ENGINEERING SYSTEMS MONOGRAPH

UNCERTAINTY MANAGEMENT FOR ENGINEERING SYSTEMS PLANNING AND DESIGN

by Richard de Neufville
on behalf and with the comments of
Olivier de Weck, Daniel Frey, Daniel Hastings, Richard Larson, David Simchi-Levi,
Kenneth Oye, Annalisa Weigel, Roy Welsch and
colleagues in the MIT Engineering Systems Division

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SUMMARY

Uncertainty management is a particularly significant long-term foundational issue for planning, design and management of engineering systems. Its importance is far greater for engineering systems than it is in traditional engineering design. This is because engineering systems—such as automotive transport, electric power distribution, and the Internet—last longer, and touch more aspects of our society than specific engineering components such as a car, bridge or power plant. The uncertainties associated with engineering systems can thus grow larger and can arise from more aspects than they do for individual artifacts. Numerous retrospective studies indicate that uncertainties often constitute a central consideration in performance of engineering systems. Uncertainty thus needs to be treated as a core element for the design of engineering systems.

Designing for uncertainty explicitly can have major consequences for the design of engineering systems. It often leads designers to create architectures and specific designs that are markedly different from designs created to meet fixed specifications. Put another way, an emphasis on strategies to deal with uncertainty—such as flexibility or robustness—may lead designers to different solutions than those that focus on optimization to meet specific criteria or specifications.

A focus on design for uncertainty implies a major cultural change in thinking about the engineering paradigm. This is because the traditional pattern in engineering is to design to specifications set outside the engineering process; as by client wishes, design codes or governmental regulations. The traditional engineering task is to optimize the technology so that it meets a set of criteria. Designing for uncertainty changes this approach. It requires us to examine scenarios in which competitive forces, shifts in customer preferences, and political events change the definition of effective design. A focus on the uncertainties surrounding engineering systems thus enlarges the definition of engineering practice; it expands it to include economies and politics among other considerations.

The paradigmatic change associated with a focus on uncertainty management is not suitable for all engineering practice. It is complementary to the well-established perspectives that have proven their value. Going beyond the more usual passive response to risks, it brings in an active approach to both the design of the engineering product and of the economic and regulatory environment that surround engineering systems. Furthermore, it gives weight to the upside opportunities associated with uncertainty, in addition to the traditional concern with downside losses and risks. In this sense the focus on uncertainty management can be seen as a significant part of the Engineering Systems approach: it reformulates and expands the approach to engineering planning, design and implementation.

This paper sets out some of the ways we might think of incorporating uncertainty management into engineering systems design.

CONTEXT OF THIS PAPER

This paper is one of three that attempt to define how a focus on the field of Engineering Systems reformulates and expands the approach to planning, design and implementation of complex, often large-scale and always significant assemblages of engineered components. These three monographs share an underlying vision: a new analytical perspective is appropriate, indeed required, when we expand our sights from the engineered product to the engineered system.

Each of the three papers emphasizes a different perspective that now appears important to the understanding of Engineering Systems. In turn, these are that:

> **Architecture is important.** As Whitney (2004) and colleagues express, it is useful and productive to consider explicitly how the parts of an engineering system interact with each other. It may often essential to do so, to enable us to deal effectively with the need to reconfigure systems in response to new possibilities and new requirements.

> **Long-term, life-cycle considerations should not be neglected.** As Sussman and Marks (2004) and others describe, we owe it to our clients to incorporate explicitly long term economic and other costs. This contrasts with practice that has traditionally neglected long-term consequences on the grounds that reasonable discount rates allow us to treat as negligible anything that happens beyond a decade or so. This premise may not be valid in thinking about engineering systems, because their effects may magnify over time and counteract economic discounting.

> **Uncertainty can be actively managed and exploited.** The unexpected developments that surround our environment can be actively managed through flexible designs that can adjust to changed conditions. Moreover, these new states can provide opportunities. Thus, we must expand our perspective from a narrow concern with risks to a larger consideration including opportunities.

These three papers build upon and relate closely to each other. For example, the importance of uncertainty grows as we take a longer-term view; the future of gasoline-powered transport systems becomes more questionable as we look 25 or 50 years into the future. Likewise, effective management of uncertainty calls for flexibility that may be best achieved through specific forms of system architectures; thus it is easier to adjust computer systems to new workloads if they are modular and permit plug-and-play changes. The three papers are complementary; they might be seen as different axes that describe key concerns in the development of the field of engineering systems.

These papers express our current view of the core areas of study and research in Engineering Systems, and are correspondingly at the heart of the MIT doctoral program in the Engineering Systems Division.

SEMANTIC CAUTION

This paper discusses a mindset of how to look at and deal with uncertainty. It is not suggesting in any way that engineers and engineering practice have failed to consider risks. It is arguing that some part of the profession should consider the uncertainties in our environment in a different way and that we would thereby be able to achieve substantial improvements in design, as has already been shown (de Weck et al, 2004). The subtext for the entire presentation is about the need for different processes for dealing with recognized issues.

