Uncertainty

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Framework for understanding uncertainty and its effects[*]

Many types of uncertainty affect the design and operation of space systems. Mature techniques exist for some classes of uncertainties, e.g. rolling up component reliabilities to calculate system reliability, and mitigating problems with redundancy. Techniques are emerging for many other classes of uncertainty, e.g. budget and policy instability and the effects of non-collocated teams during design. Uncertainty is not always a negative to be mitigated; robust, versatile and flexible systems not only mitigate uncertainties, they can also create additional value for users.

The current environment of rapidly changing technologies and markets on the commercial side, and rapidly changing technologies, threats, needs, and budgets on the defense side, has created a need for better understanding of these classes of uncertainties and their effects on complex airspace systems. This problem is recognized at a national level, and "robust", "flexible", or "evolutionary" systems and designs have been called for. Unfortunately, tools for handling these classes of uncertainties are immature, and methods for flexible or evolutionary designs are in their infancy.

The wide range of types of uncertainties and possible responses to them make unified discussions of the problem difficult. In particular, discussion of desired advanced system characteristics such as robustness, flexibility, and adaptability is plagued by poorly defined terminology. This difficulty is particularly acute when teaching both the basic problems and the emerging techniques to students of complex system design. As an aid to discussion and teaching, a framework is presented in Hastings and McManus. It includes an important set of definitions for the desired advanced system attributes.

In this chapter, uncertainty, its relation to risk, current practice in the US space industry, and the mitigation of some classes of risk through trade space analysis and tools borrowed from finance will be explored. The next two chapters explore the use of system

[*] Text in this section modified from Hastings, D., and McManus, H., "A Framework for Understanding Uncertainty and its Mitigation and Exploitation in Complex Systems," 2004 Engineering Systems Symposium, MIT, March 2004.

flexibility to not only mitigate negative uncertainties, but to exploit the positive side of uncertainties. Finally, techniques for quantifying and mitigating a difficult class of uncertainties–those due to policy decisions and changes–are explored.

Concept/Sources of Uncertainty

Uncertainty is the inability to specify something with precision. Obviously, this can pose a significant problem when making a decision, whether designing an engineering system or planning public policy. In an analytical context, uncertainty can arise about specific quantities, or about the models meant to represent system behavior. Fundamentally, there are four sources of uncertainty:
1) Incomplete information
2) Disagreement between information sources
3) Linguistic imprecision
4) Variability

Incomplete information is when a factor in a decision or model simply is not known. Sometimes this can be resolved (through research, inquiry, etc.), but not always. Some factors are necessarily uncertain because they are indeterminate – this applies to all future developments, (e.g., the US defense budget for the year 2050). Other times, though technically determinate, a factor may not be practically measurable (e.g., the number of people in China sitting down at this moment).

Uncertainty can also arise from disagreement between information sources. This disagreement itself often is often caused by the sources themselves having incomplete information (e.g., reports about the Soviet Defense budget during the Cold War). It may also arise from different assumptions or perspectives.

Linguistic imprecision is extremely common. Because little precision is required for general communication, people often fall into the habit of using imprecise terms and expressions. Unfortunately, when used with others who are not familiar with the intended meanings, or in a setting where exactitude is important, this imprecision may result in uncertainty.

The fourth source of uncertainty, variability, simply refers to change. Parameters which change over time (for whatever reason) can give rise to uncertainty. Note that some of this variability may be physically based (for example, based on quantum mechanics) or come from the very complex nature of a physical system (for example, the solar wind fluctuates based in part on the internal dynamics of the sun) or may come about from human agency (the development budget for space system often changes from the anticipated budget due to the changing political forces from year to year in the Congress).

