct from each other and definitely satisfy the property p. These so-called "crisp" sets are particularly troublesome when removed from the purity of mathematics and placed into a more common setting. Consider the set of "tall" people. How is the property p defined for the concept of tall? Typically, one would establish some threshold for which the set of people would be divided. This division results in a loss of information due to the discontinuous nature of set membership. Under this crisp set division, a person who is 1 millimeter under the arbitrary threshold is considered to be "average" while, in actuality, a more accurate description would be that the person is "fairly tall." Bivalent (true/false) logic lies at the heart of the crisp set definition and does not fully capture a range of alternatives when uncertainty is present.

Fuzzy sets, on the other hand, define the "degree of membership" for each element in a set. By following the notation and discussion introduced by Klir [Klir 1995], a fuzzy set is defined by a membership function such that it maps all members of a universal set X to a normal interval.

$$A : X \to [0, 1]$$

For example, a person's age can be described by its membership in one or more sets (see Figure 2-5). The membership to a set is not mutually exclusive nor do the sum of memberships at a given value of x add to one. A person can have a membership of 0.5 in the "middle age" set and a 0.3 membership in the set of "old" people. It merely means that the person has a certain measure of the property that defines that set.

Fuzzy sets would be very difficult to manipulate mathematically, due to the many-to-one mappings, if it were not for the concept of the α-cut. For a given fuzzy set A defined on a universal set X, an α-cut, ${}^{\alpha}A$, is given by,

$${}^{\alpha}A = \{x | A(x) \geq \alpha\}$$

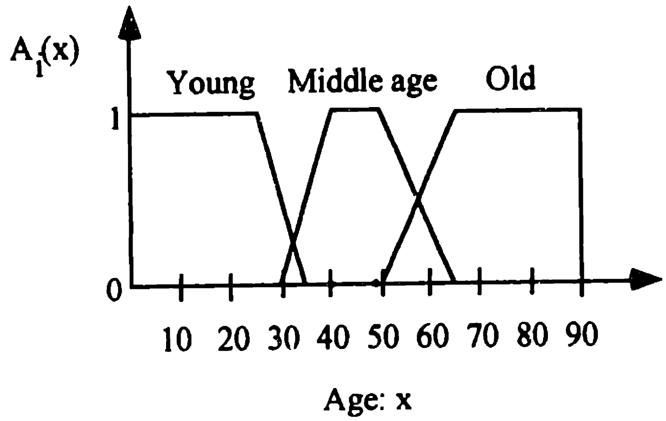

Figure 2-5: Example of Membership Functions

where $\alpha \in [0, 1]$. The α-cuts represent ordered, nested crisp sets for increasing α. Furthermore, the α-cuts define sets with members from the universal set. Through this construct, the bridge between fuzzy sets and crisp sets is made. Fuzzy sets can, therefore, be described in properties that are analogous to their crisp counterparts.

The height, cardinality and complement of a fuzzy set are also important to this introduction. The height, $h(A)$, of a fuzzy set is the largest membership grade obtained by an element in set A.

$$h(A) = \sup_{x \in X} A(x),$$

where sup is the supremum operator. The cardinality of a set A is defined by,

$$|A| = \sum_{x \in X} A(x).$$

In other words, the cardinality (also called the scalar cardinality) is defined as the sum of all of the values that the membership function achieves when applied to all of the elements in the universal set. Finally, the standard complement of a fuzzy set, again over a universal set X where all $x \in X$, is represented by the equation,

$$\bar{A}(x) = 1 - A(x).$$

Operations on fuzzy sets are similar to crisp sets. Basic, or standard, intersections and unions can be expressed by,

$$\begin{aligned}(A \cap B)(x) &= \min[A(x), B(x)], \\ (A \cup B)(x) &= \max[A(x), B(x)].\end{aligned}$$

These definitions need to be made to understand the concept of "degree of subsethood." The degree of subsethood, $S(A, B)$, for the fuzzy sets A and B, is simply,

$$S(A, B) = \frac{|A \cap B|}{|A|}. \tag{2.7}$$

This definition will be used extensively in later sections that deal with both Axiom 1 and Axiom 2.

The determination or derivation of the membership functions associated with fuzzy sets is a crucial issue for system architects since subsequent decisions will be predicated on the fidelity of those functions. Two essential aspects in the creation of membership functions are the context used as the basis for data collection [Ezhkova 1989] and the knowledge available for function determination. The results produced for membership functions are substantially different when determining whether someone is "tall," for example, if the context is set against the universal set of all fourth grade students rather than the set of all adults. Likewise, the fidelity of the set descriptions will be tainted if an ignorant person is surveyed rather than an expert in the field.

Direct data sources are obviously the best for determining membership functions and their construction from these sources is fairly clear (see [Turksen 1991], [Civanlar 1986] and [Dubois 1986]). The more difficult task, and the one that the system architect is more commonly called to perform, is to interpret the linguistic ambiguity and place it into the form of membership functions of the appropriate scale for the given context. While there are rich sources of information on the determination of preference in both the survey research and utility theory communities, a few techniques should be highlighted. Questioning one or more experts/stakeholders on the precise degree of membership for a given set element is one approach. The method of semantic differential (see [Osgood 1957]) sets scales based on polar adjectives (e.g worst/best) in the given context and then asks the expert(s) to vary the elements to determine a function. Obviously, with multiple experts, some aggregation process must be used, but in general, that construction is of secondary importance to the proper collection of the data. When an ideal prototype or polar adjectives are not readily available, then the next best alternative is to solicit pairwise comparisons for the elements in the set. This technique can be thought of as being similar to a beauty contest where an absolute does not exist, but rather some measure of preference within the set. Two references ([Saaty 1986a] and [Triantaphyllou 1990]) detail methods by which pairwise comparisons can be made.

2.2.2 Group decision-making for CA definition

In large, government-sponsored space systems, the stakeholders are found in diverse areas of endeavor and have a multitude of often conflicting interests. In the U. S. space program, the stakeholders and customers are the taxpayers, the Congress, the Administration, the science community, special interest groups and the individual factions or centers within the government. The fundamental question that is always the starting point for work on space policy is what are the "customer attributes." A number of techniques have been developed in this area. Most of them have to do with survey design and have been alluded to earlier in this document. Fuzzy sets, however, have a very simple and elegant version of these methods that may be useful when using the fuzzy extension to Axiomatic Design.

In two papers ([Blin 1973] and [Blin 1974]), a group decision model was developed that uses fuzzy sets. Consider the case where there are n decision makers. Each decision maker has a set of preferences that can be placed ordered set $\mathbf{P}_k$, $k \in \mathcal{N}_n$. This ordering is either totally or partially arranges a set of X alternatives. To arrive at a decision, this model permits decision makers with different values and goals to participate as long as they have a common desire to achieve a single decision. The model determines that decision by deriving a "social choice" function that describes an agreeable solution and the degree to which that decision is agreeable.

The authors begin the construction of the group decision model by dealing with difference of opinion through the expression of social preference S that is described by the fuzzy binary relation with membership grade function

$$S : X \times X \rightarrow [0,1],$$

where the membership grade $S(x_i, x_j)$ indicates the degree of group preference of an alternative x_i over x_j. A majority voting scheme

$$S(x_i, x_j) = \frac{N(x_i, x_j)}{n}$$

is one method of determining the social preference, where $N(x_i, x_j)$ is the relative preference of x_i over x_j with n being the number of participants. A preferred method, in the realm of space policy, may be one of aggregating social preference according to the degree of political strength a constituency representative has in the overall decision making arena. In the instance of two major players in the decision, the social preference may be modeled as

$$S(x_i, x_j) = \begin{cases} .6 & \text{if } x_i \overset{k}{>} x_j \text{ for some individual } k \\ .4 & \text{if } x_i \overset{l}{>} x_j \text{ for some individual } l \\ 0 & \text{otherwise,} \end{cases}$$

where $\overset{k}{>}$ represents the preference ordering of the one individual k who exerts a slightly dominate control over the individual l and absolute control over all other parties.

The aggregation of the social preference relation is an important step. After it is found, the nonfuzzy group preference S_{group} is found by converting S through the relation

$$S_{\text{group}} = \bigcup_{\alpha \in [0,1]} \alpha\,{}^{\alpha}S.$$

In words, this relation is merely the union of the α-cuts of the fuzzy relation S scaled by the value α. If one wishes to maximize the amount of agreement found in the choices, the intersections of subsequent crisp total orderings is examined for smaller and smaller values of α until a crisp total ordering is found. In this way, α represents the level of agreement and the crisp total ordering found through this intersection is the final agreement of the group process.

An example of this process (adapted from [Klir 1995]) can be found in trying to get eight members of the scientific community to agree on the proper set of scientific attributes that a mission should have. If h represents hyperspectral imaging objectives, m represents magnetic field measurement, g represents gravity field studies, and s represents seismic studies, then the total preference ordering $\mathbf{P}_i (i \in \mathcal{N}_8)$ can be found on a set of alternatives $X = \{h, m, g, s\}$. Consider a set of individual preferences:

$$\begin{aligned}
\mathbf{P}_1 &= \langle h, m, g, s \rangle \\
\mathbf{P}_2 &= \mathbf{P}_5 = \langle s, g, m, h \rangle \\
\mathbf{P}_3 &= \mathbf{P}_7 = \langle m, h, g, s \rangle \\
\mathbf{P}_4 &= \mathbf{P}_8 = \langle h, s, m, g \rangle \\
\mathbf{P}_6 &= \langle s, h, m, g \rangle
\end{aligned}$$

The social preference relation is derived from the "majority rule" expression listed above.

$$S = \begin{array}{c} \\ h \\ m \\ g \\ s \end{array} \begin{array}{c} \begin{array}{cccc} h & m & g & s \end{array} \\ \left(\begin{array}{cccc} 0 & .5 & .75 & .625 \\ .5 & 0 & .75 & .375 \\ .25 & .25 & 0 & .375 \\ .375 & .625 & .625 & 0 \end{array} \right) \end{array}$$

The α-cuts of the fuzzy relation S are:

$$\begin{aligned}
{}^{1}S &= \emptyset \\
{}^{.75}S &= [\langle h,g\rangle, \langle m,g\rangle] \\
{}^{.625}S &= [\langle h,s\rangle, \langle s,m\rangle, \langle s,g\rangle, \langle h,g\rangle, \langle m,g\rangle] \\
{}^{.5}S &= [\langle m,h\rangle, \langle h,m\rangle, \langle h,s\rangle, \langle s,m\rangle, \langle s,g\rangle, \langle h,g\rangle, \langle m,g\rangle] \\
{}^{.375}S &= [\langle s,w\rangle, \langle m,s\rangle, \langle g,s\rangle, \langle m,h\rangle, \langle h,m\rangle, \langle h,s\rangle, \langle s,m\rangle, \langle s,g\rangle, \langle h,g\rangle, \langle m,g\rangle] \\
{}^{.25}S &= [\langle g,h\rangle, \langle g,m\rangle, \langle s,h\rangle, \langle m,s\rangle, \langle g,s\rangle, \langle m,h\rangle, \langle h,m\rangle, \langle h,s\rangle, \langle s,m\rangle, \langle s,g\rangle\langle h,g\rangle, \\
&\quad \langle m,g\rangle]
\end{aligned}$$

The group choice is found by looking for the lowest α-cut that contains a unique intersection. The orderings on $X \times X$ are all compatible with the empty set ${}^{1}S$. The sets of alternatives that are compatible in the crisp relations ${}^{.75}S$ are:

$$\begin{aligned}
{}^{.75}O = \ & [\langle s,h,m,g\rangle, \langle h,m,g,s\rangle, \langle h,s,m,g\rangle, \langle h,m,s,g\rangle, \langle s,m,h,g\rangle, \langle m,h,g,s\rangle, \\
& \langle m,s,h,g\rangle, \langle m,h,s,g\rangle]
\end{aligned}$$

It is obvious that the intersection of the ordering ${}^{.75}O$ with the crisp relation that results in the empty set is, in fact, ${}^{.75}O$. By going to next set of alternatives, it is found that,

$${}^{.625}O = [\langle h,s,m,g\rangle, \langle h,s,g,m\rangle]$$

and the intersections are then,

$${}^{1}O \bigcap {}^{.75}O \bigcap {}^{.625}O = [\langle h,s,m,g\rangle].$$

The group decision is, with a .625 level of agreement, that the priority of science objectives should be hyperspectral imaging followed by seismic studies.

More elaborate methods, in the opinion of the author, do not lead to much better fidelity in results. In fact, in [Smith 1998], the utility of Analytic Hierarchic Processes (AHP), a similar ranking method that makes use of pairwise comparisons, is discussed in comparison to Axiomatic Design. That report explains that the reliance of pairwise comparisons at lower levels of decomposition results in far more ambiguity in the decision makers' opinions. Furthermore, AHP can suffer from detailed couplings that cause even greater clouding of the user's judgment. The advantage of the fuzzy set method discussed above is its simplicity and its unambiguous statement on the level of group agreement.

2.2.3 Fuzzy Sets and Axiom 1

Functional independence of Axiom 1, in the uncoupled condition, is defined as the condition by which the selected DPs are related to the set of FRs on a one-to-one basis. For a designer to make that determination, he/she must be capable of rendering some judgment about the relative nature of a given DP to a given FR. When AD is extended to cover fuzzy sets, an understanding of these relationships must be provided through one of two mechanisms: non-zero membership in the FR-specified set or non-empty intersection of two sets.

In the former case, the functional requirement has been written such that a certain membership value is specified. For example, the requirement may specify that the design satisfy minimum membership value of $A(x) > 0.5$. The design parameters would then be selected as the α-cut of A such that all elements in the design are compatible with the functional requirement. Formally, the design matrix would have a non-zero entry for A_{ij} when $DPj \in X$ and FRi is defined over that universal set X.

In the latter case, the FR is specified in terms of the property of the fuzzy set.