To help present this mindset, the paper deliberately uses three words that are not ordinarily part of the discourse of engineering. It does so to emphasize the special character of the approach being expounded. Conversely, these words are not considered to be interchangeable with other words that might be suitably thought to be synonyms in less intentional language and thought. These words are: Uncertainty, Management, and Option.

Uncertainty in this paper refers to the entire distribution of possible outcomes. It is in apposition to the standard engineering focus on the bad side of the distribution. An example of this one-tailed concern is the Society of Risk Analysis whose consideration of the distribution is uniquely focused on threats:

> "Risk analysis is broadly defined to include risk assessment, risk characterization, risk communication, risk management, and policy relating to risk. Our interests include risks to human health and the environment, both built and natural. We consider threats from physical, chemical, and biological agents and from a variety of human activities as well as natural events." (SRA, 2004)

This paper is equally interested in both tails of the distributions that surround engineering systems. Its premise is that just as engineers need to guard against failure, they should also enable the exploitation of unexpected opportunities that may be associated with our projects and products. Just as designers should spend time on the possible toxic effects of methanol, they should devote energy to thinking about the range of circumstances that might make fuel cells become an attractive development. Correspondingly, they should both investigate toxicity and guard against leaks, put into place ways to facilitate the development of fuel cell vehicles if the opportunities became favorable.

Thus "uncertainty" in this paper is not a synonym for "risk". Quite the contrary: it is used to expand the concern from a one-sided view of the distribution of events to a complete description and working with both sides.

Management is this paper refers to the active direction of the evolution of the engineering project. This involves shifts in design, brought on by new technologies, by different requirements due to governmental regulations or client needs, and by other factors. In this context, it is seen to be an integral part of the planning, design and implementation of engineering systems. In this milieu, it is thus a practice that requires an understanding of the system and technical competence.

The paper uses the term "management" to designate the active and proactive response to uncertainty. It is active in that it seeks to build features into the design that enable the system operators to shift the evolution of the system as needed to avoid risks or to exploit opportunities; for example by closing part of the system and redeploying assets or by expanding the system as needed by unexpected growth. It is proactive in that it seeks to change the loads on the system and thus increase its performance; for example by providing ramp metering that manages demand for highway capacity and thus prevents traffic congestion and possible gridlock. These forms of active direction of engineering systems are different from standard design practices, and may best be termed management.

Conversely, the paper is making no claim on the larger profession of management as taught in management schools or practiced in industry and elsewhere. Some of what may legitimately be associated with "uncertainty management" may indeed be "management' in the conventional sense. However, the connotation of management in this paper refers to the active direction of the enterprise developing and evolving some engineering system.

Option in this paper has a specific, technical meaning. It refers to flexibility, to the ability to adjust a design of a system in significant ways that enable the system managers to redirect the enterprise in a way that either avoids downside consequences or exploits upside opportunities.

Specifically, an option has the meaning associated with “options analysis” in economics and finance.

> “…an option gives the holder the right to do something. The holder does not have to exercise this right. This fact distinguishes options from forwards and futures… Note that…an investor must pay to purchase an option…” (Hull, 1993)

Most importantly, an “option” in this paper is not a synonym for “alternative” as it is in ordinary language. An option refers to a choice, but a choice that the system designers and managers have deliberately made possible through some effort. Thus designers who built the burners and pipelines to make it possible to shift from fuel oil to natural gas to power a thermal electric plant have created an option. This choice would not have existed if they had not gone to that effort, if they had not paid the price in time and money to endow the plant with that flexibility.

BACKGROUND

Engineers normally design to specifications. Civil works obviously have to conform to building and other codes. Military equipment has had to follow "mil specs’ or comparable civilian standards. The size and capacity of systems (such as manufacturing plants or communications systems) are typically specified to the technical team. In many circumstances, traditional concepts of best practice lead designers to particular solutions. Thus, water resource engineers like to build dams to maximum capacity on the grounds that economies of scale mean that the largest facilities are most efficient.[1] In short, engineering does not typically design for a range of possibilities. It designs to fixed criteria.

That engineers design to fixed criteria does not imply that they ignore uncertainty. The management of risk is a foundational issue in the design, development and extension of technology, as others have emphasized (e.g.: Joel Moses, 2004). It has ever been so. By and large, society expects that engineers will deliver products that do not fail. It is a design scandal if bridges fail or aircraft come apart in mid-air. Engineers themselves share this concept, as Petrowski (1994) documents. “Good designs do not fail” is a long-standing engineering mantra.[2,3] Engineering practice thus goes to great lengths to protect its products from the possibility of failure due to material weaknesses, structural inadequacies, or extraordinary loads.

Much of engineering practice is thus directed toward risk management, that is, toward the elimination of possible bad consequences. (See, for example, University of Virginia, 2004) Building extra strength into a structure, through the use of factors of safety or other procedures, is a traditional feature of good design. Building in redundancy so that the engineered artifact is robust against the failure of components, is another proven approach to good engineering.