Clarity Test/Empirical Uncertainty

The most widely used formalism for classifying uncertainty is probability. In order to be meaningful, any probability, classical or Bayesian, must pass what is known as the c*larity* *test*. To conduct the clarity test for a given probability, imagine a clairvoyant who knows all, and ask yourself whether such a person could either say unambiguously whether the event has occurred, or could give an exact value. Although this may sound trivial, it forces the necessary clarity for the probability to be meaningful. For example, "What is the price of gasoline?" does not pass the clarity test. This would have to be refined to something like "What was the price of gasoline at the Shell Station on Mass Ave in Cambridge at noon on January 4, 2001?" Only if it passes the clarity test is a probability worth trying to determine.

Let us define *empirical* quantities as measurable properties of real world systems, which must pass the clarity test. We can now discuss uncertainty in empirical quantities, which can arise from seven sources (expanding on the sources of general uncertainty, above):
Statistical variation
Subjective judgment
Linguistic imprecision
Variability
Inherent randomness
Disagreement
Approximation

1. Statistical variation: Arises from random error in direct measurements of a quantity because of imperfections in measuring instruments and techniques.
2. Systematic error and subjective judgment: Arises from biases in measurement apparatus & experimental procedure as well as from key assumptions by the experimenter.
3. Linguistic imprecision: As described above. For example, phrases such as "fairly likely" and "highly improbable" give rise to uncertainty. Defining something so it passes the clarity test should get rid of this.
4. Variability: When there is a natural frequency distribution associated with a variable, such as the weight of newborn children in Washington, DC over a year.
5. Randomness: Describes quantities which must be viewed as random. One type of randomness is inherent: for example, in principle (specifically the Heisenberg Uncertainty Principle), the position and velocity of an electron cannot be known simultaneously. There are other quantities that although not technically random must be treated as such, because we cannot compute them accurately enough (e.g., weather prediction is very sensitive to initial conditions).
6. Disagreement: arises from different technical interpretations of same data, as well as from different stakeholder positions in the outcome.
7. Approximations: Examples include numerical (finite difference) approximations to equations and model reduction by approximation (e.g., spherical cows).

A Taxonomy of Uncertainty

For aerospace products, a useful taxonomy of uncertainty is the following:

Development Uncertainty

Political Uncertainty – development funding instability
Requirements Uncertainty – requirements instability

Development Cost Uncertainty – uncertainty of staying within budget
Development Schedule Uncertainty – of staying within schedule
Development Technology Uncertainty – uncertainty of technology performance

Operational Uncertainty

Political Uncertainty – operational funding instability
Lifetime Uncertainty – uncertainty of performing to requirement in a given lifetime
Obsolescence Uncertainty – uncertainty of performances to evolving expectations
Integration Uncertainty – uncertainty of operating with other necessary systems
Operational Cost Uncertainty – uncertainty of operational cost targets

Model Uncertainty

Physical Uncertainty – Use of finite physical models
Numerical Uncertainty – Use of numerical approximations
Simulation Uncertainty – Use of finite simulation tools

It is often necessary to think through all these uncertainties as aerospace products are designed.

Risk and Uncertainty

It is important to note that risk and uncertainty are not synonyms. Uncertainty can have an upside and a downside. Risk is always associated with the downside of uncertainty. The notion of risk is basically a combination of two concepts: probability and severity. That is, we decide how risky something is by asking two questions:
How likely is this to happen? (probability)
How bad would it be if this did happen? (severity)

Before going further, let us clarify a few terms. A *hazard* is anything potentially costly, harmful, or undesirable. Hazards lead to risks. The connection between hazard and risk is an *event* – a situation in which someone/thing is exposed to the hazard. It is important not to confuse these terms. A pot of boiling water is a hazard, since it could cause harm. How risky is it? We cannot say, without information about who/what is exposed to it. If we specify an event, such as a person bumping the pot (and getting burned), then we can assess the probability and severity, and from these the risk (note that both are required; either alone is insufficient, i.e., uncertainty does not necessarily mean risk).