This case is the more common one found in the system architecture problems. An FR specified in these terms would simply refer to the "goodness" of a particular aspect of the architecture and DPs would then merely need to express the values of that property on some universal set. In this case, the FR would be represented as the crisp set $FRi = A(x)$ over some universal set X and a design parameter $DPj = B(x)$ would be a fuzzy set. The functional dependence found in the design matrix would be notated by a non-zero entry if and only if $A \cap B \neq \emptyset$.

The common aspect of both of these fuzzy expressions of the Independence Axiom is that they do not result in a quantitative value in the design matrix. While that may be disappointing with regard to the calculation of semangularity and reangularity, quantitative measures of the fuzzy sets and their relationship to uncertainty can be found in the evaluation of Axiom 2.

2.2.4 Fuzzy Sets and Axiom 2

As mentioned earlier in this discussion, the handling of uncertainty is at the center of system architecture and design. However, when one speaks of the uncertainty, clearly there are a number of different ways to look at the same concept. The literature seems to have recently coalesced into some standard definitions for different types of uncertainty (see [Klir 1993], [Klir 1988], [Kosko 1990], and [Dubois 1985]).

There are two basic branches of uncertainty: vagueness and ambiguity (see Figure 2-6). Vagueness refers to the lack of definition or distinction. This category of uncertainty is the most commonly thought of version of fuzziness. This type of uncertainty refers to a system's ability to distinguish, in some way, between the boundaries of sets. Other terms that refer to this type of uncertainty are haziness and shapelessness. Vagueness, in a system architecture setting, refers to the measure of how successful one was in reducing the stakeholders' desires into customer attributes and functional requirements. Ambiguity, on the other hand, refers to the difficulty in assigning a one-to-many relationship. This type of uncertainty is more closely associated with the ideas found in possibility and probability theory and represents the type of un-

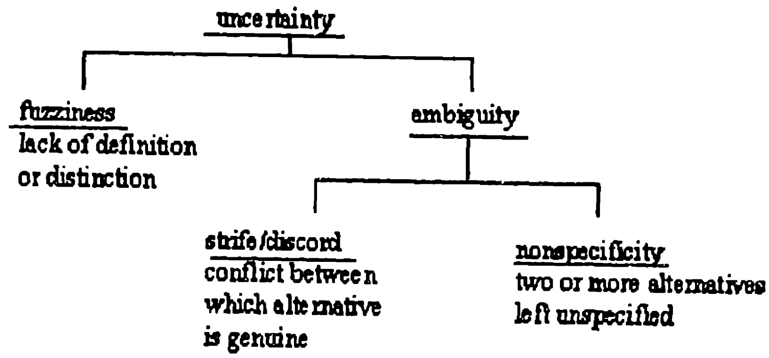

Figure 2-6: Types of Uncertainty

certainty that causes system architects and designers a great number of problems.

Ambiguity can be further decomposed into two types: nonspecificity and strife (or dissonance). Nonspecificity refers to the uncertainty where two or more alternatives exist. A measure of the degree of nonspecificity is reflected in the number of alternatives that are present. In contrast, strife refers to the type of ambiguity that exists when there is disagreement as to which alternative is genuine. This form of ambiguity is not one that arises very often in engineering applications since the production of a design, by definition, generates an alternative that leaves little room for discrepancy in substantiation.

It is the measure of nonspecificity that one is concerned about when investigating a design problem. In fact, architecting can be thought of as a process of following the principle of minimum uncertainty. This principle is merely an arbitration method by which one narrows down the various systems until one finds one that meets an acceptable level of minimum uncertainty. This principle, and its value in design, is best explained through a discussion of Hartley information.

Consider a set of alternatives X and a set of selections s made on that set. When a selection is made on the set of alternatives, all ambiguity is eliminated. The amount of information conveyed by this selection can be thought of as the amount of ambiguity removed in this problem. The amount of information that is found in s selections from a set of X alternatives should be proportional to s and should reflect the cardinality of the set $n = |X|$. By expressing that mathematically using a proportionality constant equal to one, it can be shown that,

$$I = \log_2 n^s = \log_2 N$$

where n^s reflects the number of all possible sequences of s selections and N is the total number of alternatives regardless of their selection. The choice of the base 2 logarithm is a convention that reflects the information contained in a true/false condition (i.e., one bit of information is realized when a true value is selected from the two alternatives). It should be emphasized that the Hartley measure is associated with a choice amongst alternatives. As the number of alternatives increase, the uncertainty and the information needed to be specific increase.

This description of nonspecificity is exactly what the Information Axiom refers to. Yet, until this point, Axiom 2 only referred to crisp sets. The implications for its extension to fuzzy sets can be seen by referring back to a more generic definition of the information content given by,

$$I = \log_2 \frac{A_{sr}}{A_{cr}}$$

where A_{sr} is the system range and A_{cr} is the common range. In this definition, the respective ranges are given in terms of probability distribution functions. The fuzzy set equivalent to this arrangement is found by examining the degree of subsethood for a fuzzy set describing a DP with its corresponding FR. So, for a fuzzy set A which describes the system range of possible instances for a given DP and a fuzzy set B that describes the characteristics of the FR, then the information content can be expressed by,

$$I = \log_2(\frac{|A|}{|A \cap B|}).$$

This extension of the information content definition can be established by both example and further definition.

In a decision making model proposed by Bellman and Zadeh (see [Bellman 1970]), an example of the fuzzy information content definition is provided when a set of goals and constraints are described by fuzzy sets $\mu_C : X \to [0,1]$ and $\mu_G : X \to [0,1]$. (It should be noted that the same universal set does not have to be common to the membership functions. All that is needed is the existence of a function $f : X \to Y$ that describes the mapping from a set of actions X to a set of outcomes Y). A decision in this model is then achieved whenever

$$\mu_D(x) = \min[\mu_G, \mu_C]$$

which uses the standard fuzzy intersection specified in definition of the information content. The decision on buying a house may clarify this discussion. If the FRs for buying a house are described by fuzzy sets that include the price of the house G_1, the quality of the schools G_2 and the relative ease of getting to work G_3, and their corresponding sets three housing areas (seen as the constraints of the problem) are given by $A_i, B_i, C_i, i = 1, \ldots, 3$, then the information content and the decision is given by,

$$\begin{aligned} I_A &= \sum_{i=1}^{3} \log_2 \frac{G_i \cap A_i}{A_i} \\ I_B &= \sum_{i=1}^{3} \log_2 \frac{G_i \cap B_i}{B_i} \\ I_C &= \sum_{i=1}^{3} \log_2 \frac{G_i \cap C_i}{C_i} \end{aligned}$$

where the standard fuzzy intersection is assumed and the minimum information content is selected.

By examining two extremes of the fuzzy information content, some more detail on this type of nonspecificity can be achieved. Consider the case where the area of the system range shrinks nearly to zero while the area of the design range remains constant. In this case, the DP has become an element of a crisp set that has the same property as the FR set. In the example above, this case would correspond to examining a particular house (with corresponding crisp definition of price, school quality and drive times) within the context of the fuzzy sets of FRs. Here, when several individual houses were considered, the maximum membership of the set of decisions $D = G \cap C$ would be represent the preferred house. The other interesting extreme is the case where only the property of the fuzzy set is specified without providing a membership function over a universal set. In this case, the design range is equal to the system range and the common range is equal to one. Again, this method of specifying an FR would be equivalent to stating that one wanted a "good" price for a house without giving explicit boundaries as to what "good" means. In this case, a generalization of the Hartley function (see [Higashi 1983]) has been developed to measure the nonspecificity of fuzzy sets.

$$U(A) = \frac{1}{h(A)} \int_0^{h(A)} \log_2 |^\alpha A| d\alpha \tag{2.8}$$

The so-called "U-uncertainty" is easily calculated and can be understood as being the measure of all the nonspecificity that it represented by a given fuzzy set. From an AD standpoint, it also benefits from the fact that it, like its Hartley counterpart, measures bits of information.

One last comment on uncertainty and information should be made before proceeding on to an illustrative example of these modifications. A system architect's job is often referred to as one that deals in complexity. Ashby (see [Ashby 1973]) defines "the measure of complexity by the quantity of information required to describe the vital system." Suh states, in his Theorem 23 of his AD theory, that a large, flexible system is not necessarily complex if it has a high probability of satisfying the FRs specified for the system. Clearly, these and other attempts to formally capture the meaning and implications of complexity have the central theme of having to do with information. Since it has been shown that a type of uncertainty and information are interrelated, some general strategies for dealing with complexity become obvious. Aggregation is a natural strategy that comes out of these basic concepts since it produces a manageable amount of information and uncertainty at that level of aggregation. The subsystem and the Integrated Product Team (IPT) are forms of this type of aggregation. The Independence Axiom is also a means of reducing complexity by insisting on a structure of design and a minimum set of problem variables. The latter issue of a small number of variables is particularly important for large, space systems that regularly have to fight the battle against the growth of the system's mission (i.e., "scope growth"). Likewise, complexity should always be a necessity driven by the requirements and constraints on a system. Space systems are generally very complex due to the difficult requirements (e.g., operate continuously for 10 years in extreme environmental conditions) and constraints (e.g., weigh the absolute minimum and come in under a tight cost ceiling). System architects need to recognize these instances when complexity is called for and only go to more complex systems, using these and other strategies, when the uncertainty of the system needs to be reduced. It is remarkable aspect of AD that so many rich prescriptive and descriptive concepts can be drawn from two simple axioms.

2.3 Example of Fuzzy Axiomatic Design

An example of the use of the fuzzy AD method may further illustrate the utility of the technique. Consider the case of designing a passive space-based radar payload. These payloads have recently become popular in the scientific community for determining a wide variety of environmental parameters such as the depth of snow over various surfaces and the amount of moisture in the soil as a function of the region and the time of year. The primary difficulty with these systems is that they require an extensive set of ground truth measurements in order to make the proper interpretations of the radar images. Yet, ground truth is an elusive quantity that requires a wide number of parameters to be adjusted. Factors include the time of day, the time of year, the Sun angle, the atmospheric conditions, polarity and a great many other secondary items. For an individual site, these parameters are not easily handled for the system architectural discussions. The payload design is further complicated by the data delivery methods and the details on the size and use of the instrument. A description of the *FRs* and *DPs* of the system may make the payload architecture decisions clearer.

At the architectural level, the microwave radiometer payload can be considered to be a small, closed, rigid system that, by definition, only has a small number of functional requirements. For this particular example, a 900 km altitude polar orbit is selected from a higher level analysis of the satellite systems. Furthermore, the image analysts have stated that an overlap of only 10% will suffice for the purpose of correlating adjacent images. With these constraints, the *FRs* for the microwave radiometer are:

FR_1 = The resolving power (resolution) on the ground near the vicinity of the nadir point shall be, at minimum, 18 meters.

FR_2 = The scan frequency of the radiometer shall be, at a minimum, 1.5 beamwidths per minute.

FR_3 = The data latency to the end user shall be between six and eight hours.

FR_4 = The calibration quality must be good for one of the established ground truth sites.

At this point, the distinction between two types of functional requirements should be made. As alluded to previously, AD can handle both technical and non-technical parameters. The former type of requirements are typically called " Technical Performance Parameters (TPPs)." The latter type of requirements are often called "Figures of Merit (FOMs)" or "Measures of Effectiveness (MOEs)." A brief examination of the functional requirements for the microwave radiometer architecture indicate that the first two requirements refer to TPPs that require some detailed analysis to understand their coupling. The latter two functional requirements are MOEs that lack the definition required to completely specify their characteristics through rigid mathematical formulations. Ranges of values, based on the MOE, will be determined for these requirements.

The angular resolution of an electro-optical system is defined by basic physics to be

$$\theta_r = \lambda / D$$

where λ is the wavelength and D is the aperature diameter. An approximate measure of the resolving power is $h \cdot \theta_r$. It should be noted that h is fixed at 900 km for this satellite and the microwave wavelength of interest is $\lambda = 3$ cm. Likewise, the equation for the scanning frequency f_{sc} can also be expressed in terms of a few variables.

$$f_{sc} = \frac{\rho V_x \theta_s}{h \theta_r}$$

In this equation, ρ is the degree of overlap (0.1), the along track velocity is specified by V_x, and θ_s is the scan angle for the payload.

An architecture for this payload can now be examined by the careful selection of DPs. Clearly, the diameter and scan angle of the instrument are critical to its technical performance. A mission scenario might also be selected to combine a large amount of on-board storage capacity to off-load the ground operations requirements. Furthermore, the system may only request a few ground stations that are already servicing several systems. Finally, the payload architect has isolated four ground truth sites that are suitable for this mission. The design matrix produces the following decoupled design.

$$\begin{bmatrix} FR1 \\ FR2 \\ FR3 \\ FR4 \end{bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 \\ X & X & 0 & 0 \\ 0 & 0 & X & 0 \\ 0 & 0 & 0 & X \end{bmatrix} \begin{bmatrix} DP1 \\ DP2 \\ DP3 \\ DP4 \end{bmatrix}$$

The specific selection of the DPs is found after working through the equations for the TPPs and evaluating the potential coupling with the MOEs.

DP_1 = Aperature diameter D of 1 m,

$DP_2 =$ Scan angle θ_s of 50 degrees,

$DP_3 =$ A store-and-forward method of communication is selected for data delivery to multi-tasking ground stations,

$DP_4 =$ One of four ground truth sites are available that provide "good" calibration.

At this point, the structure of the architecture is acceptable according to Axiom 1 and a minimum information architecture needs to be determined. The technical parameters have been selected so as to exactly match the design requirements so their contribution to the information content is zero.

$$\begin{aligned} I_{\text{total}} &= I_{\text{aperature}} + I_{\text{scan angle}} + I_{\text{data}} + I_{\text{truth}} \\ &= 0 + 0 + \log_2(A_{sr}/A_{cr}) + \frac{1}{h(A)} \int_0^{h(A)} \log_2 |^{\alpha} A| d\alpha \end{aligned}$$

Two systems, designated A and B, are evaluated. A rough calculation of the data communication system indicates the data latency is equally likely to be anywhere from 7.0 to 9 hours for system A and 7.5 to 8.5 hours for system B. This results in a system range area of 2 hours and a common range area of 1 hour for system A and a system range area of 1 hour and a common range area of 0.5 hours for system B. The resulting information contents are both 1 bit. Thus, the characteristic of small variability in one system is equivalent to fair amount of overlap in the other system. The Information Axiom states that both systems are equally good architectures.