Somewhat paradoxically, risk management in engineering revolves around fixed specifications. This is for two reasons. On the one hand, fixed specifications simplify engineering analysis. For example, when a building code specifies that the designer shall use a factor of safety of 1.7 in

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[1] This logic fails if production does not reach the capacity of the project, for example if the demand for hydropower is less than the capacity of the facility. At that point, the larger, more expensive facilities may have higher average costs than smaller facilities.

[2] Counter-examples of this practice may be found. Some consumer goods have been designed the wear out early, to encourage additional sales – the notion of ‘planned obsolescence.’

[3] In dealing with systems with multiple stakeholders, one may also remark that different stakeholders may have noticeably different concepts of what ‘failure’ means, either at a given time (as when environmental groups confront economic interests) or over time, in line with changing requirements or standards. These arguments do not change the essential nature of the mantra, even as they challenge how it might get interpreted.

designing against live loads (ASCE, 1996), it relieves the designer from having to make any kind of probabilistic analysis – some group of experts has done this work already. On the other hand, fixed specifications protect the engineers: they know that if they comply with these specifications, then they will by definition have done "good engineering" and are protected from responsibility if their structure fails. In any event, traditional engineering typically manages risk through fixed specifications.

The specifications are of course often based on some probabilistic analysis. Starting around 1909, the design of telephone systems used Erlang distributions to estimate the specification for the capacity and number of switchboard operators required (Wikipedia, 2004). Buildings in earthquake areas must meet the specifications of the seismic codes, based upon some assessment of the frequency distribution of the intensity of shocks (for example, Nikolaou et al, 2001). The specification of redundancy in aircraft subsystems is likely to be based on estimates of the mean time between failure of components (for example, Hugues et al, 2002).

GAPS IN TRADITIONAL PRACTICE

The traditional engineering approach to uncertainty leaves out two important aspects of uncertainty management. First, its narrow focus on "technological failure" leads it to disregard uncertainties that create opportunities. Thus, it does not fully manage uncertainties – it tends to deal only with one tail of the distribution. Second, its focus on "technological failure" means that it disregards failures due to economics or other causes. However, a fully responsible approach to the design of engineering systems should not just care that the product performed as specified, but that it also makes sense to the client or the public. To deal with uncertainty fully, we must bridge these gaps.

Uncertainty often creates unexpected opportunities. The popularity of the Internet, totally unanticipated by the first designers, created many new opportunities. In general, the design of a technology should anticipate the ways in which it might succeed, and build in ways to enhance the means to capitalize on this good fortune. Designers should deal with the upside of the probability distribution just as they deal with the downside. They should build in the capability to deal with these extraordinary circumstances. Dealing with both the upside and the downside of uncertainties is not incompatible. Thus in the early 1960s the designers of the bridge across the Tagus at Lisbon built in both seismic protection against the known historical possibility of earthquakes, and extra strength to allow for double-decking of the bridge in case traffic ever expanded substantially. Some twenty years later, the Portuguese exercised this option to double-deck the bridge – a design first (Gesner and Jardim, 1998). To deal fully with uncertainty, the engineering profession cannot only focus on risk management; it must also manage opportunities.

Engineering practice must also recognize that much of the uncertainty that affects the success of engineering systems comes from other than purely technological factors. Market and technological uncertainties may be the key factor in the success of a technological product. For example,

- Motorola's Iridium system of communication satellites was a $5 billion failure largely because it did not anticipate the development of ground based cell phones.[4]

[4] According to Kaiser (2001) in the Chicago Tribune: "Iridium LLC, owner of the bankrupt $5 billion satellite system backed by Motorola Inc., has endorsed a $25 million bid for its ill-starred space network from a group led by ex-airline executive Dan Colussy. Although Iridium has received dozens of offers since declaring bankruptcy in August 1999, this is the first time the company has given its support to a potential buyer."

The project justifiably received acclaim as a technological marvel as it did achieve goals that pushed the engineering frontier. In terms of providing value for money however, it was a huge loss. Thinking of this as an engineering success is rather like boasting of great surgery when the patient dies on the operating table.

- The original design of Boston/Logan's Terminal E did not anticipate the deregulation of the airlines and that this "International" building would serve domestic traffic for New York Air, Northwest and United. Conversely, the new design for 2003 did not anticipate the technical innovation of electronic check-in kiosks and the provision of many traditional check-in counters made the terminal obsolete upon opening.

Despite these and many other examples, engineers almost never consider market risks associated with their design. The analysis of markets and customer usage is neither in the engineers' job descriptions nor in their training. Such factors as marketing, industrial organization, innovation studies and other elements of applied social science are widely labeled as "soft" studies that are not part of engineering. In practice, such factors are left to other divisions of the organization; the engineering section focuses on the "hard" stuff. This is true although these issues may have great impacts on the performance of the engineered systems. The general pattern is that engineers receive some specification of usage, typically as a deterministic projection of demand.

Dealing with the gaps in the traditional engineering approach to uncertainty will change the engineering paradigm in two important ways. It entails a new attitude about uncertainty, and an enlargement of the scope of how it should be analyzed. These innovations will run against the grain and be difficult to accept. Thus:

- The recognition that uncertainty can be helpful – one of the fundamental lessons of the new science of “options analysis” – will be difficult to accept for those who have focused on risk management and the idea that uncertainty is bad.
- The mandate to consider market and other political factors in the design of technology will not be easy for those who never had this as a serious part of their training or practice, and may furthermore have been taught to despise these “soft” subjects.