Risk can be assessed either quantitatively or qualitatively. If both the probability and severity can be quantified, the risk is simply the product: risk = probability * severity. For example, if the probability of a computer server "crashing" in a 24-hour period is 10^{-6}, and if the cost of a crash is estimated to be $2,000,000 (for lost revenue while the system is down, plus repairs), then the risk of relying upon such a server is about $2 per day. This could be compared with the cost risk of an alternative.

Assessing risks is not always straightforward, however. The probability or severity of an event may not be known (e.g., the probability that your car will break down tomorrow), or not agreed-upon (e.g., the severity of global warming). Many risks may be associated with a given hazard. Risks associated with a complex system, such as a nuclear power plant, may involve long chains of events. For all these reasons, deciding exactly what to include, and how to treat it, can be difficult.

Finally, there are many different types of risk – as many as there are values that can be threatened. Among the most prominent types are safety, cost, schedule, technical, and political risk, and most decisions involve more than one of these. An important part of risk management is deciding which types of risk to assess, and how they should be compared to make decisions.

We now turn to space systems specifically. The insightful report by the Young panel showed the effect on two space systems of requirements and cost uncertainty. As the report shows, the uncertainty and the subsequent decisions to handle the associated risk have had negative consequences on both systems. In the next section, we explore via a case study, how current space system designers deal with uncertainty. This case study is discussed at more length in the thesis by Walton.

Case study of Uncertainty analysis in conceptual design in space systems

Introduction:

The significance and presence of uncertainty is something that developers of space systems cannot escape. This section explores this fact. How indeed do designers in industry deal with the presence of uncertainty in early conceptual design? Four sites were investigated that represent a cross section of the space systems development industrial base as seen in Figure 1. The organizations interviewed in the cases serve commercial, civil and military customers. 26 individuals were interviewed in total at the sites whose functions were tied directly to conceptual design (conceptual designers, directors for advanced development) and were intimately aware of the role of uncertainty in conceptual design (risk practioners and project management).

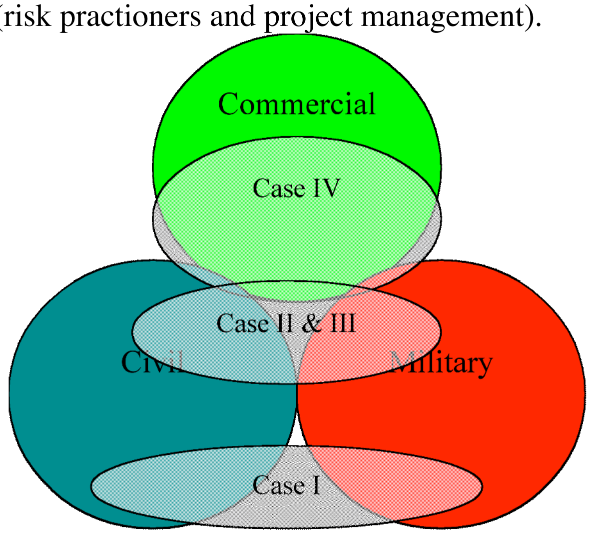

Figure 1: Cases along sector lines

The presence of uncertainty has classically been treated as the necessary evil that is embedded in the margins of design and has been done so through predominantly qualitative means. The results of this process have created the possibility of problems creeping up in the later design stages. It therefore leads to the question of: Can these uncertainties that exist in early conceptual design can be better understood? The answer that comes out is a definitive yes. But as much as the answer may be derived, how should such an approach be possible to implement.

A final note is that the qualitative analysis presented here results in findings that are, in general, local and contextually bound. Multiple perceptions of the same events are expected and acceptable, which can often be difficult for schools of natural science that seek single generalizable suggestions.[i] Nonetheless, the overarching themes and challenges observed are of significant importance and direct relevance to the overall success of this research as these sites represent a significant fraction of the organizations focused on space systems development.