The selection of ground truth sites is a bit more complex. As mentioned earlier, the availability and quality of a ground truth site is determined by a wealth of factors that are themselves often difficult to quantify. At the architectural level, this type of detailed analysis is not appropriate. Therefore, a set of membership functions are found through rough data reduction (by looking at the number of rainy days for the site, variability as function of time of year, etc.) and expert discussions as outlined in the earlier sections of this chapter. For each of the four sites, a membership function ($\mu_i, i = 1, \ldots, 4$) was derived that reflects the amount of hours in a year that a site has "good" conditions for producing a ground truth measurement (see Figure 2-7). It is important to note that to meet the intent of $FR4$ the actual measurement of nonspecificity should be conducted on the complement of these sets $\bar{\mu}_i = 1 - \mu_i$ and thereby architect the payload system with the best ground truth site. When the U-uncertainty of each of the sites is calculated, the information content associated with each site is, respectively, $\langle 11.43, 10.76, 11.22, 11.31 \rangle$. The choice of site no. 2 is interesting, in that, since it provides a different selection than if the architect had used only information about the percent of the year that the ground truth site was available. Site no. 4 is available 85% of the year, while site no. 2 is only available 82% the year. The information containing the quality of the measurement is clearly reflected in the choice of the latter site.

In summary, the fuzzy AD approach provided an architectural solution for a remote sensing payload. The method provided a) some insight into the decoupled nature of the aperature diameter and scan frequency and b) a selection between competing choices of data systems and ground truth sites (i.e. either data system A or B, and site no. 2).

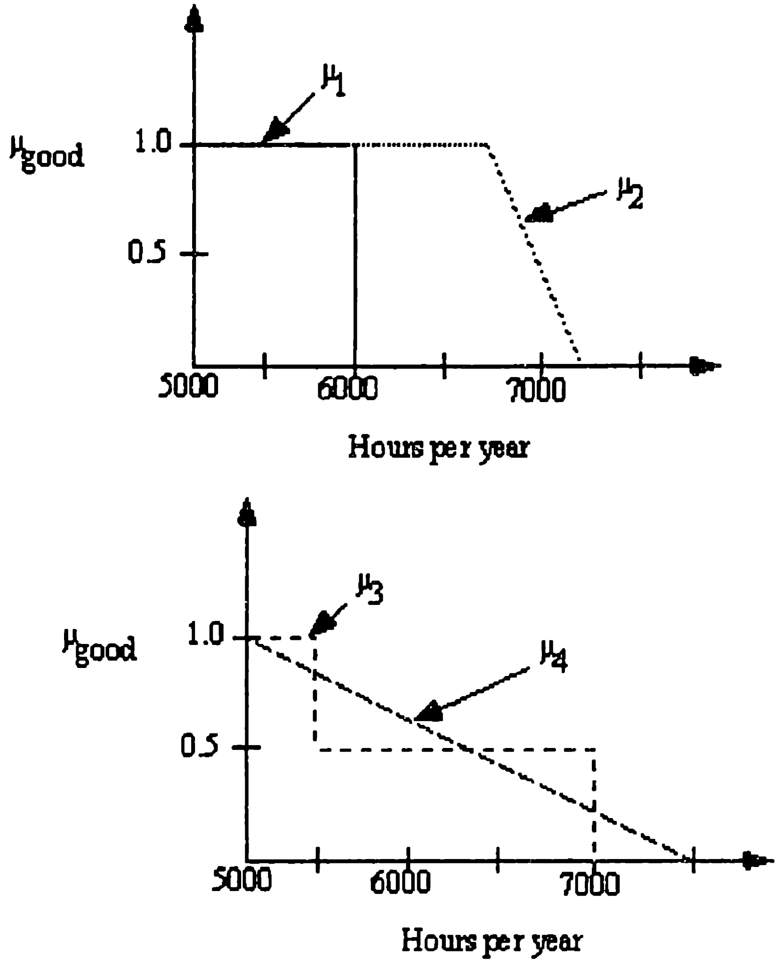

Figure 2-7: Membership Functions for Four Ground Truth Sites

Chapter 3

Factors in Space System Architectures

Space system architectures are some of the most complex in engineering. Yet, it is rare that they are discussed in a rational and structured context. As mentioned before, most of the space system architectures are either (a) evolutionary, (b) founded by a visionary or (c) guided solely by some heuristics and a mission statement. In this section, the factors affecting space system architectures will be briefly explored using the AD framework.

A list of space system architecture headaches clearly demonstrates the "mixed bag" characteristics of the required decisions:

- the use of nuclear power plants or propulsion and the considerations of powerful environmental groups and State Department concerns,
- the need for a suite of different launchers for different missions and the desire for a lean public sector,
- the regular conflicts of the science community over what is really "important" or "good" science,
- the application of new technology versus the need for rapid and cost-effective

development using Commercial-Off-The-Shelf (COTS),

- the inter-agency rivalry requiring that certain centers have "pieces of the pie,"
- the Congressional election cycle, the need for distributed production to meet a wide constituency and the long development process for complex space systems.

All of these decisions have been made in one program and, therefore, any discussion of large, complex space systems must begin, and to a lesser extent, end with the Apollo Program. A major legacy of the Apollo Program is unquestionably its innovations and institutions. *Science* magazine in 1968 [Wolf 1968] summed up this thought by stating:

> In terms of numbers of dollars or of men, NASA has not been our largest national undertaking, but in terms of complexity, rate of growth, and technological sophistication it has been unique ... It may turn out that the [the space program's] most valuable spin-off of all will be human rather than technological: better knowledge of how to plan, coordinate, and monitor the multitudinous and varied activities of the organizations required to accomplish great social undertakings.

That Apollo was a success for NASA is not to say that it did not profit from the an extensive infusion of talent and techniques from industry and Department of Defense programs. Seamans and Ordway [Seamans 1977] expressed that debt and went on to say that Apollo was not unique in its characteristics. They claim that large-scale technical endeavors maintain a common set of characteristics. They include:

1. **Interdisciplinary Character** - The array of scientific, technological, social, political, and other personalities brought together in situations where they would normally not have professional contact.

2. **"State-of-the-art"** - Large-scale technical endeavors have solved most of the basic scientific problems, but their size and complexity excel in many ways what is generally considered possible at the time of the endeavor's initiation.

3. **Selling** - Promoters of the program must be able to articulate how the execution of the program will result in the satisfaction of the initiating need or goal.

4. **Funding** - Adequate funding is required at all stages of the program's execution. It is important to note that many programs fail to secure funding for periods after the critical start-up phase.

5. **Support** - The program can not always be justifying its existence. A level of continuous support must be supplied once the program has been bought and resources provided.

6. **Manpower** - Well-qualified and motivated personnel must be available to the program in terms of both constant participation and surge capability.

7. **Planning and Analysis** - Structured deployment of resources is a necessary condition for a large-scale endeavor. However, the forces and conditions of a program change on a regular basis and new baselines need to be created and evaluated.

8. **Communicating Information** - The massive amount of data must be collected and organized in a manner that is meaningful, not only to management, but to the program personnel at every level.

9. **Visibility** - The motivation for solving problems can come from many directions, but public visibility is a strong motivator that is common to the sheer mass of a large-scale endeavor.

10. **Decentralization** - Management can not make the number of decisions necessary to solve all the problems in a large system. Authority must be decentralized to provide any kind of reasonable execution.

11. **Flexibility** - Management can not insist on a rigid course of action either in technical or managerial terms. Policies, budgets, and allocation of resources must be transferable as the needs of the enterprise change.

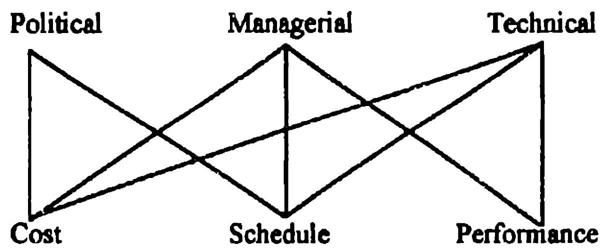

Figure 3-1: Interaction of Common Factors and Program Measures

12. **Control and Integration** - While flexibility and decentralization are needed, large-scale programs require formal mechanisms for exercising the appropriate levels of constraint on decisions within the program.

13. **Risk and Uncertainty** - Failures are expected in these programs. The complexity of the system drives large-scale systems to unforeseen states that will not permit proper execution of the mission.

These characteristics can be roughly categorized into items that are political, managerial or technical in nature (i.e., four primarily political items, seven managerial items and two technical items). Furthermore, these categories or factors can be related back to the basic measures used in project management: performance, cost and schedule. Figure 3-1 shows the first order effects on each factor on each measure. It should be noted that political factors, again to first order, affect only cost and schedule, and performance is only affected by technical and managerial considerations. All other factors and measures are interrelated. This result is significant if one puts these interactions into the AD framework.

3.1 Conjectures for Space System Architecture

The previous brief discussion demonstrates some of the characteristics of large-scale systems. Given this and the number of decisions that have to be made for virtually any space system, the following two claims about space system architectures must be addressed. Once the conjectures have been accepted, some simple examples can be attempted to test the sensibility of the framework.

Conjecture 1 *Mission success for space system architectures is related to the following functional relationship* $MS = MS(T_s, M_s, P_s)$ *where* T_s *represents the technical success of the design,* M_s *is the management success of the program, and* P_s *is political success of the design.*

Conjecture 2 *Each of these three factors,* T_s, M_s, P_s, *are a composite of other factors:*

$$\begin{aligned} T_s &= T_s(TR, TD, TE), \\ M_s &= M_s(OD, GC, PC, PK) \\ P_s &= P_s(CM, EM, DS, RM, SO). \end{aligned}$$

The terms within in those factors are:

TR - Technical Risk
TD - Technical Design
TE - Technical Execution

OD - Organization Design
GC - Govt/Contractor Relationship
PC - Process Control
PK - Process Knowledge

CM - Clear Mission Objectives
EM - Early Milestones
DS - Divided Spending
RM - Regular Milestones
SO - Spin-off Objectives

It should be emphasized that these are factors and not functional requirements. Clearly, for example, Technical Risk and Technical Design will be automatically taken into account when the AD process is used in the decision making process. These factors are outlined simply for definitional purposes so that further examples can be discussed and the basis of the method explored.

Example 1: Consider the Skunk Works development of the SR-71. The SR-71 is an extremely advanced stealth reconnaissance aircraft. It flies at over Mach 2 and has an number of complex technologies that must work together if a flight is going to be successful. Kelly Johnson, the leader of the Skunk Works at that time, was legendary for picking the best and brightest engineers and putting them to work. This development was acquired during the height of the Cold War when intelligence was considered absolutely vital.

$Factor1$ – Management Success $DP1$ – Isolated, hand-picked team

$Factor2$ – Technical Success $DP2$ – New tech. & old aircraft designs

$Factor3$ – Political Success $DP3$ – Clear need for intelligence

$$\begin{bmatrix} F1 \\ F2 \\ F3 \end{bmatrix} = \begin{bmatrix} X & 0 & 0 \\ X & X & 0 \\ 0 & 0 & X \end{bmatrix} \begin{bmatrix} DP1 \\ DP2 \\ DP3 \end{bmatrix}$$

This is a decoupled design (when factors are made roughly equivalent to FRs). This is significant since it can tell the system architect where the potential problem areas are. In this case, the political and managerial issues will not require a lot of attention, but getting the right technical solution and the right technical people is essential to the program's success.

Example 2: Two very different lunar missions form another good study of this AD framework for space systems. The Apollo Program and the more recent Lunar Prospector missions are obviously very different missions. The Apollo Program spent billions of dollars over a ten year period to develop new technologies, integrate them in novel ways and conduct tests in a nationwide use of facilities. It also had clear mission objectives and a strong public will behind it. Lunar Prospector, on the other hand, was part of a new class of NASA missions that have a budget cap of $250M and a short lifespan. This size of exploration program does not even appear on the political landscape and, due its cost/schedule constraints, must be extremely simple. While Lunar Prospector is a good space system example of an uncoupled design,

$$\begin{bmatrix} \text{Ts} \\ \text{Ms} \\ \text{Ps} \end{bmatrix} \begin{bmatrix} X & 0 & 0 \\ 0 & X & 0 \\ 0 & 0 & X \end{bmatrix} \begin{bmatrix} \text{``Off-the-shelf'' systems} \\ \text{One contractor} \\ \text{Discovery class} \end{bmatrix}$$

the Apollo Program has a significantly different design matrix

$$\begin{bmatrix} \text{Ps} \\ \text{Ms} \\ \text{Ts} \end{bmatrix} \begin{bmatrix} X & 0 & 0 \\ X & X & 0 \\ X & X & X \end{bmatrix} \begin{bmatrix} \text{Man on the Moon} \\ \text{Center Responsibilities} \\ \text{New and Complex} \end{bmatrix}$$

The Apollo Program had Kennedy's goal of putting a "man on the Moon before this decade is out." It was clear, concise, and had the Cold War competitiveness behind it. The Apollo Program had to satisfy other political needs and management needs by dividing up the parts of the development. (Florida would handle launch processing; Alabama would handle launch vehicle production; Texas would handle program management and crew activities; etc.) The program also had to build something radically novel using a massive management structure while contending with this political pressure. This design matrix states, in a similar way as the SR-71 example, that problems should be expected in the areas of management and technology, with technology being the most difficult.

In summary, this discussion on the top-level factors in space system architectures has illustrated a few points:

- Large, government-sponsored space system appear to be affected by only a few factors involving technical, managerial and political issues.
- These factors are, in their most basic case, interrelated when placed in the context of standard managerial measures of performance, cost and schedule.
- AD should provide an architect indications of where potential problems will

most likely appear.