Thus the process of incorporating uncertainty management into engineering systems is not merely a matter of organizing methods and techniques. This transition will involve a profound shift in approaches to engineering that will take significant time and effort.

THE OPPORTUNITY

Now is the right time to develop a comprehensive approach to the management of uncertainty in the planning and design of engineering systems**.** Recent developments have created major new opportunities to improve the procedures and practice for dealing with the uncertainties facing designers. These stem from:

- Conceptual reformulations of the design issues,
- Technological advances that reshuffle the relative importance of elements of concern, and
- Major methodological achievements.

Together, these elements indicate that the engineering profession has the possibility of making significant advances in the way it manages uncertainty in the design, development and evolution of engineering systems.

Conceptual reformulation: A significant conceptual reformulation is the shift in emphasis from “risk” to “uncertainty”. The traditional emphasis has been on various modes of “risk management”, of protecting the system, its users and the engineers responsible, from technical failures in the system. This requirement has in no way diminished, of course. What is new is the recognition, when we consider the performance of an engineered system in its larger commercial and political environment, that uncertainty may provide opportunities as well as dangers. For example, unexpected higher demands for a product provide opportunities for those manufacturers who can shift their production to meet that demand, and who can exploit a flexible platform to create new models that satisfy the unexpected demand. Likewise, the designers or producers whose goods cannot be extended to meet the unexpected demand will have failed in their missions, even if these goods perform excellently to their narrow technical specifications. Designers today need to consider managing not only the downside possibilities, but also the upside potentials. They need not only to bulletproof their designs against technical failures, but also enable them to evolve and adapt to new circumstances.

Engineering systems are especially sensitive to this reformulation. This is because these complex devices require enormous efforts. They are likely to have significant, long-term roles in our society. Society is therefore most likely to judge their performance according to norms far beyond strictly technical measures. Moreover, the community is likely to shift its criteria over the life-term of the system. The design of the automobile illustrates these points. Good design is not just a measure of standard road handling of a specific vehicle. Good design involves the configuration of platforms and manufacturing systems that can adjust shifting consumer preferences as to model type and evolving governmental directives embedded in environmental regulations.

Technological advances: The time is now for the focus on the management of uncertainty because of huge advances in information technology. These enable analysts to deal realistically with the many states and scenarios that are part of a full analysis of uncertainty for an engineering system. Indeed, a thorough analysis of uncertainty might easily require the consideration of hundreds, if not thousands of versions of a deterministic analysis. As a general rule, this computational problem has limited the ability of the engineering profession to develop credible analyses for the management of uncertainty. Now, however, the computational problem is disappearing.

Most obviously, orders–of-magnitude increases in computational power enable designers to simulate the performance of systems. What was a major exercise only a few years ago, today is a routine classroom demonstration. Analysts can now routinely simulate the response of systems thousands of times without much effort. The increase in analytic speed and memory capacity in computers is, however, only the beginning of the story. The profession has been developing a range of methods for drawing meaning out of these calculations so that we can use the results in productive ways. In short, as these advances continue, we are in the process of a revolutionary change in the way we can analyze, and thus manage, uncertainly.

Complementarily, advances in information technology are thoroughly improving the way we can monitor our systems, deduce their development, and thus manage their performance and evolution in the context of uncertainty. For example, the way companies distribute their products now is vastly different from what it has been. The traditional process involves creating a hierarchy of buffer stocks between the producer and the consumers. It provides safety against stock-outs, at considerable cost due to the immobilization of capital and the need to dispose of obsolete stocks at bargain prices. The new processes, whether in manufacturing (such as Dell) or transportation (such as Walmart) use information to track the state of the system, to anticipate trends, and to assure that production will, as closely as possible, provide what is needed at the right time. Correspondingly, the best designers of supply-chain systems have completely revamped these processes, so that they can manage the uncertainty effectively.

Methodological achievements: In recent years, new theoretical foundations have emerged that enable significant improvements in design methodology. Two examples are “real options” and “robust design.”

Real Options: Financial specialists have developed the theory and means for evaluating financial flexibility known as “options analysis”. This path-breaking advance, recognized by a Nobel Prize, has revolutionized the financial markets over the last 25 years. Much of this can and is being applied to physical systems, under the rubric of “real options”, that is, options analysis applied to physical things. This literature has been exploding over the past 5 years or so, in textbooks, journal articles, and the trade press (see for example: Trigeorgis, 1996; Luenberger, 1998; Amran and Kulatilaka, 1999).

The development of options analysis holds the promise of enabling the engineering profession to calculate the value of flexibility. Previously, this had not been possible – with the consequence that this attribute was systematically neglected. If a thing cannot be acceptably quantified in engineering, it does not have much of a chance of being considered seriously. Although the promise of being able to calculate the value of engineering flexibility is there, making good on it will require extensive work over years.