Case 1 [6 Interviewees-Group]

The first case focused on conceptual design studies for both military and civil space system projects. These conceptual design studies are done using dynamic real-time techniques that have become more common across the industry. Through the use of collocation of experts, the customer and a team leader, amazing progress and consensus on conceptual designs have been demonstrated. Of course all the work for the design studies are not completed in the collocated team collaborative sessions, but instead a great deal of upfront model building, planning and discussions with the customer enable the sessions.

The conceptual design approach adopted by this site leads to some interesting aspects of design concurrency and customer feedback that can be achieved. There were two distinguishing features of this site that should be brought out and explained that differentiate it from the other cases.
Close involvement with the customer - the continual feedback and presence of the customer is an attribute that isn't found at the other sites. With this continuous informal contact, customer acceptance of uncertainties can perhaps be better understood and explored.
Study phase of conceptual design – very early stage of design characterized by uncertainty in everything including what the customer wants.

The conceptual designing that is conducted in this environment suffers from perhaps the most uncertainty due to its very early relation to the overall design process. With the experience of conducting as many as twelve architecture analyses for a customer in an effort to explore the tradespace, this exploration is only limited by the capability of the tools and time that the customers and designers have to expend. At this stage of development, the customer is often not sure what they value and what they need.
With regards to uncertainty analysis in early conceptual design, most analysis is done on a qualitative basis and through a method that resembles an ad-hoc uncertainty assessment, where each subsystem and system engineer reports to the customer what are the greatest sources of uncertainty in their purview, including some estimate of a likelihood and impact. From these individual sources of uncertainty, the highest area(s) are sometimes brought to the discussion of architecture evaluation and pursuit. It is clear that there's no formal responsibility for the system/interface level uncertainties in

the design, and further there is no means of aggregating individually identified uncertainties

Although the technical uncertainties are dealt with in this non-aggregate, individual way, the cost uncertainty is approached from a different perspective because it is handled by one individual's responsibility. Because statistical models provide the costing for the system, the team can quickly identify the historical uncertainty of previously developed systems from the approximation curve fit statistical model they are using to cost the proposed system. In this way a quantitative estimate of uncertainty can be given to the customer in terms of cost. The estimates of cost are generally calculated using mass and power properties of spacecraft, estimations of software complexity guidelines of code cost estimations. As a rule of thumb, the 50^{th} percentile of the cost distribution is presented to the customer (but note what the Young report said about this).

The evaluation of multiple concepts (as many as twelve) for customers is unique with respect to other sites. This is not to say that other sites don't explore the tradespace, as will be discussed. Instead it shows that the exploration was one in which the customer was not involved, in general.

Ideas of any formal risk management process in early conceptual design don't exist at this site. Instead, at this stage of the study the process of uncovering uncertainties and risks are the main focus. A further hindrance to any risk management is the over-the-wall handoff that is typical of this study phase in aerospace conceptual design. Once studies and conceptual designs have been explored at this site, the end product is generally a report of some sort that brings out the conclusions of the analysis, the trades that were made, and the recommendations of the team. The majority of the analysis and models are not available, however, following the conclusion of studies. The post-study relationship becomes one that is primarily contextual in assisting any downstream realization of the project.

From discussions with individuals at the site, it is clear that they would welcome methods for looking at uncertainty more holistically in early conceptual design. One interviewee imagined a "risk station" could be incorporated into the concurrent designing environment to fit in with the current process.

Case 2 [6 Interviewees-Group]

The second case we explored included an organization that in contrast to the previous case was under contract to design and build the conceptual designs they worked toward. This was a fundamental difference that distinguishes some of the characteristics and the interests of the second (and remaining) case over the first. This fact puts uncertainties into the economics of the company and therefore one cold argue should be more visible in the end analysis.

Primarily a defense and civil space systems development contractor, the programs that are found at this location tended to be very unique, advanced, high cost and having lengthy development times. The effect of uncertainties on programs from the company perspective were definitive in terms of their prioritized impact on schedule, cost and technical aspects of the program. It was clear that although this is the predominant priority, the order might switch depending on stakeholder perspectives.