- AD, in the case of a design that clearly has coupled functional requirements, instructs the system architect to find a different architecture.

While this was strictly a notional exercise and not truly an exercise of the AD method (since neither true functional requirements or design parameters were examined), it did demonstrate some basic concepts. Actual functional requirements will be developed in the next three sections.

3.2 Political Considerations

There is an old adage that "good judgment comes from bad experience." The recent history of large, government-sponsored space systems is populated with failures that came to be primarily attributed to poor understanding or operation within the political arena [Hingerty 1997]. Ambitious programs such as space-based missile defense and President Bush's Strategic Exploration Initiative are just two examples where the political process was insufficiently developed to support the endeavors. If so much of a program's success rides on its political attributes, what are the best practices for the political process associated with a large-scale system? Myron Tribus [Tribus 1982] in "Seven Commandments for the Survival of a Technological Society" presents some convincing guidance on how system architects should deal with the political process. His "commandments" are:

1. Thou shalt not launch a program without clear goals.
2. Thou shalt not depend on public support for things in which the public has no interest.
3. Thou shalt not tell lies even in a good cause.
4. Thou shalt not undertake vast programs with half-vast strategies.

5. Thou shalt not organize the opposition nor fashion weapons for the hands of thine enemies.

6. Thou shalt not leave thy programs in the bowels of a bureaucracy.

7. Thou shalt not attempt to steer a course without feedback.

This political advice can be categorized very well and is widely supported by other authors. With the exception of the commandment concerning bureaucracies (which will be addressed later in the managerial section), the advice can be grouped into items concerning funding & value, power & constituency, trust, and cost.

Funding/Value

Funding and value is interlinked in the political sphere [Logsdon 1995a]. It is so interlinked that many often state that "politics = money" (see Chapter 10 of [Rechtin 1997]). That view is an oversimplification of a much more complex process. Politics, by definition, is an exchange of power. Therefore, the question becomes how is value determined so that funding will be exchanged for that value.

In space systems, Harris [Harris 1992] states that there are three types of fundamental benefits. **Intellectual** benefits are one type and refer to the scientific questions that are investigated using spacecraft. **Utilitarian** benefits are another type and are found in space systems through their spinoffs, Earth applications, and industrial products. Finally, **humanistic** benefits are found in space systems through their use in national policy objectives (e.g., national security, national prestige, international cooperation, etc.), cultural effects and collective spiritual effects. As evidence of these structures within the current space policies, one need only turn to the most recent White House policy statement [White House 1998]:

> For four decades, the United States has led the world in the exploration and use of outer space. Our achievements in space have inspired a generation of Americans and people throughout the world. President Clinton believes that we should maintain this leadership through a strong, stable,

and balanced national space program based on revolutionary new partnerships with the private sector and with other spacefaring nations. Our space activities represent a critical investment in America's 21st century economy. Maintaining our leadership role in space will serve national security, foreign policy, and economic goals. To that end, the Clinton Administration has vigorously supported policies and programs designed to cut costs, increase efficiency, and spur scientific and technological advancement.

Clearly, the ranking of each of these benefits can and will be subject to the power structures associated with each of the decision-makers, but there is a general order when viewed in the aggregate. In fact, Maslow [Maslow 1964] stated that needs can be an element or elements in a hierarchy. Furthermore, this hierarchy can be found at every level of a society. Table 3.1 lists those needs. While the mapping is crude at best, it is an interesting exercise to see where Harris' three benefits of space systems fall in this hierarchy. The humanistic benefits rank only second to the utilitarian aspects in this hierarchy (safety needs vs. physiological needs). Also, the highly publicized benefits of space science fall very low in the hierarchy.

This comparison of Harris' benefits to a Maslowian interpretation of political priorities appears to be valid when compared to several space programs. A number of Department of Defense programs that have been very complex and very expensive have sailed through the political process based on support from defense policy makers that have backed the programs as essential for national defense. Likewise, legislation that supports the development of communication system infrastructures on-orbit has received wide support. Even on similar space systems, this comparison still remains valid. Mars Pathfinder had a lot of exciting features and had the ability to mentally transport the taxpayer to the surface of Mars. Yet, many would state that its science production was not nearly as significant as that produced by Mars Global Surveyor (MGS) launched soon after it. It can be contended that MGS, while important, could not have, if it had needed to, translated its value in the science community into the

Number	Category	Examples
1	Physiological needs	Food, air, health
2	Safety/security needs	Protection from attack or environment
3	Belongingness and love	Group membership, having a mate
4	Esteem needs	Self respect, having respect of others
5	Need for self-actualization	Becoming everything that one is capable of becoming
6	Cognitive needs	Understanding how one is related to universe
7	Aesthetic needs	Seeing beauty and order

Table 3.1: Maslow's Hierarchy of Needs

kind of support needed for larger appropriations. The size of the human spaceflight budget versus the size of funding allocated for robotic missions is another political reality that confirms this hierarchy.

With the ranking of the benefits of government-sponsored space systems as utilitarian, humanistic, and intellectual, the architectural implications become evident and sound familiar to individuals who have spent an extensive amount of time considering these issues. In the political environment, utilitarian benefits are highly prized, but can't be taken too far. By this it is meant that, technology transfer, while a fundamental desired outcome of space systems, can not be taken too far until industrial forces begin to recognize a particular technology area as preferred and will request similar funding elements. (It should be further noted that OMB Circular A-76 explicitly prohibits the government from "getting into the business of doing business.") For this reason, while the technology transfer aspects of a system architecture produce strong funding support for a program, this benefit can not be emphasized too much. Humanistic benefits, by contrast, are the "bread-and-butter" of space systems. NASA was born as a political instrument of a Cold War policy. The extraordinary support it enjoyed during the early 60's were a demonstration of the passion by which the public enjoyed the contest with the USSR and the need for balance in a bipolar political world ([Logsdon 1995b]. Likewise, when Space Station Freedom collapsed under its own weight, the International Space Station was created as a foreign policy tool that is to serve as an emblem of the United States' position as a leader of partners going into space ([Marshall 1997]). Lastly, the preferences of certain constituencies must be addressed and are addressed by the more humanistic benefits. In a society that spends tens of millions of dollars each year on space-related entertainment products, an interest in outer space is an unambiguous fact found in national and international surveys (see [Logsdon 1997] and [Edin 1997]). Capitalizing on these interests and the other benefits of space systems by instituting structures within their programs that highlight these items is the challenge that faces every space architect.

Power/constituency

The essential nature of a large, government-sponsored program is that the political process owns your program. A program manager may lead, and a bureaucracy may be its advocate, but, in the final analysis, politics dictates its present and future. If funding follows value within the political process, the predecessor to funding is the exercise of power for the purposes of supporting constituencies. Yet, power in Washington D. C. is widely distributed and always changing ([Jones 1996]). Furthermore, the movement is based on the perceptions of members of Congress whose strongest motivator, generally, is reelection. The way to understand the process is to find out who benefits from supporting your program, who pays for your program, and who will consistently resist the acquisition and development of your program.

For large appropriations, there are a number of tensions within the political process. Some of these tensions have already been discussed in terms of value in the political realm: civil space vs. military space, science vs. application, human vs. robotic, and commercial vs. government-sponsored. However, the tensions and the players in the process are not just limited to the branches of government. Inter-agency and intra-agency rivalries have to be understood. Lobbying groups, external technical review groups, non-profit organizations, and powerful individuals all have a place in the process. The media and the so-called "two constituencies" (the public and a Member's colleagues in Congress) are also dominant participants in this on-going discussion. All of these players must work together, to a greater or lesser extent, for the complex activity of politics to create the funding which permits the process to go forward [Air 1990].

Often, space system architects are at a disadvantage when they enter the political arena because they are used to a particular method of problem solving. In engineering and science, assumptions are made, data is collected and logical deduction carries the day. Politics works through negotiation, perception, compromise, and past experience that develop a solution whenever the votes converge on an answer. Feasibility and desirability have to be brought together into a consistent framework to provide a long-term constituency. All the players have a different view of the same project and an architect's job is to ensure that the perceptions are ones that are currently favorable and that they remain favorable. In engineering terms, it is a robust design problem where the fluctuations are caused by the shifting character of the political power structure.

Suh [Suh 1997] mentions four different ways by which a design can be made robust. Each of them revolve around making the functional requirements FRs insensitive to variations in the associated DPs. In the context of power and constituencies, the robust design solution that is available to the space systems architect is one of educating the centers of political influence. A primary role of a system architect is to know what information is important to a program's future and to provide structures for generating that information. Unfortunately, as stated before, the program's present and future resides in the hands of a diverse and changing group whose needs and concerns also change. The education, therefore, must begin with an understanding of the type of program that is being promoted. As many Department of Defense officials will claim, the process of interesting key personnel on the value of logistics spares and other supplies is a nearly impossible job because these items appear to be uninteresting to most power centers. Systems, if they are to survive the generally long development times, must have a scale and novelty that attracts the attention and interest of powerful individuals and groups [Logsdon 1990]. Programs that attempt to do new and large things are of the appropriate stature for individuals who are very influential. It is a convenient fact of politics that small programs are often as difficult to promote as large ones, so large scale programs are often selected. The next piece of educational material that needs to be considered by the space system architect is the way a program increases the influence or prestige of the individuals that support their program. This may be as simple as explaining the distribution and multiplying effect on jobs in a particular area of the country, or as complex as discussing the overall influence of technology spin-offs on industries that are of interest to that individual or group. The third and final constituency that often gets neglected during the system architecture stage is the general public. When a program is completing its development or is coming into the operational phase, it generally receives a fair amount of attention. However, the public can be a vocal advocate even at the earliest stages of a program if they are brought along as participants and not merely observers of a complicated process.

It should be noted that power and constituency is a two-way street. Congress provides funding and in return, a space system is supposed to return tangible and intangible benefits to the supporting constituencies. This connection should always be kept in mind whenever one is zealously advocating a space system's development.

Trust

A reported exchange, in Jones' reference on Congressional involvement and relations, reflects a common feeling within organizations that develop large, government-sponsored space systems:

> A senior DoD acquisition official, appearing before an authorizing committee, stated: "Gentlemen, what we'd like to know is when are you going to stop micromanaging our business?"
>
> A senior, veteran professional staff member of that committee replied: "Sir, when you start."

It is often the case that space system managers have wished that Congressional oversight would stop or at least be minimized. However, oversight, while recently an increasing role of Congress, has its roots firmly within the Constitution (Article 1, Section 8). The major expansion of the Congressional role occurred in 1974 when the GAO was authorized to assist Congress in program evaluation and assessment. While this expansion has not been welcomed by a number of programs, Congress clearly has the responsibility to assure that the funds that it appropriates are being properly spent.

The issue of trust comes in when Congress has a particularly large annual appropriation for a single program. The vastness of the Executive Branch and all of its agencies will always outstrip the abilities of Congressional staffs and its investigators to study all the programs in all the agencies. Therefore, the oversight function must have a large component of pursuing those programs that appear to be going poorly ([GAO 1986]). In politics, the facts of the situation are not as important as the perception. A program must develop a reserve of goodwill toward its activities to receive continuous and vigorous support. The premiums of goodwill are negotiated at the initiation of the discussions concerning the program and will be regularly monitored during the course of its development. Goodwill premiums are just like rent payments: the trust in their arrival is derived from years of hard work, and that trust can dissolve in a very short period of time if a few "payments" are missed.

The dissolution of trust is never quicker than when an already concerned oversight committee feels that it is not getting the full story. Identifying and reporting mistakes is essential to assuring the concerned Members that a program is forthcoming. However, that oversight committee does not reside in the complex and difficult world of space systems development. A context has to placed on those mistakes so that they are not interpreted inaccurately. For example, launch failures are part of the cost of doing business in the aerospace industry. Each failure is extremely expensive and results in the loss of valuable hardware and thousands of hours of work. If that failure was the result of negligence or mismanagement, then major changes should be implemented and reported to the oversight function. However, if the failure was the somewhat unavoidable result of a quality escape in a business that requires 100 percent reliability, then statistics about the overall performance of the system need to be highlighted and its capabilities relative to other industry standards emphasized.

Trust is also gained through regular and *early* milestones. A program must be able to demonstrate its ability to deliver on promises made during initial funding discussions. Early success, which provides political capital to supporters, will generate greater support and result in less oversight. It is important to note that Congress works on two year, four year and six year cycles, and strategic planning for most agencies is on a five to ten year basis. Those cycles are valuable, but the only one that really matters is the yearly cycle. (It should be noted that this yearly cycle is a contraction from the longer cycles of four years or two years experienced in the 1960s and 1970s (see [Acker 1993])). Accurate, current and consistent reporting can result in a perception of a well-managed and diligent program. Research, Development, Test and Evaluation (RDT&E) Exhibits, Procurement Exhibits, Unit Cost Reporting, Contract Award Reports, Selected Acquisition Reports, and periodic studies and analyses, when properly crafted and filtered, can keep a program out of political trouble for an extended period of time.

Again, turning to a quote from Jones' guide, a staffer for the appropriations committee is reported to have stated: "Show me a program that is well managed and I will show you a program Congress has stayed away from."

Cost

The dominant measurement of the political viability of a program is its cost. No other metric provides a better yardstick by which performance in a political environment is determined. All costs, however, are not equal. Total costs of a program are initially important to a program, but final costs are not. (A slight caveat should be placed on that statement. Final costs are significant only to the extent that they affect operating costs which, in turn, affect the annual budgets of an acquiring agency). The government works on a cash-flow basis ([Oleszak 1989]), so if a program experiences an overrun in a given year, then in a flat or declining budgetary situation, those additional funds must come out of another budget item. Obviously, this exchange of funds is never politically popular with either supporters or opponents. In contrast, as long as a program remains popular, retains its constituency, and maintains the trust of its supporters, then the funding line will continue even when previously estimated life cycle costs have been exceeded (see H. Mandell's [Mandell 1983] and K. Heiss' [Heiss 1971] discussions of Space Shuttle cost estimation as one example). The government is merely reflecting the wider business setting in which it operates. The cost of capital in the U. S. is high and demands short timescales for performance. As stated earlier, performance, in the political arena, means hitting predetermined milestones within the annual costs.