In this connection it is important to note that the options analyses developed in finance generally do not – and cannot – be applied directly to engineering. This is because the financial analysis assumes that the elements of concern (the assets) are traded in efficient markets characterized by widespread trading, complete information, and an extensive history that provides reasonable statistics. The uncertainty associated with an engineering system, however, often relates to new technologies, markets or regulations for which historical data are unavailable. Moreover, the markets assumed and key for the financial analysis rarely exist for the products of engineering systems.[5] The financial analyses thus need to be adapted for use in the design and management over time of engineered systems.

Initial applications of options analysis to real systems indicate that this approach leads to substantial improvements in design. Embedding flexibility into diverse systems (ranging from the design of bridges to communications satellites) already optimized for performance under traditional deterministic concepts has reportedly led to substantial savings in numerous cases (see de Weck et al. 2004)

Robust Design: Another example of a recent methodological advance for engineering systems is “robust design” – a set of design methods for improving the consistency of a systems function across a wide range of conditions. The theoretical foundations for robust design began to emerge when R.A. Fisher (1935) developed techniques for planning and analyzing experiments. These theoretical foundations expanded rapidly to form a major sub-discipline of statistics known as Design of Experiments. The techniques were soon adopted for engineering. For example, Response Surface Methods enabled manufacturers to optimize processes for fixed operating conditions (see Myers and Montgomery, 2002)

For engineering systems, the most important use of Fisher’s work was probably Genichi Taguchi’s pioneering development of “robust design” methods that apply Design of Experiments to reduce the effect of uncertainties on a system (see Roy, 2001). Taguchi was the first to advocate the practice of deliberately and systematically inducing “noise factors” in experiments so that systems can be made less sensitive to variations in customer use conditions and internal degradation. By this means, it has been possible to improve quality without raising manufacturing

[5] The valuation of options in finance rests upon the idea that (1) it is possible to build a “replicating portfolio”, that is a set of assets that exactly mimic the outcomes of the option, and (2) that therefore the price of the option is determined by arbitrage with the value of this portfolio. In general, these conditions do not exist for options associated with engineering systems.

costs. Thus, these methods gave Japanese companies a significant competitive advantage in the 1970's and 1980's, and Japanese products became known for their exceptional quality, reliability, and value. This represented one of the clearest historical examples of an engineering design method having a direct effect on commercial competitiveness. It is hard to say how much the US trade gap with Japan was due to robust design methods, but we do know that these methods were adopted aggressively by US firms, and that subsequently the quality of US-made products improved substantially.

A TYPOLOGY

Different approaches to the management of uncertainty are likely to be better for different phases of the design, operation and evolution of engineering systems. Which methods, and which emphases are most relevant and productive in different cases is an interesting subject of research that is already attracting attention (e.g., Ramirez, 2002). Without presuming to be definitive, a two-way typology is worth exploring here because it suggests prospective areas of research interest. One dimension considers the time-scale, the other the type of response.

Time Scale of Response: This typology focuses on the time scale at which engineers and managers might choose to manage uncertainty. These would range from the shortest to the longest terms.[6] Thus, it might be reasonable to think about decisions that were:

> Operational,

> Tactical, and

> Strategic.

Operational decisions concern immediate concerns, for example, how we are going to run the railroad today or this week – these concern schedules, the distribution of empty cars and the allocation of motive power. Tactics refer to decisions that take place over a somewhat longer scale; for example, it would concern decisions about acquiring rolling stock for the railroad – the number and type of car. Strategy deals with the long-term issues, such as building new rail lines or marshalling yards.

Different kinds of data might be most interesting for these kinds of decisions. Thus it has been suggested that operational decisions might focus on the variance in loads and demands on the systems. In this context one would be thinking in terms of ways in which to harmonize the short-term discrepancies between the loads and the capabilities of the system.

On a longer, tactical scale, one might focus on the tails of the distribution of performance. This would include major opportunities for improvement, and the major risks such as the possibility that the systems might break down.

At the strategic level, little has been done so far in engineering. This may be where the greatest opportunities lie. One reason little has been done at this level is that in order to deal at the strategic level, analysts need to consider a wide range of factors that have traditionally been beyond the concern of engineers. For example, the engineers in charge of the technical design of communications satellites focused on providing some specified amount of capacity at minimum cost. It was not their job to consider the market risks, the likelihood that the markets might be different from what they had been told, or to integrate these factors into the design for the constellation of satellites. Moreover, the technical design team almost certainly had little competence in this area. However, as de Weck et al (2004) document, if they had been able to

[6] [Exactly how long these terms are might not be fixed. They might depend on the speed at which the system could change, on its time constants. Thus a long period for chip designers might be one or two years, whereas it might be one or two decades for highway designers.]

incorporate this understanding into their design, and thus been able to configure the system so that it could evolve to meet actual demands as needed, the design might have saved about 25 to 30% of the cost on an expected value basis.

Mode of Response: There are at least three basic ways to manage uncertainty. One can either reduce the uncertainty itself, or enable the system to respond to it better. In terms of enhancing the system, one can either strengthen it against a shock, or make it more flexible so that it can adjust to the shock. Thus we could think of responses that:

- Control uncertainty, as by demand management,
- Protect Passively, as by building in robustness, and
- Protect Actively, as by creating flexibility that managers can use to react to uncertainties.