Individuals at this organization found that uncertainty analysis in early conceptual design would be a very useful in the pre-proposal and proposal phase as the trade space is being explored. The largest source, according to the consensus of interviewees at this site, were those arising from requirements instability-the ability to understand what the system needs to do. From this, they see a challenge to not only understand the uncertainty in a system that is developed under constant requirements, but also one that exists in a more dynamic customer environment. It has therefore become a major challenge for them to achieve a forward looking/anticipatory strategy that enables real foresight into potential outcomes in an uncertain environment in addition to the current approach of dealing with uncertainties as they arise.

Facing this dynamic environment of evolving requirements, it appears parallel path development would be common. This is more the exception than the rule as it applies to design though. One example of parallel design paths explored was given as it applied to a major component design. During one development project three hydro pumps were carried through design until prototypes had been developed and tested and the uncertainty had been reduced to a level acceptable to make a decision on which variety to choose.

Case 3 [9 Interviewee-Individual]

The third case looks at conceptual design at an organization that works predominantly with government customers-military and civil- to design and develop space systems. This site, much like that in case two is focused on one-off, highly advanced space systems that have cycle times that are generally much longer than that of commercial systems.

Like the space systems developed in the previous cases, the systems that are designed at this site represent some of the most advanced technology. There were two main groups that were interviewed at this site, those working on military systems and those working on civil programs. Although the two reside at the same location, it was clear that the treatment of uncertainty for the different customers did differ. The military programs suffered greatly from requirements creep and the uncertainty of operational issues that require real-time support and information delivery to the warfighter. In contrast, the civil programs were hampered by the risk aversion of the customer due to the high visibility of space missions.

Closely related to the topic of uncertainty was the notion of value about which information is uncertain. Utility and value were brought up in nearly all interviews as being a key aspect of understanding how early conceptual design was carried out and how uncertainties were thought of. One example was the case of a proposal for an advanced system whose design tradespace was fairly well understood, but the customers definition of value, or “best value”, was not well known

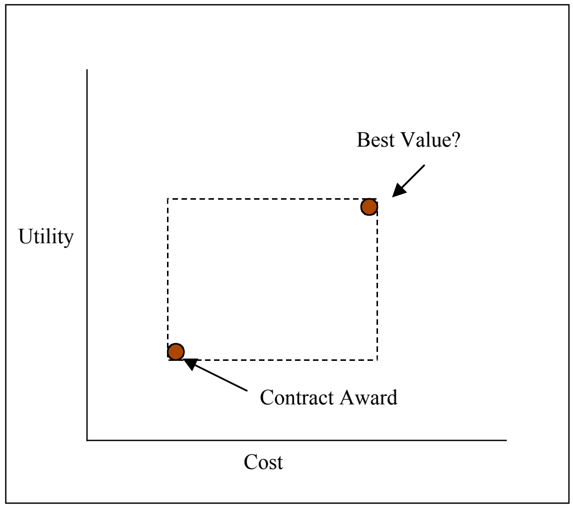

Figure 2: Government Contractor Perspective

Figure 2 is used to represent this situation. The dashed line represents the envelope that the contractor believed the design should fall within and further believed from the customer that the "best value" design in this program's case was maximizing utility of the mission given a capped budget. They later found out after the award was given to a competitor that the customer was far more concerned with minimizing cost and just meeting minimum utility levels. It was the interviewers belief that the customer could do a better job to make those types of trades more explicit and increase the possibility for dialogue. He did cite that the customer communication was dependent on the different customers. For example, on one mission it was clear that the Air Force was seeking the highest utility for a $400M budget.

Pre-proposal and proposal efforts at this site have "cost the company 10s of millions of dollars if not hundreds and can be as long as a two year effort." During this time the trade space is explored and the customers perception of value is extracted along with the criteria for proposal selection might be. Uncertainty analysis during this stage of design is used to place margins on different characteristics of the architectures. One program example was discussed that telling the truth about the uncertainties of the system led them to lose a competitor whose proposal they viewed as a paper study without adequate margins. This places uncertainty analysis in a juxtaposition where the analysis may in fact work against winning a proposal.