Cost estimation is widely referred to as an art (see [Novick 1962] and [Stewart 1982]), while cost control is a subset of management techniques. The system architect must realize these different properties when structuring a program. The architect should place more emphasis on the generation of detailed early cost models, while using more standard methods (e.g. development reserves, spares allocations, logistics margins, etc) to cover the uncertainties inherent in the management of a complex technical development. Over-optimism is the most common feature of early cost estimates and has its source in three areas: political pressure within the government to stay within certain budgetary guidelines, contractor data and estimates that are produced under "lowest bid" cost criteria, and the lack of definition of the technical products and processes when the cost estimate is made. Each of these forces have effective counter-strategies [Rhoads 1992], and the movement to commercial acquisition practices is showing clear benefits in recent procurements. In fact, by the government's previous insistence on contracting according to the cost of an item, it has effectively restricted its flexibility by ignoring marketplace pricing mechanisms. "Shared risk", the motto of cost-based contracting, has promoted a system by which early cost estimates come in too low, reserves for peak years are not available, and program stability is jeopardized.

It is a system architect's responsibility to assure that the cost estimates are of the highest fidelity possible, that they retain a total cost margin, that they provide adequate reserves in peak years, and that they reflect the most competitive price available in the industry. Only by properly exercising this duty can a program successfully negotiate difficult political waters.

3.2.1 Top-level Political Functional Requirements

The discussion of political factors has highlighted the discriminators that lead to successful programs. To apply the Axiomatic Design framework, a set of functional requirements must be defined. Based on this research, the highest level requirements are:

> FR_1 = Establish program objectives in political terms and according to political values,
>
> FR_2 = Institute program structures that recognize power centers,
>
> FR_3 = Build trust in your program's execution,
>
> FR_4 = Structure the program costs to fit the government's appropriations environment

It should be noted that only the top-level functional requirements can be specified since lower levels of decomposition is only possible when a set of appropriate DPs are selected for these FRs.

3.3 Managerial Considerations

Large, government-sponsored space systems have become increasingly managerially complex as they seek to diversify their funding sources and responsibilities through the greater use of commercial and international involvement. This trend has led to the emergence of the Multi-Organization Enterprise (MOE) [Horwitch 1979]. The MOE is, like any system, a whole that is greater than the sum of its parts. The emergent properties include:

- A single and focused organizational mission that is the sole area of collaboration for the members of the MOE,
- The occasional presence of both public and private organizations,
- A collection of different cultures, assumptions, priorities and goals that require constant evaluation and understanding,
- The conflict between the needs of the MOE and the needs of the parent organizations that have supplied portions of their abilities to the MOE's mission,
- An organization of unique size and diversity.

MOEs are not a new phenomena. After World War II, a number of MOEs were developed to solve many social and technical issues through interdisciplinary methods. Examples of MOEs include the Liquid Metal Fast Breeder Reactor Program in the U. S., Airbus in Europe, the Jubail Industrial Complex in Saudi Arabia, and the recent Sea Launch organization (led by U. S. -based Boeing). The MOE, in recent years, has been evolving into an ever more complex entity as the world markets and governments become increasingly interconnected. Due to this fact, the success of the MOE has become less predictable. Horwitch, who has extensively studied the MOE, claims that even the most promising MOE "often flounder on the shoals of implementation and management [Horwitch 1982]." The expanded nature of the MOE does not permit the transferral of best practices from multi-business corporations, since the MOE contains distinctly different organizations (e.g., public and private sector organizations). The challenge for the system architect is to try to understand the essential factors for devising and implementing an MOE management strategy.

Case study investigations have produced copious findings on managerial practices within MOEs (see [Carleton], [Intecollegiate], and [Womack 1996]). One common theme in these studies is that the concept of strategic "fit" (the appraisal of organizational properties and comparing them to threats and opportunities in the environment) which works well in single, private sector firms does not have its counterpart in the MOE. The lack of strategic fit for an MOE is due to its ability to change rapidly and without many early indicators. These so-called "radical transformations" can destroy the enterprise (e.g., the U. S. Supersonic Transport Program). The simple internal change and movement of a MOE can also have dire consequences. System architects for MOEs can minimize their exposure to these types of risks by structuring their programs in ways that retain fluid and adaptable aspects. This objective can be achieved by carefully crafting the organizational structure, by instituting strong leadership, by providing detailed development controls and information systems, and by monitoring the external interfaces to their program. These structures and their value in architectural design of MOE management systems is the subject of this section.

Organizational Structure

Organizing a program may be one of the most significant issues that a space systems architect may face. As "form follows function," it should be remembered that function also follows form. If an organization is designed to operate in a particular way, and then is given tasks that are not in line with that operational philosophy, the mismatch can cause delays or the demise of a program [Holmes 1994]. The evolving organizational complexity of successive major NASA programs demonstrates one reason for the difficulties experienced in Space Station Freedom (see Figure 3-2 and the final report by the Advisory Committee on the Redesign of the Space Station [Advisory 1993]). With a little bit of analysis, however, a system architect can evaluate the characteristics of the organization and, either develop a new organization to support the development tasks or, assign tasks only to organizations that are structured to accomplish those tasks.

Tom Kochan *et. al.* [Kochan 1996] have spent a considerable amount of time investigating the ways in which an organization can be evaluated. The basic three perspectives that are presented in this research are the cultural perspective, the political perspective and the strategic perspective. The first perspective, the cultural perspective, refers to the intangible feel of the organization. A cultural perspective examines the symbols, analogies and phrases that best describe that organization.

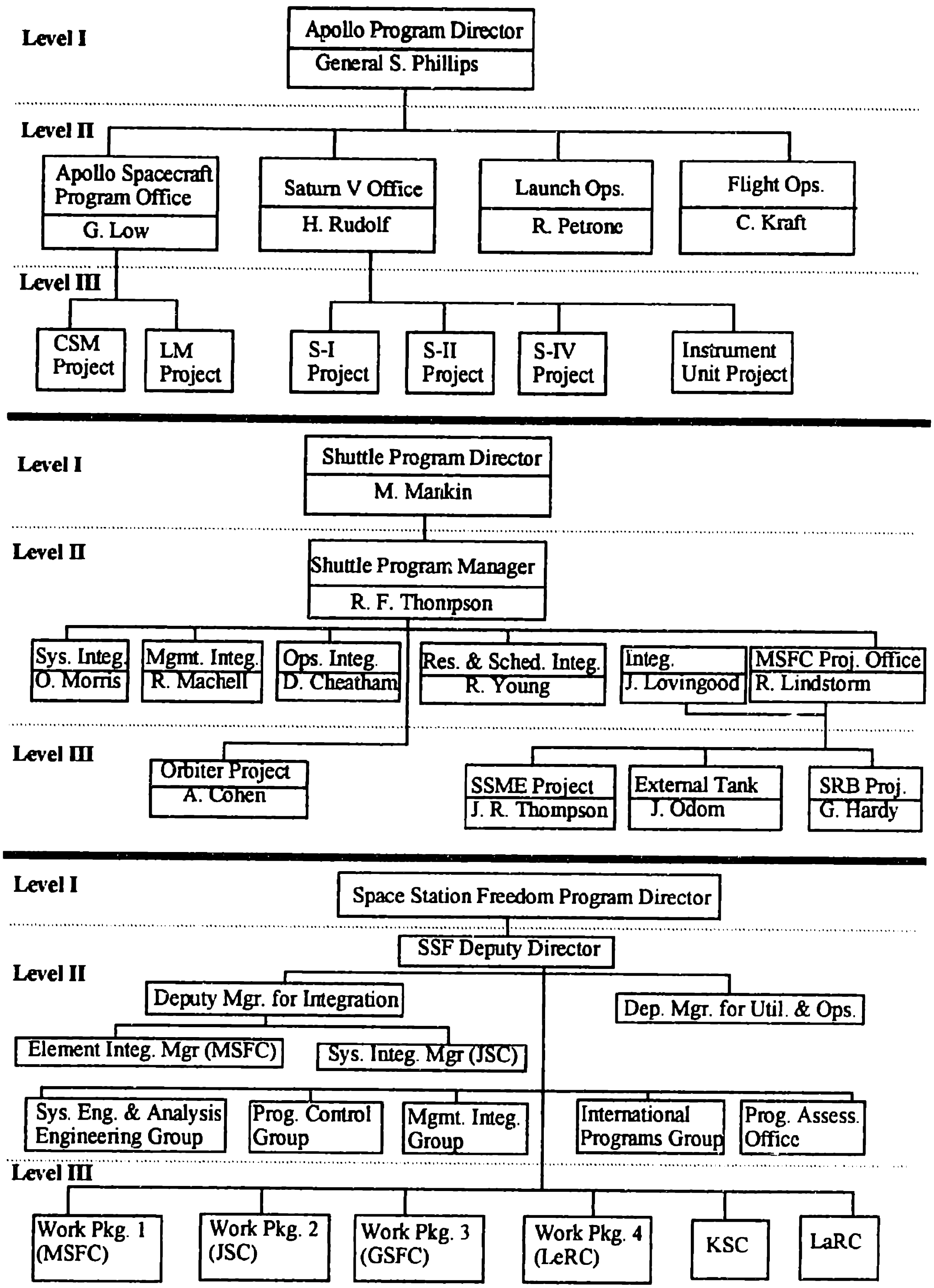

Figure 3-2: Three Major NASA Organizations

The political perspective describes how power is exchanged in a group. Finally, the strategic perspective allows an architect to examine the organization's roles, responsibilities and missions. In a MOE, the use of this multiple perspective analysis can also provide an early indications where friction and misunderstandings may occur [Fiske 1984]. For example, most commercial organizations have a simple strategic focus to them in that they seek to maximize their return to their investors through extensive short-term and long-term profit generation. Academic institutions, by contrast, have other measures of performance such as technical capability, prestige and influence in their community. Finally, a public sector organization generally has written or unwritten rules by which advancement is dictated. As it will be discussed later, each of these organizational types can be found in a MOE and each has value when given the appropriate mission.

Since most large, government-sponsored space systems have a very large public sector component, a few words about the perils of bureaucracies should be mentioned. Halprin, Clapp, and Kantor at the Brookings Institute have developed the idea of the "X-factor." This X-factor is the property that can cause your program to fail simply because it resides within a bureaucracy. Any public sector organization that has more than a handful of people in it and has been in existence for any substantial time starts to take on a set of bureaucratic characteristics. As such and in view of the lack of profit motives, it will consider that the employment of its personnel its primary purpose and all other items secondary. Due to this characteristic, it will try, at all costs, to resist reductions of force even if they benefit the stated mission of the bureaucracy. It will also resist changes in direction and changes which require a new set of skills since changes inevitably modify power structures. Consequently, it also will try to modify every new mission to the existing tasks, rules and procedures. Finally, it will fight to gain control over any project it sees as a threat and will then quietly bury it. While some of these comments may, at first glance, appear to be critical, no value judgment is actually being made. The system architect should realize, however, that the rule-based nature of public sector systems will lead to abilities in certain areas and resistance in others.

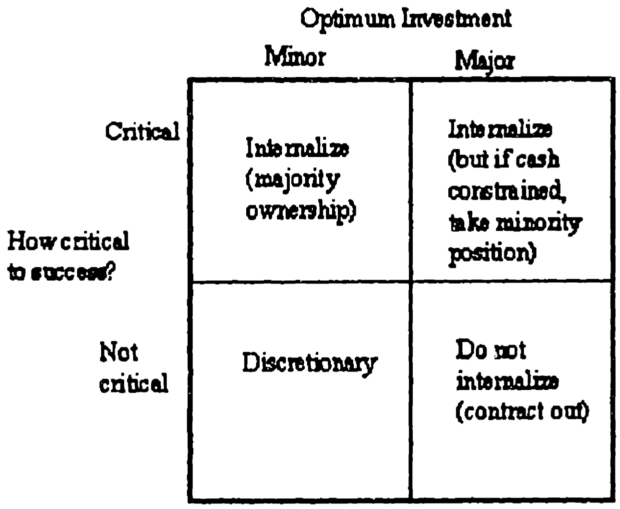

Figure 3-3: Integration Decisions Using Complementary Assets

David Teece [Teece 1987] explores the role of various organizations in the research and development process and how their different abilities are best combined to produce a successful product. In this setting, Teece introduces the concept of "complementary assets." Complementary assets are those assets, physical or functional, that reside outside of the originating organization that must be in place to meet an organization's objectives. For example, a company may have the best new product in a given industry, but if it does not have a competent distribution system as a complementary asset then it has little chance of succeeding financially. The value of this complementary asset concept is that it provides a certain amount of guidance for the classic "make-buy" decision process. Figure 3-3 shows one application of the discussion of complementary assets in its evaluation of the integration of capabilities into one's organization. In developing the MOE for a large, government-sponsored space system, the system architect should evaluate government, contractor and other organizations with an eye toward their organizational characteristics and the assets that are complementary to the lead organization.