Whereas we may not be able to control forces of nature to any great degree, we can definitely affect much of the uncertainly caused by market fluctuations or other social pressures. Demand management is a clear example of this. By adjusting the price or quality of service provided by a system at different times, it is possible to increase or decrease the demands on this system. For example, stop lights on the ramps leadings onto freeways can control the access in response to the level of traffic downstream, and can thus regulate the level of congestion and the overall delays to the system (see Caltrans, 2004). Anyone thinking seriously about the overall performance of an engineering system should include demand management among the possible ways to manage uncertainty.

In terms of protecting a system, we can first of all think of various forms of passive protection, which will function without any significant management decisions. We can make the system robust; in short, we can “bullet-proof” it. Redundancy of parts is a standard way of achieving operational robustness in engineering systems. Robustness, thought of as the ability of a system to maintain its operational capabilities under different circumstances, can also be obtained in different ways. For example the architecture of the system might permit alternate routes to circumvent disabled parts – think of the of the air traffic control system operating under localized high demand or bad weather. Many of these ways have already received considerable attention over the past decades, and are regular parts of traditional engineering design. Mostly, they apply at the tactical and operational levels of design.

Alternatively, we can think of dealing with the uncertainty by enabling the system designers and managers to take specific decisions to alter the configuration of the system depending on the circumstances. In the language of finance, we can create options that they can exercise in case the circumstances warrant. Classic forms of options are those to expand or contract a system, and to accelerate or delay the implementation of some part of it. Thus we can design a system or a product so that we can delay its final configuration, and thus enable the system designer to make this artifact conform more closely to what is desired. The field of real options encompasses all these forms of active dealing with uncertainty.

Learning from Experience: Learning from experience is a necessary ingredient for intelligent development of longer-term tactical or strategic decisions. Responses to uncertainty should be highly connected across the several time scales. What the system managers and designers can observe now should inform what they do later.

Learning from experience can, as the responses, be active or passive. One approach is to observe what happens and deduce trends and other characteristics of uncertainty. This is the approach taken in classic financial analysis for example. Analysts will examine the market data, identify trends if they exist, calculate the variance of the distribution, and then proceed to calculate the value of the options they will use to hedge against risk or exploit opportunities. Likewise, system managers can simply observe the development of traffic and loads.

Active learning is also possible – and often most productive. We can think of our short-term decisions as steps in a Bayesian process, and deliberately construct them as effective learning processes. This is in effect what is done in the Taguchi method, which thinks of variations in the system as experiments from which product designers can learn to reduce and control uncertainty.

This approach is not confined to product design. Active learning can also be introduced into much larger systems – such as communication or transportation networks. For example, Evans and Clarke (2002) discuss how air traffic controllers can use different schemes for allocating runway slots to aircraft under similar weather or traffic conditions, and thus learn from these experiences how to improve the traffic flows on a tactical basis.

Translating the possibility of learning into practical application is a challenge. Organizations usually delegate the responsibility for operational, tactical and strategic decisions to different groups. Moreover, these groups typically are made up of persons with distinctive backgrounds and skills. The person who has self selected (or been selected) for a career in operations is unlikely to be compatible or conversant with the planners in the strategic sections. Thus, learning across time frames is not easy. One of the research tasks for Engineering Systems is the question of leaning how to design institutions to deal with learning across operational, tactical and strategic dimensions and then to translate this knowledge into effective ways to manage uncertainty.

Two-Way Table of Responses: Combining the possible time scales and modes of response leads to the two-way typology for managing uncertainty in Engineering Systems. Table 1 gives a generic version of the concept, and Table 2 provides a concrete example of its application.

These tables illustrate the way that the focus on the management of uncertainty reformulates and expands the approach to engineering planning, design and implementation. Taking the perspective of Engineering Systems, the entire Table 1 constitutes areas of research and practice. This view contrasts with the traditional concept of engineering that might be said to focus on passive responses at the operational and tactical level.

Time Scale and Mode of Response	Uncertainty Management	System Modification	
		Passive: Robustness	Active: Flexibility
Operational			
Tactical			
Strategic			

Table 1: Two-Way Typology of Ways to Manage Uncertainty in Engineering Systems Design

Time Scale and Mode of Response	Uncertainty Management	System Modification	
		Passive: Robustness	Active: Flexibility
Operational	Correcting a new source of variation revealed by statistical process control	Increasing a machine tool's stiffness so to avoid chatter and thereby improve surface finish	Design a machine to detect chatter and change feed rate automatically to avoid poor surface finish
Tactical	Investing in a system to control manufacturing process parameters like temperature, pressure, and humidity	Robust parameter design – selecting levels of processing parameters that ensure adequate performance over a wider range of conditions	Organizing a plant (e.g., into cells) so that it can adapt to month-to-month changes in product mix.
Strategic	Implementing a system (e.g., 6) by which you work with your employees and suppliers to continually improve quality and cost.	Setting up a technology strategy so that your plant can meet the new accuracy demands that are forecast to be needed in ten years	Managing a network of suppliers so that you can add emerging new capabilities and drop suppliers that become uncompetitive.