When discussing the issue of pursuing parallel options, one interviewer cited that he did know of instance where a customer did retain multiple system level designs because they were attracted by a advanced technology system but were not comfortable with it as a single path so they carried another contract with a less advanced concept as well. However, he added that in terms of one contractor offering options customers adopted the position that "we didn't allow you to propose option". Instead of this position, the interviewee shared that his ideal proposal would include options in much the same way as automobiles carry options packages where "the customer can choose the barebones option or accept all the bells and whistles or anything in between".

Sources of uncertainty can come from anywhere and at this site many of those commonly overlooked were brought out including uncertainties associated with critical skills resources and the supplier base. The consequences of both can be significant, for example drawing out the schedule and technical risks in the case of lack of critical skills. The relationships that different job functions have with respect to uncertainty are significant to discuss. There were some different interpretations of the interaction between concept designers, risk practioners and program/project management and uncertainty. However, the differences can best be characterized as follows: conceptual designers are generally focused on subsystem margins to cover uncertainties but have the greatest knowledge of where internal uncertainties arise, risk practioners are interested on abstracting higher level of the architecture to address maturity or interfaces, and PMs have a high system level focus, like the risk practioners, but are also trying to budget and reign in the conceptual designers to the point of failure in addition to factoring in external uncertainties.

The greatest sources of uncertainty at this particular site were found to be uncertainties in requirements, funding, and critical skills. It was pointed out that the requirements uncertainty arises not just from the customer though, the internal requirements flowdown of customer requirements provided as much of the uncertainty in the end.

Table 1: Military and Civil Sources of Uncertainty in Conceptual Design

Source of Uncertainty	*Number of Interviewees Citing the Source in Top 3*
Requirements	8
Technical	6
Funding	4
Produciblity/Supplier	3
Critical Skills	1
System Integration	1
Political	1
Schedule	1

The formal risk management process of this site is primarily qualitative, but appears to be the most formal of the approaches seen elsewhere. A rule of thumb of 8.5% of the development cost was given that is typical in budgeting risk management and mitigation. This information serves as a useful jumping off point in justifying savings that risk management can result in.

Case 4 [5 Interviewees-Individual]

The final case bridges the gap to a predominantly commercial space systems design and development operation. The interesting distinction between commercial and government approaches to space systems development and the role of uncertainty in early conceptual design is brought out in this case.

This site is a leading developer of commercial space systems and the culture in place is far more acclimated to the commercial customer than that of the military customer. For the most part, the space systems that are sold from this site are direct derivatives of previous developments. Common bus platforms are used to lower costs and speed up delivery time to the customer. From a commercial standpoint this is a very effective approach, as most communication satellite are not pushing the envelope of performance, instead the customers are in general satisfied by the evolutionary advancement of the technology. This is in sharp contrast to the cultures of the first three cases that rely heavily on military and civil customers who are often looking to advance the state of the art.