Along those lines, acquisition managers spend an inordinate amount of time trying to understand how best to procure items from the private sector. Contract types and mechanisms can range from cost plus fixed fee (CPFF), cost plus incentive fee (CPIF),

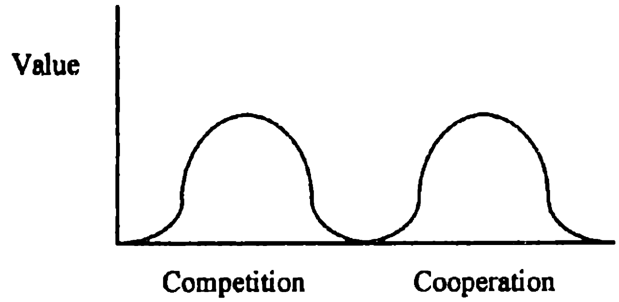

Figure 3-4: Bipolar Model of Contracting

cost plus award fee (CPAF), firm fixed price (FFP), negotiated contracts, competitive bid contracts, and "fly before buy" contracts. These contract types describe the various kinds of relationships that are trying to be established. The relationships can be adversarial, arms length, cooperative, partnerships or teams. Yet, Bacharach and Lawler [Bacharach 1984] and Broedling [Broedling 1987] summarizes the general basis of contracting by boiling down these relationships as matters of either competition or cooperation (see Figure 3-4). Maximum value for the government is achieved when either cooperation or competition is the center of the contracting approach. The degree of dependence that the buyer and seller share is based on the commitment of each party to the outcome and the degree to which the party has alternative sources for producing that outcome. This framework is important for the system architect to understand due to the fact that, not only does he/she need to decide which assets should be developed in-house or in other organizations, but what are the motivating factors that will lead to the best outcome. Practices such as the quantification of non-price factors, the use of variable incentive specifications, and policies that keep the government out of subcontracting decisions all have to be proposed to maintain this delicate balance between trust and verification. While there is no single answer to the best contracting practice, an organization that ignores this fundamental interface will find the contract requiring more attention than the end product.

Finally, the space system architect should recognize the composition of the contractor workforce and ensure that the best products are developed through the diversification of perspectives. Gans and Sterns [Gans 1998] have studied successful research and development institutions and have found that an "ideas market" is essential for the prevention of stagnation in strategically important advanced technology fields. This ideas market is the set of organizations that do not capture value through the production or manufacture of their product concepts, but rather through the marketing of their intellectual property to producers and developers. Ideas markets are created, maintained and grown when information asymmetries exists, the transactions costs of buying and selling intellectual property is low, and the expectations on the intellectual property are well matched on both sides. For the space system architect, Gans and Sterns' concept should be very familiar. The Department of Defense and NASA have repeatedly turned to academia to revitalize programs and generate innovative thinking within their respective organizations. When considering an organizational structure, the system architect should make sure that this ideas market is incorporated into the development.

Leadership

A MOE's diverse nature is one of its strengths, but it is also one of its weaknesses. The broad and complex technical and non-technical issues can overcome even some of the best designs. A common thread in successful large-scale developments has been the presence of a strong program champion and strong program leadership.

The attributes of good program management are found in numerous references (see [Gaddis 1959] for one good example). Program leadership needs to be able to communicate effectively across a number of different cultures, a variety of technical disciplines and reduce complicated issues down to a simple set of ideas that everyone can understand. In doing this, the leaders need to motivate the participants in the program by raising the mission above selfish agendas. Furthermore, program leaders need to value and encourage, within careful bounds, change and dissent within the endeavor. This latter attribute is tied to the leaders' "emotional intelligence" (components of emotional intelligence are self-awareness, self-regulation, motivation, empathy, and social skill as seen in [Goldman 1998]) and represents that intangible quality that many describe as a certain "presence."

Dr. Wernher von Braun was fond of stating his role in the Saturn V program was to pick good people, get them all pointed in the right direction and then "light a fire under them." That statement may be one of the best summaries of leadership: develop a capability, provide a vision and keep everyone motivated to achieving that vision. The architects of many successful systems have understood this value of leadership, and it remains fundamental for space system architectures.

Process Knowledge and Control

The majority of management literature is populated with discussions on program development process knowledge and control ([Fortescue 1991] and [Armstrong 1995]). Its role in the system architecture process is regularly seen as a somewhat obvious result of a large development. While a MOE will eventually develop the tools to manage its business, some comments about the information and controls needed to operate large-scale developments are appropriate.

The Apollo program is reported [Bilstein 1980] to have turned a corner toward success when it issued "Directive No. 9." This directive instituted formal management approaches to baseline definition, performance measurement and analysis, problem resolution, management reporting systems, and the creation of a program control center. Each of these tools for obtaining knowledge about the development process can be found in other forms in other programs. The "one-pager" is another information management tool that has received a certain amount of attention in recent years [Schoenfelder 1997]. This method, which also takes the form of weekly activity reports from managers, places all the information about cost, schedule and performance that senior managers need to see in a single page. These two approaches, the Apollo program information center and the simple one-pager, bound the amount of information processing needed for a program. By these two examples, it should be clear that the information has to be made the right size for a program. A system architect needs to develop those structures that insure that information about the development process flows to all levels of MOE management.

Process control, which results from process information, usually takes the form of the phase/gate system of formal design reviews that represent major program milestones. While a system architect may quickly identify this structure as key to a program's success, program control also covers several areas that are not covered in that process. Configuration management and working toward a well-defined baseline is a structure that any large-scale program must create or it will rapidly lose control of the development. Change control boards can be created to assure that the "right" people are in the room whenever decisions are made to move the design in a proposed direction. Yet, neither the phase/gate approach nor the controls on the configuration lie at the heart of a development. Resource and schedule controls act as the very center of a development system and a lack of excellent tools in this area will generate trades in cost, schedule and performance that can frustrate and even destroy a program. In fact, the results of a General Accounting Office audit of 940 projects indicated that costs exceeded plan by about 50 percent and the schedules ran over by 33 percent when project management did not devote a significant amount of effort to developing and maintaining cost and schedule management tools [Schoenfelder 1997].

Program Interface Administration

Management of a MOE should contain structures that always recognize the inherent instability of the organization. A MOE has been brought together to achieve an objective, but disruptive forces are often more powerful and compelling than that objective. Forecasting the evolution of the MOE is difficult, at best, and impossible in some cases. In the event that MOE management can foresee the change, the constraints on a large-scale development, once in motion, can be so severe as to prohibit any adequate mitigating strategies. An even worse condition occurs when MOE management are surprised by a change and do not have the time or tools developed to handle this change in the MOE structure. The effect of the recent economic downturn in Russia on the International Space Station is just one example that demonstrates how unstable MOEs are and how damaging a major modification in the relationships within a MOE can be.

A space system architect needs to build in contingency plans for MOE variability and build "off ramps" into the system. Again, turning to the ISS, additional flexibility in the assembly sequence would allow the different members to delay and even change their contributions without significant impact on the overall mission objectives. The partial completion of mission objectives has to be part of a system architect's metric for success in the very unstable MOE environment.

A system architect also needs to recognize the building and maintenance needs of a MOE. By that, it is meant that to develop an efficient and effective MOE, there is a much higher level of coordination, debate and negotiation that occur that are not present in single organization developments. These relationships require a great amount of care and attention on a regular basis. While this is a discussion of the required management function, a system architect might address this requirement by building in additional cost and schedule margin just to account for this interface administration.

3.3.1 Top-level Managerial Functional Requirements

Development within a multi-organization enterprise is only performed when necessity demands it. The managerial system rapidly becomes complex, unstable and cumbersome. However, if the system architect takes some care in designing the managerial system, there is a far greater probability of success. Based on this research, the highest level requirements are:

FR_1 = Provide the complementary assets needed to produce the system,

FR_2 = Produce a strong leadership culture,

FR_3 = Develop systems for obtaining information about the development process,

FR_4 = Provide for managerial constraints that control the development process,

FR_5 = Establish program interface administration techniques

While these *FRs* may not have readily apparent sets of *DPs*, Chapter Four provides a discussion of managerial issues that face the human exploration of Mars. That discussion should make some of the tools of AD more clear.

3.4 Technical Complexity and Risk Factors

Risk can be defined as the range of impact to the performance of a system that results in the realization of an uncertainty. While uncertainty and complexity, as discussed in Chapter Two, are often interrelated, it is important to note that a risk has an additional component: consequence. A system may be highly uncertain in a particular area, but still be low risk due to the consequences of realization of the risk are insignificant. For example, the stability of personal computer operating systems are fairly poor, yet the risk is found to be low due to the fact that a simple reboot will recover all but the most recent data and capabilities.

This relationship between uncertainty, risk and complexity is a central theme for system architects. Spacecraft designer George Low confirmed this when he, in his own way, discussed the validity of the Independence Axiom [Low 1971]:

> Another important design rule, which we have not discussed as often as we should, reads: Minimize functional interfaces between complex pieces of hardware. In this way, two organizations can work on their own hardware independently. Examples in Apollo include the interfaces between the spacecraft and the launch vehicle and between the command module and the lunar module. Only some 100 wires link the Saturn vehicle and the Apollo spacecraft, and most of these have to do with the emergency detection system.

Eberhard Rees, deputy director for research and development at Marshall Spaceflight Center, likewise stated: [Bilstein 1980]

> "Even when weighed in the balance against sacrifice of performance, de-

sign simplicity should be strongly favored."

Each of these quotes and numerous others found in [Rechtin 1991] confirm this emphasis on understanding uncertainty and risk.

Axiomatic Design addresses these items through its axioms. The Independence Axiom accounts for the ideas of fault propagation and isolation, while providing the designer with the opportunity for better quality production through an explicit definition of a functional requirement for an individual piece of the system. In this way, the Independence Axiom addresses both the nature of uncertainty and consequences of a risk. Yet, the more fundamental way that Axiomatic Design addresses risk is through the Information Axiom. The uncertainty of the system is reduced through the use of this axiom, and, thereby, amounts to an overall minimum risk position.

While Axiomatic Design has the ability to address risk factors in a system, the quantification of risk is often a very complicated issue at the architectural level. Three methods are discussed here to provide a background from which system architects can view their specific issues. The first method, the "notional" approach, can best be characterized by work performed in the field of technology innovation. Abernathy and Clark [Abernathy 1985] present the concept of the transilience map that describes the relative position of a technology (and its inherent development risk) to other technologies. In Figure 3-5, the map has axes that describe a private sector orientation, but different axes, such as technology and organizational capability, have also been applied to this mapping process. With this approach, one can methodically approach the types and relative difficulties in developing a particular system. Other notional approaches include the technology S-curves [Christensen 1992] and the use of technology readiness systems that have been developed within the Department of Defense and at NASA. A different approach is to simply survey expert opinion. Some investigators have found this to be valuable and references on utility theory and Analytic Hierarchic Processes have been provided earlier. It is rare that this method delivers a great deal of satisfaction to either architects or their supervisors. Finally, there are the more formal methods of probabilistic risk assessment and fault tree gen-

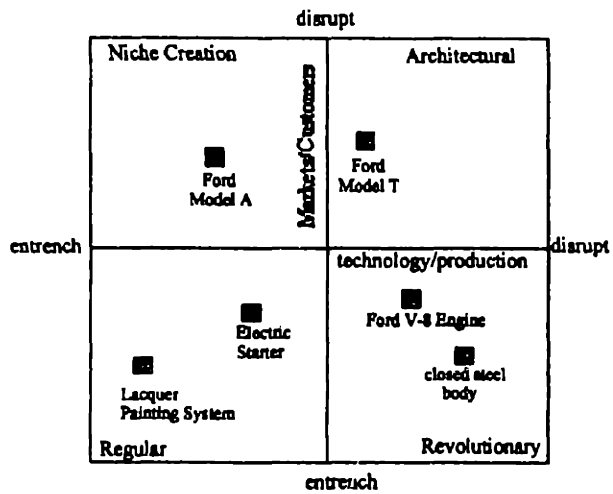

Figure 3-5: Example of a Transilience Map

eration. Unfortunately, these tools improve with fidelity as the design moves toward greater detail. Some work has been done on an architectural level [Merrihew 1996], but the limits of this type of analysis are still present ([Bell 1989] and [Garrick 1988]). In short, it is felt that, at the architectural level, a notional approach to risk analysis is most appropriate with more detailed methods being reserved for detailed analyses.

Before leaving a discussion of risk, the importance of testing to risk reduction should be highlighted. A system architect should thoroughly understand that testing is the single most important factor that leads to a high degree of reliability. In fact, testing is, in the AD framework, a method for reducing the information content of the system. Yet, technical performance of the system is only part of the story. An Air Force study has shown a correlation between cost and schedule overruns and lack of extensive testing [Reig 1995]. Risk mitigation takes a number of forms, but the system architect should structure a system to contain as much testing, from component testing through system mode testing, as is available in an annual budget.

Chapter 4

Architectures for Human Exploration of Mars

"All the most important mistakes are made on the first day" is a common adage that applies to system architecture. If the best and widest considerations are not given to the system architecture, then it is very hard to recover later in the development. The design of architectures for human exploration, due to their size and complexity, are especially venerable to this failing.

In this chapter, a brief review of the past and current Mars missions are discussed. The customer attributes associated with exploration are examined from available resources. After this discussion, some analysis, based on the previous AD framework, will be conducted on missions of this type, in general, and the specific architectural decision of whether the Moon should play a part in Martian exploration efforts.

4.1 Review of Mars Mission Architectures

Mars mission architectures have been an area of extensive study over the past fifty years. Only with the advent of true rocket capability during the 1950s and 1960s did some of the technological hurdles begin to give way to realistic scenarios. Werner von Braun's *Mars Project* [von Braun 1954] was the first of many mission plans that described how the job could be done with existing and nearly existing technologies. The basic architecture for von Braun's mission was a massive undertaking. A flotilla of ten spaceships would leave for Mars on a conjunction class mission with 70 men. "Landing boats" would land on skis at the frozen north pole and the crew would travel to the equator to prepare for the arrival of other boats. The 449 day stay on the surface would end with a trans-Earth injection using the remaining seven spaceships. While this scenario may seem to be overly complex and expensive, von Braun was working with the known technology of the day and still anticipated many of the problems current designs seek to overcome (e.g., micrometeor impacts, zero gravity affects on human physiology, and the logisitics of life support systems).