Table 2: A Two-Way Typology of Ways to Manage Uncertainty in Engineering Systems Design for Manufacturing Systems (courtesy of Daniel Frey)

EXPANDING THE DOMAIN OF ENGINEERING

Organizational issues will be critical to the effective management of uncertainty in engineering systems, perhaps especially at the strategic level. An appropriate configuration of the engineering group responsible for an engineering system is likely to be central both to the success of the analysis and original design, and to the management of the system over time.

The composition of the original design group will be key because it largely determines which kinds of uncertainties get recognized. For example, if no one on the team has any competence in market analysis or demand forecasting, then the uncertainties in future markets are likely to be neglected in the design effort. The case study of the communication satellites suggests that this is what happened in that system. (de Weck et al 2004) To the extent that the design team ignored the market risks, focusing instead on meeting its performance specifications optimally, the design effort also ignored the kinds of flexibility they could have inserted into the system that would cope with market uncertainties. For example, they could have launched the system with a small-scale inaugural system that could be expanded as needed. This might be a more expensive path to meeting the design specification for the complete system (depending on economies of scale and on how far into the future deployments could be deferred, which would reduce present value costs). Even it were, the staged development would be far cheaper than the full-blown system if it happened that the full capacity were not needed. In short, when dealing with long-range strategic issues, as happens in the design phase, it may be critical to take a much wider view of the engineering team than is now done.

Most importantly, system managers need to deal with the organization of the group that will be running the engineered system. Embedding flexibility into the system implies the need to have managers empowered – both by authority and by knowledge – to exercise that flexibility. This means that the ongoing management of the system needs to incorporate technically qualified persons who can influence the exercise of the flexibility when desirable. Furthermore, to be effective, these persons need to be monitoring the system and its context so that they can be aware of when it would, in fact, be profitable or otherwise desirable to exercise the flexibility and evolve the system to some alternative, more suitable technical trajectory.

If we want to be successful as designers of engineering systems, if we really want to improve the way engineering systems are evolved and delivered, then it would seem that we have to think about how we can foster the right context for the ongoing management of these systems. Shaping the appropriate organizations will be an important part of our task.

CURRENT SITUATION AT MIT

Many MIT faculty, in the Engineering Systems Division and beyond, feel that the rubric of "Uncertainty Management in Engineering Systems Planning and Design" involves a collection of exciting research issues. We believe that strong efforts in this area, in collaboration with colleagues elsewhere, will lead to major changes for the better in the way we design and evolve engineering systems. We look forward to expanding our network of like-minded colleagues and actively solicit your participation in this enterprise.

REFERENCES

Amran, M. and Kulatilaka, N. (1999) *Real Options: Managing Strategic Investment in an Uncertain World*, Harvard Business School Press, Boston.

ASCE (1996) *Minimum Design Loads for Buildings and Other Structures* ASCE 7-95, American Society of Civil Engineers, Reston, VA.

Caltrans (2004) "Ramp Meter F.A.Q." Available: http://www.dot.ca.gov/dist4/rmfaq.html

De Weck, O. et al (2004) "Enhancing the Economics of Communications Satellites via Orbital Reconfigurations and Staged Development," *Journal of Aerospace Computing, Information, and Communication*. (In press)

Evans, A. and Clarke, J.-P. (2002) "Responses to Airport Delays—A System Study of Newark International Airport, MIT International Center for Air Transportation, Report ICAT 2002-06-00, Cambridge, MA. Available: http://icat-server.mit.edu/Library/fullRecord.cgi?idDoc=117

Fisher, R. A. (1935) *The Design of Experiments*, Oliver and Boyd, Edinburgh and London, UK. Also republished by Hafner Publishing Co., New York, NY (1971).

Gesner, G. and Jardim, J. (1998) "Bridge within a Bridge," *Civil Engineering*, October, Available: http://www.pubs.asce.org/ceonline/1098feat.html

Hugues, E. et al (2002) "Application of Markov processes to predict aircraft operational reliability," 3rd European Systems Engineering Conference, May 21-24, Toulouse, France, Available: http://perso.wanadoo.fr/andre.cabarbaye/pdf/articles/Article3.pdf

Hull, J. (1993) *Options, Futures, and Other Derivative Securities*, 2nd Edition, Prentice-Hall, Englewood Cliffs, NJ.

Kaiser, R. (2001) "Iridium bankruptcy - an end to the flares!" article in Chicago Tribune Oct 31, 2001, as reported at http://www.heavens-above.com/iridiumdemise.asp

Luenberger, D. (1998) *Investment Science*, Oxford University Press, Oxford, UK.

Moses, J. (2004) "Foundational Issues in Engineering Systems: A Framing Paper," presented at the MIT Engineering Systems Symposium, 29-31 March, at MIT, Cambridge, MA, Available: http://esd.mit.edu/symposium/monograph.