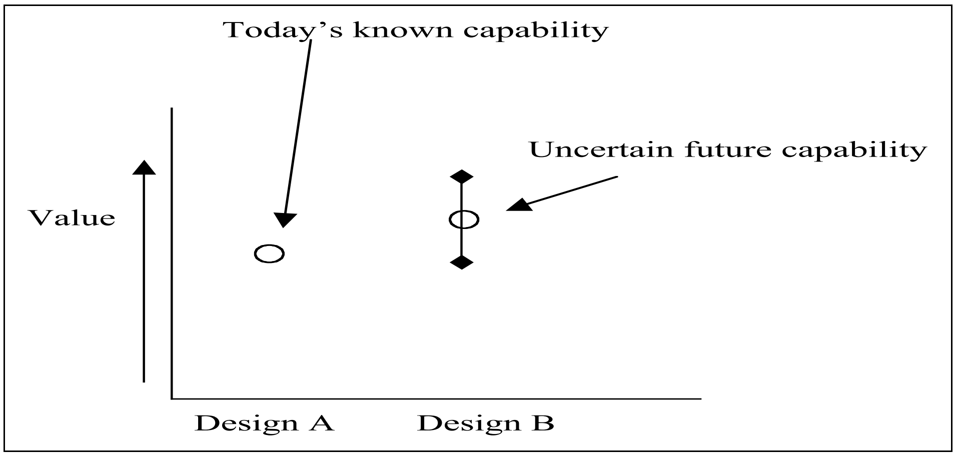

Figure 3: Commercial Contractor Perspective

Figure 3 shows the common perspective of commercial goals in space systems. In general, there is no urgency to jump to the next uncertain future capability if today's capability is well known and satisfies the needs of the customer. This perspective results in two things. First a much slower evolution of space systems in the commercial environment and second a conceptual design effort that is much faster and involves little trade space exploration.

With this condition, it became readily apparent that the amount of individual satellite conceptual design for each customer's satellite is far less than efforts for government customers. Having said this, it also becomes clear that the role of uncertainty on the commercial customer programs is not as significant as on brand new space system developments. Of course there are areas of the system that carry some uncertainty, like new components or the stability of the customers cash flow or the integration of a payload with the platform bus. Instead of focusing on the current platforms development and sales, the area of the site that deals with new platform development serves as a jumping off point for investigating uncertainties in early conceptual design.
Developing a new communication bus platform is comparably complex to many of the government programs observed at the other sites. Further the uncertainties that exist in launching a new platform are substantial, as they are trying to develop platforms that will not satisfy one customer, but many customers and that will serve as a backbone of sales and will be competitive with other companies' platforms for some period of time.
An insight that arose from this site was the use of, what is referred to as, *handover books*. These books are created during proposal phases of development and are used to

document the rationale of the decisions involved in the proposal. As is often the case, those who work on the proposal may not be involved in the later phases of design and usually their tacit knowledge is not captured. With handover books, risks and uncertainties are documented for the design team. The motivation for the books was experiences with "unexpected" surprises that would arise in later stages of design after the proposal team had moved to other projects.

Table 2: Commercial Sources of Uncertainty in Conceptual Design

Source of Uncertainty	*Number of Interviewees Citing the Source in Top 3*
Requirements	3
Schedule	2
Produciblity/Supplier	2
Critical Skills	2
System Integration	1
Technical	1
Inadequate Review	1

Overarching Themes and Challenges from Case Studies

This section summarizes some of the crosscutting themes and insights that have been uncovered from the cases. The themes represent important implications as research evolves and contributions are made to improve the conceptual design effort and the quality of knowledge that is gained from the effort.

Uncertainty in Conceptual Design: This is perhaps the most significant of the themes as it applies to contribution of any research that might be conducted. From the four cases it's clear that the role of uncertainty in conceptual design is significant; it can guide decisions or it can be punishing if not identified. The ever-present existence of uncertainty makes the topic very difficult to capture even qualitatively, but deep interest is present in the industry for evolving perspectives on how identification and even quantification might be done more easily.

Risk Assessment/Management: This phrase best reflects the immediate thoughts and implications of uncertainty in the industry. Risk assessment and uncertainty analysis are indeed closely related, and therefore the analysis would be remiss to exclude the risk assessment/management that is being carried out, if any, during conceptual design. From the four sites, it became clear that the role of risk assessment/management is not a major effort in conceptual design and by and large does not enter the effort until later stages of design.

Dynamics of Decisions: The concept of decisions being made on uncertain information is driving this theme. It is clear from previous research that a great deal, up to 80%, of the space system costs are being committed early in conceptual design with very uncertain information. Therefore, the current process of decision making is important to the overall impact that this or any research on uncertainty in conceptual design could have.