As the Apollo Program progressed, NASA began to look beyond the Moon. It sponsored a series of industry studies in 1964 with participation from Lockheed, General Dynamics, and TRW [Industry 1964]. The General Dynamics and Lockheed reports both required nuclear thermal propulsion, swingby trajectories, artificial gravity and the an advocacy of launch vehicles larger than the Saturn V that was under development. The TRW design also has characteristics that may be familiar to those working on current architectures. This proposal recommended aerocapture at Mars, Mars orbital rendezvous, and a crew of six. Each of these missions had short Mars surface stays and recommended the use of artificial gravity to offset the basic unknowns concern the long-term effects of zero gravity.

While study of missions to the Red Planet continued during the 1970s, the next major set of studies were conducted after President Bush's announcement of the Space Exploration Initiative. The 90-Day Study [NASA 1989] and the Report of the Synthesis Group [Stafford 1991] are major architectures that emerged out this initiative. The 90-Day study, a very controversial internal study, defined five reference missions. Each of these missions had a different focus. For example, one of the missions looked at the earliest landing on Mars. Other studies included items as far-reaching as permanent lunar habitats. The missions focused on many of the new technologies that would have to be developed for these kind of missions to go forward and resulted in a widely reported overall cost of $ 400 billion. While the approaches may have been technically sound, the perceived increases in NASA's budget were considered to be far too expensive for many space policy makers. The Synthesis Group, in a similar vein, examined a set of four architectures: an early, quick Mars mission, a mission with a mix of lunar and Mars activities, a program that emphasized a lunar base and a Mars mission, and, finally, an architecture that developed lunar resources for the inclusion in a Mars mission. The missions approach the problem of space exploration from very much the same large infrastructure approach of the 90-Day study. Again, these authors turned to nuclear thermal propulsion and heavy lift launch vehicles as a necessary technology for future development.

The most recent studies have been some of the most creative and detailed studied conducted to date. The architectures that are most regularly considered are Zubrin's Mars Direct architecture [Zubrin 1996] and the Johnson Space Center's Draft Reference Mission (DRM) [NASA 1997]. Zubrin's mission has produced a stir in the exploration community due to its strong emphasis on in-situ propellant development and its strong advocacy. Zubrin's mission is a split mission that sends cargo and crew at different launch opportunities. During the two years that separates the initial launch and the final launch, the cargo on Mars has deployed a propellant production facility that is necessary for the crew to return home. While Zubrin's mission architecture is very similar to the DRM, many within NASA feel that it does not provide the redundancy and risk reduction needed for protecting the crew and the large investments in this type of mission. The DRM uses rapid transits with a nuclear thermal engine, Mars orbit rendezvous and an additional habitat on the surface to provide a more robust and safer mission. Appendix A contains a detailed summary of that mission.

The DRM and its updates, being the most recent and credible architecture in a government-sponsored setting, will serve as the basis of discussion for further analysis of Mars architectures.

4.2 Customer Attributes for Exploration

Why Mars? This is the first question that a space system architect needs to ask to determine the customer attributes (CAs). As mentioned in Chapter 3, this is a particularly difficult question due to the diverse nature of the stakeholders and the rapidly changing landscape of the space policy makers. Several recent attempts, however, have made some progress toward answering some of these questions. In particular, three groups have made attempts at understanding the rationale behind going to the Moon: The Office of Technology Assessment [OTA 1991] study of exploring the Moon and Mars, the Space Policy Institute's Symposium after the recent announcement of the discovery of possible fossil life on Mars [Space 1996], and the Why Mars Workshop [Duke 1992].

The OTA study argues that there are five reasons for the exploration of the Moon and Mars: (1) Return the United States to a preeminent position in space activities, (2) Humans have a fundamental desire to explore, (3) Exploration would improve U. S. competitiveness, (4) Exploration would increase our scientific understanding of the Solar System, and (5) Human exploration would return other indirect benefits to U. S. society. An interesting aspect of this list is its clear mapping to the political hierarchy developed in Chapter 3. This result should not be surprising considering the composition of the study group. This list should be considered a good starting point for further developing customer attributes of government space policy makers interested in human exploration initiatives.

Similarly, the Space Policy Institute's symposium contained the text of a speech by the NASA administrator that clearly reveals the attribute's of the Agency's policy. Dan Goldin, the current Administrator, first cited the need for a vision. This vision was based on a need for understanding the human race's role in the larger context of the universe. In regard to this, he stated that the Origins program (a program to look for other planets and their evolution process) and Mars exploration are different ways of attempting to satisfy the same objective. Secondly, he stated that NASA needs to "develop a credible plan for the President and the American people so we can have a contract with them." Finally, Mr. Goldin stated that there must be an education process by which the American public is educated about the "cornucopia of benefits that would flow from Mars exploration." These are valuable pieces of information. A vision, a plan and an lobbying effort are the requirements from the Administrator. Again, when placed in the context of his responsibilities, these are very much the customer attributes of a manager of a large organization.

The scientific and engineering communities have made their top-level customer attributes known through the proceedings of the Why Mars Workshop in 1992. The attendees condensed their thoughts into five categories (which, happily, are not too different from previous attributes): (1) Understand human evolution and the creation of life, (2) Perform comparative planetology, (3) Provide internationl cooperation, (4) Advance the current space technology capabilities, (5) Provide inspiration to the general public in the area of science and technology. It was from these attributes that the DRM was developed.

Finally, modest attempts have been made to capture public opinion. In addition to the previously cited references ([Logsdon 1997] and [Edin 1997]), the Space Policy Institute also conducted a small survey during its symposium. In that survey, respondents were asked what are the highest priority reasons for exploring Mars. The top reasons for performing this type of mission were for basic science reasons, for discovering evidence of past life and for making progress towards the creation of a permanent Martian presence. While this emphasis on scientific study may be surprising, it should be noted that the respondents were predominantly individuals with graduate degrees. This survey, therefore, only represents a small demographic in a larger population. NASA recognizes this fact and has recently planned two efforts to address that situation. First of all, a Customer Engagement Group has been formed to examine what the public wants, who are the other interested parties, and how best to bring them into the decision making process. The second effort is an initiative by the Exploration Office that is looking explicitly at the public needs with regard to exploration. Using a method that surveys individuals before and after educational materials are provided, the Deliberative Poll technique, developed at the University of Texas, should fill some of the holes in NASA's knowledge about customer preferences.

Appendix B presents a list of customers attributes and functional requirements based on the resources cited above. Two general conclusions can be drawn from this analysis. First of all, the functional requirements are general and do not provide any specific direction for a detailed set of mission designs. This finding can be supported by recognizing the broad differences in opinions within the space community and the very general nature of support from the public at large. An ancedotal example of this finding can be found in the enthusiastic support given to Senator Glenn's flight which was much greater than is typically found for other human missions. Thus, it may be concluded that while there are general attributes that can be derived from existing data, there are some latent customer needs that have not been satisfied or understood. Secondly, the specific functional requirements developed in Appendix B represent a good confirmation of the validity of the generic functional requirements developed in Chapter 3. This result is encouraging and should be emphasized so that lower level decompositions, when data becomes available, can turn to those generic findings for further guidance.

4.3 Comments on Exploration Decisions

Without detailed, mission specific customer attributes, functional requirements can not be fully developed. Yet, even without these items the AD framework can be used to provide some clarity in the decision making process for human missions to Mars.

The functional requirements in Appendix B point to a design matrix that has the most common form of:

$$\begin{bmatrix} \text{P} \\ \text{M} \\ \text{T} \end{bmatrix} \begin{bmatrix} X & 0 & 0 \\ X & X & 0 \\ X & X & X \end{bmatrix} \begin{bmatrix} DP_P \\ DP_M \\ DP_T \end{bmatrix}$$

where P, M, T represents all the political, managerial and technical functional requirements, respectively, and the *DPs* correspond to each of those requirements. This is identical to the form presented for the Apollo Program and highlights the essential nature of large, government-sponsored civil space systems. Civil space systems have mission goals that generally fall fairly low in the hierarchy of political needs. Furthermore, human spaceflight systems currently require large, multi-year budget outlays. Therefore, the design matrix becomes decoupled due to the need to establish the political parameters first. Then, in response to those developed parameters, an architect can establish the managerial aspects. Finally, the technical definition can be produced only after the previous two sets of parameters have been assigned.

The process is best explained through a more explicit description. After a regular poll of the stakeholders in the process is taken, a need for a mission emerges with specific functional political requirements (i.e., value, constituency, cost and trust). With that information, an architect can establish a management system that will support those political requirements. Finally, the technical definition of the mission can be defined with an explicit functional requirement that provides a mission statement that can be further decomposed.

This analysis using the AD framework clearly explains why many human missions to Mars remain unfulfilled while the technology and mission designs have been available for a considerable amount of time. The mission architects have been providing a "technology push," as described in business texts, instead of a "customer pull." Essentially, a product is being developed without knowing if that is what one wants to sell. Womack and Jones [Womack 1996] in their book "Lean Thinking" emphasize this pull philosophy and explain that successful product development relies on the concept of the *value stream.* This stream represents how organizations identify customer value and reduce all extraneous activities that, during the development, delivery and operations, do not enhance that customer value. As an organization improves the identification of customer, relates that to its value stream, produces a flow that allows customers to pull this value from the enterprise, a reinforcing cycle appears that continues to optimize that system and lead to more product successes. The deficit of Mars mission architectures is not in their technical aspects, but can be found in the lack of understanding of the value stream and the enabling structures to support that flow.

4.3.1 Specific Comments on the Lunar/Mars Decision

The Draft Reference Mission (DRM), as stated in Appendix A, represents NASA's current best thinking on a human mission to Mars. Recently, there have been a number of voices within the Agency that have posed the challenge of placing lunar exploration within the larger framework of the DRM. The AD framework can provide some guidance as to whether these requests make some sense.

The design matrix, when augmented with lunar objectives, would appear to be something like:

$$\begin{bmatrix} \mathrm{P} \\ \mathrm{M} \\ \mathrm{T}_{Mars} \\ \mathrm{T}_{Moon} \end{bmatrix} \begin{bmatrix} X & 0 & 0 & 0 \\ X & X & 0 & 0 \\ X & X & X & X \\ X & X & X & X \end{bmatrix} \begin{bmatrix} DP_P \\ DP_M \\ DP_{Mars} \\ DP_{Moon} \end{bmatrix}$$

This is a coupled design and requires redesign. This is not a surprising result and is actually an outcome of one of Suh's theorems. Theorem 5 from his book *Principles of Design* states that "when a given set of FRs is changed by the addition of a new FR, ...the design solution given by the original DPs cannot satisfy the new set of FRs." This result states that looking for ways to place lunar objectives into the original DRM design is a futile exercise. However, this does not mean that lunar exploration and Mars exploration objectives are incompatible. It simply means that a system architecture must always reflect and begin with its top-level objectives.

So where does the Moon lie in an overall exploration initiative that culminates with a human Mars mission? The end of Appendix A provides some technical guidance as to the utility of some key elements of the DRM in human exploration of the Moon. Yet, the real value of lunar initiatives have little to do with the architectural aspects of missions to Mars. When placed in an overall exploration strategy, lunar missions, both human and robotic, begin to include other large and vocal constituencies, and thereby enlarge the power base needed for exploration initiatives. Lunar missions, due to their regular and relatively frequent launch opportunities, can provide incremental political milestones that will provide satisfaction to supporters and develop a measure of trust that currently may be lacking. Obviously, testing of DRM elements may be an aspect of lunar missions, but convincing arguments can be made that most of this testing can be more cost effectively conducted by other means. However, the value of the testing objectives met during lunar exploration should not be evaluated in that sense. Instead, the diffusion of cost elements to programs other than Mars exploration and the lower annual outlays that can be tolerated with a stretched out schedule for Mars exploration should be considered. Internal Aerospace Corporation cost studies, which are partially represented by some data found in [Abramson 1993], demonstrate that spacecraft development programs that extend much beyond six years have experienced significant cost increases. Thus, an integrated architecture of exploration,that includes both lunar and Mars exploration objectives, can result in smaller programs that can be more effectively managed over shorter timelines and can be partitioned into more politically viable pieces. Appendix C makes the case that this type of architectural decision has strong parallels to the Apollo-era decision on rendezvous options.

Chapter 5

Summary

Axiomatic Design is a method for rationally applying two heuristics to any design. In the case of space system architectures, this technique provides the architect with a framework by which the major factors that affect his/her architecture can be exposed and compared. At the highest levels of space system architectures, the customer needs and their resultant functional requirements have a lack of definition that is difficult to handle with purely objective measures. For this reason, fuzzy set theory has been added to the Axiomatic Design formalism so that detailed architectural analysis can be conducted during this top-level decomposition. Fuzzy set theory, when addeed in this way, also permits a more detailed definition of uncertainty and its interaction with issues of architectural complexity.

The highest levels of space system architectures have also been shown to have some unique characteristics. Large, government-sponsored space system architectures must be designed with explicitly defined political, managerial and technical functional requirements. This emphasis on combining these non-technical parameters with the more common technical parameters results in architectures that are more robust to changing national priorities, can more easily be implemented and are more successful in meeting their pre-planned objectives. A generic set of functional requirements in the political and managerial settings have been developed for the unique situation of large space system acquisitions.

Finally, Axiomatic Design has been applied to human spaceflight initiatives. The case has been made that these systems are inherently decoupled and require an architectural decision process that starts with a political analysis, moves on to evaluate the managerial impacts of this political process and, finally, produces specific technical mission designs that satisfies the other two parameters. Without applying this decision making order, a human spaceflight initiative may remain solely a conceptual design. The current Draft Reference Mission and other Mars mission designs lack a first principles analysis of customer needs. Surveys of the general public and policy statements by stakeholders have resulted in only a very few general customer attributes These attributes must be refined by further and regular data collection so that mission specific attributes can be derived. Thus, it should be clear that these space system architectures have finite lives and their applicability changes with shifting stakeholder requirements. As a final piece of analysis, the utility of lunar missions, as part of a larger exploration program that includes Mars missions, was also shown to be beneficial when political and managerial effects are brought into the architectural discussion.