Barriers to Change: This theme is important to discuss as it guides how research may or may not be accepted in different organizational cultures or processes. It can provide a great deal of guidance on the how and when question of implementation of the research, i.e. how uncertainty information should be represented, when the analysis might fit best into the conceptual design process at different sites.

Advanced discussion of uncertainty

In this framing paper, we have argued that uncertainty is a central element of the design of space system architectures. Note that there is nothing in that sense unique about space system architectures. Space system architectures are one type of complex engineering system. DeNeufville argues that many types of engineering systems are subject to large uncertainty and that the developing theory of real options allows the ability to associate value with the uncertainty in a way that allows contingent decisions to be made. Panetta carefully distinguishes where risk should be managed in complex space systems from an analysis of how it is actually done.

We have argued that while some types of uncertainty arise due to linguistic imprecision, much uncertainty arises due to human agency or is based in irreducible statistical variation. The concept of human agency as a form of uncertainty is further explored in the paper by Hastings, Walton and Weigel. It is argued in this paper that since attempting to control human agency is an exercise in futility, the uncertainty induced by human decisions must be treated as an irreducible uncertainty (like the uncertainty principle in quantum mechanics). This idea that human agency constitutes a fundamental type of uncertainty is well explored in Zuckermann.

In a paper by Thunnissen, the uncertainty in space system design due to statistical variation is explored. He shows convincingly that the traditional approach of carrying "rules of thumb" in conceptual design may give both overestimates and underestimates of the true statistical variation in the design of a pressure vessel on a space system. This indicates that these "rules of thumb" should be treated and used with great care and may not be that useful to an appropriate space system design. For example, the well known rule of thumb that says that at PDR, the margins should be 30% may not be appropriate.

Yet another source of uncertainty in the design of a space system architecture is due to the nature of the team enterprise chosen to execute an actual design. This is explored by Garber and Pate-Cornell. They show that that choosing geographically dispersed teams to design and build a space system introduces risk into the design. In order to minimize the risk, the boundaries between the teams must correspond in some natural way to the boundaries in the space system architecture and of course to the competencies of the teams. In this paper they develop a detailed model that allows a designer to assess the risk and margins associated with his or her management choices. A well-known example of where this did not work well was in the highly publicized failure of one of the Mars spacecraft which was designed and built between JPL in Pasadena, CA and Lockheed Martin in Denver, CO. The JPL team worked in metric while the Denver team worked in British units. The lack of an appropriate conversion in the navigation algorithms led to the spacecraft crashing into Mars.

Since uncertainty has been introduced as central and irreducible in the design of complex space systems, a natural question is how to model and incorporate it at the concept design stage into the architecture in a way that is central (rather than peripheral as the industrial case studies pointed out). In two papers extracted from his thesis, Walton points out that financial portfolio theory deals with uncertainty in a central manner when a stock portfolio is constructed. In the stock market, one cannot choose a portfolio and treat the risk as an add on after the portfolio has been constructed. He then generalizes portfolio theory to the case of space system conceptual design. He argues that just as one can build a portfolio of individual stocks who behavior is anti-correlated, one can build a prtfilio of space system designs who behavior under uncertainty is anti-correlated. In particular, investment in anti-correlated (with respect to uncertainty) conceptual designs may allow portfolios which have less overall uncertainty at a given performance than individual architectures. Of course, this result is well known to anyone who has invested in the stock market. He then shows in a companion paper (Walton2) that for some space system architectures, the use of uncertainty as a central design principle leads to a different Pareto optimal front (& therefore optimal architectural choices) from the Pareto front chosen on the basis of performance and cost. His work has been critiqued on several grounds. These include a critique of how far space system designs are like stocks (are they divisible) and the assumptions of normal distributions. Nevertheless, his work was one of the first to systematically analyze how to centrally incorporate uncertainty into design rather than after the fact.

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[i] Krathwohl, 1997 #78