Appendix A

Draft Reference Mission Summary

The Draft Reference Mission, or DRM, is a proposed human Mars exploration architecture developed by the Exploration Office at NASA's Johnson Space Center. This architecture has been developed as a tool that is intended to bring forward commentary and identify key drivers in the development process. The first version, published in July 1997 in NASA Special Publication 6107, has received a wide amount of attention from the exploration community and not a small measure of praise. In the months since that publication, the Exploration Office has made several modifications to their architecture as they move to the next iteration of the DRM. This summary of the DRM reflects some of those more recent modifications. Changes include reductions in payload launch packaging and masses, and the combination of the Mars entry aeroshell with the habitat structure.

Mission Objectives

The DRM's objectives are to conduct:

- Human missions to Mars to verify a way that people can ultimately inhabit Mars.

- Applied science research to use Mars resources to augment life-sustaining systems.

- Basic science research to gain new knowledge about history of the Mars environment.
- Basic science research to search for evidence of past life.

Mission Assumptions

- Limit the length of time that the crew is continuously exposed to the interplanetary space environment.
- Define a robust planetary surface exploration capacity of safely and productively supporting crews on the surface of Mars for 500 to 600 days each mission.
- Define a capability to be able to live off the land including the dependence of creating fuel from the Martian atmosphere and closing the life support loop.
- Rely on advance in automation to perform a significant amount of the routine activities throughout the mission and account for the difficulties of dealing with the the 20 minute communication time lag.
- Assume three human missions to Mars. The initial investment to send a crew to Mars is sufficient to warrant more than one or two missions. Each mission will return to the site of the initial mission thus permitting an evolutionary establishment of capabilities on the Mars surface.
- Use a "split mission" strategy, which sends cargo and crew at different launch opportunities.

Mission Architecture

The DRM has been developed so that crews are taken on a fast transit between Earth and Mars (approximately 6 months), while cargo vehicles use minimum energy trajectories. As a result of the relative planetary geometries, this scenario results in Mars surface stays of 500 to 600 days. While at first glance, this extended stay on the surface may seem difficult and dangerous, it actually provide greater mission security. The mission lenghth requires the designer to create a robust capability at Mars. This robust function at Mars, however, permits aborts to Mars in the case of malfunctions in transit to the planet.

Cargo missions are launched during the first opportunity (i.e., the first alignment of the Earth-Mars geometry). There are two components to each cargo element. There is a propulsion stage and a cargo stage. Each cargo element is launched from Earth on a Shuttle-C/Energia type launch vehicle that has a 80 metric ton to LEO capability. These elements are then docked in LEO to form three separate vehicles and sent on a trajectory to Mars.

The cargo vehicles consists of an Earth Return Vehicle (ERV), a cargo vehicle that includes a Mars Ascent Vehicle (MAV), and the Habitation module (HAB). The ERV is a crew habitat for the trip back from Mars that also contains a fully fueled chemical Trans Earth Injection (TEI) stage. This vehicle is injected into a 1 Sol orbit and remains there through the duration of crew transit to Mars and their surface stay. The second cargo vehicle delivers a propellant production module to the surface of Mars, rovers and the ascent vehicle. The third cargo vehicle, also going to the surface of Mars, delivers an inflatable laboratory and a nuclear power plant. After this vehicle lands, a semi-autonomous operation will be conducted to transport the nuclear reactor approximately 1 kilometer from the ascent vehicle. At this location, it will be activated so that it can begin to produce the oxygen and methane required to launch the crew to Mars orbit where it will rendezvous with the ERV for the trip home.

The crew will depart several months after the Mars-based propellant production activities are completed. The crew will head to the Red Planet in the surface habitat and capture into a highly elliptic Mars orbit. This vehicle will then head to the surface and land in close proximity to the previously deployed assets.

Mission Elements

There is a good amount of commonality in the DRM architecture. For example, the MAV and the ERV both use RL10-class engines that have been modified to burn LOX/CH4. Likewise, the return habitat is a near duplicate of the one that the crew used on its outbound leg. With this being stated, it should also be mentioned that there are some key elements of this architecture that require significant new developments.

Shuttle-C Class Launch Vehicle

The single biggest development hurdle to any Mars architecture is the development of the Earth-To-Orbit capability for large payloads. In an era of smaller spacecraft and smaller launch vehicles, the current development activities do not support a new launch vehicle start. However, the Exploration Office has sought to significantly reduce these costs by turning to derivative launch vehicles that can be rapidly and inexpensively developed. The Shuttle-C system, that would be capable of 80 metric tons in LEO, has been extensively studied and may fall directly in line with the current activities of the Shuttle Upgrade Program.

Nuclear Thermal Engines

The propulsion stage, called the Trans-Mars Injection Stage (TMI), uses three 15,000 lb. thrust NERVA derivative (NDR) engines, which have an Isp of 900 seconds. A shield between the NDR engine and the LH2 tank protects the cargo from radiation built up in the engine. It should be noted that the TMI stage for the piloted vehicle also uses the same basic elements, except it has a fourth engine to provide the thrust needed for the fast transit. An additional interesting aspect of this propulsion system is that it also provides extensive electrical power during the trans-Mars trajectory. This "bi-modal" features provides a unique power-rich aspect to the spacecraft systems.

Inflatable Structures

Inflatable structures may represent the enabling technology that reduces launch mass will providing large and comfortable living environments for the crew. Currently, the Johnson Space Center is designing mock-ups of this type of habitation volume and testing materials that may be used for its development. The International Space Station is also looking toward this technology to increase its on-orbit volume. Initial studies indicate that there may be sufficiently rigid materials and designs that could support the habitation requirements.

Integral Biconic/Shroud

The Mars orbit capture as well as most of the descent maneuver is performed through the use of a single biconic aeroshell. The integrated aeroshell also acts as the Earth ascent shroud and is also part of the Hab structure. This integrated structure is an excellent way of providing a mission critical system in a form that does not require extensive on-orbit verification. It should be mentioned that the descent is not fully accomplished using aerodynamic surfaces. The descent stage also uses the previously mentioned four RL10-class engines that burn for the final 500 m/sec required for successful landing on the surface.

Nuclear Surface Power and ISRU

A 1-kilowatt power source on the surface of Mars is a difficult task without the use of nuclear power systems. In the DRM architecture, the surface nuclear reactor is required to provide enough power to produce propellants for the MAV and cached reserves for the closed-loop life support systems. This In-situ Resource Utilization (ISRU) reduces the overall mission cost due to the lower initial mass required in LEO.

Rovers

While imposing a constraint on all the missions (3 total) that they return to the initial site in order to build infrastructure, mission science objectives will, in contrast, require a diversity of sites to be investigated. Therefore, surface transportation systems will be needed. Rovers that are capable of going on extended expeditions for many kilometers over rough terrain are an essential part of the DRM's exploration strategy.

Potential Lunar Components

The question of whether a lunar mission is helpful in the overall Mars exploration initiative depends on the general utility of DRM elements incorporated in that mission.

Lunar exploration has been fairly limited to date. Even with the recent exciting findings by Lunar Prospector, the Moon still has a number of unexplored aspects. In particular, the far side of the Moon and the polar regions have characteristics that have a great amount of scientific interest.

As the Mercury and Gemini programs prepared the way for Apollo, additional surface exploration of the Moon may provide a testbed for systems critical to Mars exploration. Some examples are cited below so that discussion in the main text may have a richer context.

- Autonomous and semi-autonomous operations could be evaluated during lunar surface activities. Far side activities could be very useful when evaluating the communications systems needed to relay telemetry and science data back to Earth.

- Surface power systems could be tested for robustness under harsh environmental conditions and for long duration performance. Autonomous deployment of the surface system could also be evaluated under rough terrain conditions.

- Rover capabilities would require extensive testing. While most of this testing may be more suitable for Earth-based testing, their deployment and robustness may be better reviewed under operational conditions.

- Nuclear thermal rocket technology must be extensively tested in the space environment. Pulsed tests of the system for transportation to the Moon would provide valuable data while simultaneously providing valuable discoveries on the lunar surface.

- Habitability of crew compartments can also be evaluated in transit to the Moon and while on the surface. Dust contamination of the crew compartment is a particular concern. Mitigating systems can receive an extensive workout on the lunar surface. Other human factors-related items such as long duration spaceflight effects on human physical and psychological abilities will be evaluated as part of the International Space Station program.

- Initial justification and development of the Shuttle-C class launch vehicle can be spread to the lunar program, thereby reducing the allocated costs to the human exploration of Mars.

Appendix B

Customer Attributes for Human Exploration

Given the surveys and public statements referenced in the main text, there are a set of CAs that can be derived for human exploration initiatives. At the highest level, the customer attribute is merely to provide a connection to space activities which is realized in an FR to provide human spaceflight missions. The next lower level is given by decomposing this top-level attribute with the information provided by policy makers, NASA leadership, the scientific and engineering communities and the general public.

The "Level 1" Customer Attributes and Functional Requirements can then be described as:

CA1 = Establish U. S. leadership.
CA2 = Produce valuable science data.
CA3 = Inspire the general public.

FR1 = Produce "firsts" in exploration.
FR2 = Engage the science community in mission planning and operations.
FR3 = Educate and involve the public.

It should be noted that there is also a constraint imposed on this system to stay within current fiscal constraints. This constraint, like all customer attributes, needs to be re-evaluated at regular occasions.

The "Level 2" Customer Attributes and Functional Requirements can also be decomposed:

CA11 = Establish economic leadership.
CA12 = Establish political leadership.
CA13 = Establish technical leadership.

FR11 = Establish extensive commercial contracts and technology transfer support.
FR12 = Engage the international space community and provide direction.
FR13 = Provide "cutting edge" missions that utilize advanced technology development.

CA21 = Produce data on space physics.
CA22 = Produce data on space biology.

FR21 = Involve the planetary and space physicists in mission planning and operations.
FR22 =Involve the biological scientists in mission planning and operations.

CA31 = Emphasize the novelty of efforts.
CA32 = Educate the general public on technical and scientific aspects of the missions.
CA33 = Present information on the space "frontier."
CA34 = Personalize the experience.

FR31 = Provide novel features to all missions.

FR32 = Allocate resources for technical outreach programs.

FR33 = Provide opportunities for visionary discussions.

FR34 = Provide technological and public relations resources that relate solely to the experience of space exploration.

The uncoupled nature of this design can aid in its implementation. It should be mentioned that while each of these can be decomposed further, more detail about the specific needs of the customers needs to be gathered. However, these generic *CAs* and *FRs* do provide a good point of departure for future analyses.

Appendix C

The EOR vs. LOR Decision

The reason some of us wanted EOR was not just to go to the moon but to have something afterwards: orbital operations, a space station, a springboard. LOR was a one-shot deal, very limited, very inflexible.
— Jesco von Puttkamer, NASA-MSFC engineer

By 1969, it was apparent that there was no logical sequel to the lunar landing, and that the agency would have to redeploy its resources in a radically different direction. Had NASA selected earth-orbit rendezvous instead, the lunar landing could still have been achieved and NASA would have had at least a ten-year start on deploying a space station, rather than waiting until 1982 to let contracts for its design.
— Hans Mark and Arnold Levine, *The Mgmt. of Research Initiatives*

The LOR decision, however, had other ramifications for the U. S. space program; it meant that the country would skip the well-laid plans for a manned space station.
— James R. Hansen, *Spaceflight Revolution* [Hansen 1995]

A classic example of comparative system architecture decisions in space systems architecture is the Apollo Program's debate on whether to conduct a lunar-orbit rendezvous (LOR) or an Earth-orbit rendezvous (EOR).

The very famous and powerful German rocket team, led by Dr. Werner von Braun, strongly favored the Earth rendezvous option. In this option, a large rocket would lift a payload into low-Earth orbit where it would rendezvous with a previously launched payload. These attached pieces would then head to the Moon. The assembled spacecraft would descend to the lunar surface, support crew activities on the surface, and then return the astronauts to Earth where reentry would be conducted in the standard capsule reentry format. The EOR design would require the development of a launch vehicle even larger than the Saturn V, called the Nova, to execute its mission.

An engineer at NASA's Langley Research Center, named John Houbolt, headed the other LOR decided that a better design was to launch the assembled spacecraft directly into orbit, break that spacecraft into two pieces at the Moon, and only descend/ascend with one piece of the spacecraft. The benefits of this design were that it only required one Saturn V launch to produce the necessary on-orbit capabilities to conduct a mission to the Moon.

Many individuals believed that this lunar rendezvous option had far too many uncertainties to be attempted. At the time of the decision (1961 - 1962), rendezvous was an unknown quantity. Yet, in its defense, NASA was also experiencing regular failures in its launch vehicle program and one launch sounded very attractive when compared to two. Furthermore, the LOR architecture had many of the technical parameters (less fuel, only half the payload, better testing partitions, and somewhat less new technology) in its favor.

It finally came down to a very large meeting on June 7, 1962 at the Marshall Spaceflight Center where both sides of the rendezvous argument presented their cases. During previous discussions on the subject, many of NASA's most powerful individuals were convinced of the value of the LOR approach. Yet, at this meeting, Dr. von Braun, the greatest advocate and beneficiary of the EOR approach, threw his considerable weight behind LOR. The architectural decision in this case had a clear component that involved the technical merits of each design, however, one non-technical factor may have played a crucial and decisive role. In this case, several authors and participants in the decision [Hansen 1995] have stated that the schedule pressures made the lunar rendezvous option more attractive in the final analysis. Ultimately, the Apollo program had to meet President Kennedy's political objective of placing a man on the moon and returning him safely within a decade. George Low, the director of spacecraft and flight missions, reinforced that idea when he stated in 1982 "that had the Lunar Orbit Rendezvous not been chosen, Apollo would not have succeeded." Obviously, given the success of Apollo, the architectural decision was sound.

However, it is interesting to examine the same decision if the schedule pressure was removed (as it is currently) or expanded to permit less ambitious development. The political environment might have tolerated the large on-orbit and launch vehicle assets needed to build a long-term NASA strategy. While this can only remain a conjecture, it provides an interesting context for debates concerning another large human exploration program such as a mission to Mars.

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