Myers, R, and Montgomery, D. (2002) *Response Surface Methodology: Process and Process Optimization Using Designed Experiments*, 2nd ed., Wiley-Interscience, New York, NY.

Nikolaou, S. et al (2001) "Evaluation of Site Factors for Seismic Bridge Design in New York City Area," *Journal of Bridge Engineering*, Vol. 6, No. 6, November/December, pp. 564-576

Petrowski, H. (1994) *Design Paradigms: Case histories of Error and Judgment in Engineering*, Cambridge University Press, Cambridge, UK.

Ramirez, N. (2002) "Valuing Flexibility in Infrastructure Developments: The Bogotá Water Supply Expansion Plan," SM Thesis, MIT Technology and Policy Program, May. http://ardent.mit.edu/real_options/Real_opts_papers/Thesis%20NRamirez%20May_2002.pdf

Roy, R. (2001) Design of Experiments using the Taguchi Approach: 16 steps to Product and Process Improvement, Interscience.

Society for Risk Analysis (2004) web page: http://www.sra.org/

Cutcher-Gershenfeld et al. (2004) “Sustainability as an Organizing Design Principle for Large-Scale Engineering Systems,” presented at the MIT Engineering Systems Symposium, 29-31 March, at MIT, Cambridge, MA, Available: http://esd.mit.edu/symposium/monograph.

Trigeorgis, L. (1996) *Real Options: Managerial Flexibility and Strategy in Resource Allocation*, MIT Press, Cambridge, MA.

University of Virginia (2004) web site for the Center for Risk Management in Engineering, http://www.sys.virginia.edu/risk/

Whitney, D. et al. (2004) “The Influence of Architecture in Engineering Systems,” presented at the MIT Engineering Systems Symposium, 29-31 March, at MIT, Cambridge, MA, Available: http://esd.mit.edu/symposium/monograph.

Wikipedia (2004) “A, K, Erlang,” http://en2.wikipedia.org/wiki/A._K._Erlang

APPENDIX A
SOME IDEAS ABOUT MANAGING UNCERTAINTY IN ENGINEERING SYSTEMS

VALUING FLEXIBILITY IN DESIGN (REAL OPTIONS ANALYSIS)

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SUMMARY

The development of coherent approaches to value flexibility would enable the designers of engineered systems to make informed judgments about what kind of flexibility should be incorporated into specific designs. This would be a major contribution.

This is because:

> Flexibility demonstrably adds value to design, if we have it;

> However, adding flexibility to a design in general adds costs;

> Yet we so far have no good means to value flexibility in general;

> So we do not as a rule, "design" flexibility into systems (we may incorporate this feature with some intuitive sense, but this is not solid engineering practice).

THE ISSUE

Design that is blind to uncertainties associated with major impacts on the system must be second best. If we account for the actual context of a system, we can surely create a better design. Being fully aware beats myopia. This seems self-evident.

We should be able to do much better by engineering systems to respond effectively to their context. Indeed, case studies indicate improvements on the order of 30% - in terms of overall improvement of economic performance are possible. For example, an analysis of the life cycle cost of deploying communications satellites can be far less if the design uses a flexible, staged plan of deployment. (de Weck et al 2004) Naturally, the actual improvements in performance for any system will depend on the possible range of circumstances. The main point is that the possible improvements may be as great as those that might devolve from any purely technical analysis.

To incorporate the contextual elements, we collectively need first to develop the analysis techniques that will allow us to account for their uncertainties. This involves two qualitatively different tasks:

> The characterization and assessment of the uncertainties associated with forecasts, with markets, with the speed and nature of innovations, and with political events; and

> Efficient procedures for translating these uncertainties into measures of value that can be compared with the cost of providing the engineered system to adapt flexibly to new opportunities or new circumstances.

In parallel, we also need to demonstrate to the engineering profession the advantage of reframing of the design problem:

- from one that meets specifications,
- to one that provides the best performance over a range of scenarios.

This will doubtless be hard to do. Although we like to think that, as rational engineers, we are open to anything that improves performance, the reality is that the kind of reframing we anticipate will require a deep shift in attitudes that will not come easily. For example, the 30% advantage associated with the staged deployment of a satellite communications system depends essentially on reframing the design question

- From: "meet the specified capacity at low life-time cost"
- To: "design so that the system can meet the specified capacity as needed, according to the development of the market".

This shift requires that engineers get involved in marketing forecasts, examine their variability and, in general, spend a lot of effort on this subject, which today is outside their purview. Discussions with the chief technical officers of the Iridium and Globalstar communications satellites confirm that this kind of mind shift is difficult for some to make.

THE OPPORTUNITY

The development of "options theory" provides a way to quantify the value of flexibility. The methods associated with the corresponding "options analysis" provide an entirely new way to value assets that exist in the context of uncertainty. Since all significant assets have risks and opportunities, options analysis affects the valuation of practically all assets. Thus, these methods have revolutionized financial valuations over the last 25 years or so. They have created entirely new ways of assessing the worth of assets and developed many new markets.

"Real Options Analysis" applies options theory to physical assets. This field has been exploding over the last five years or so. These procedures come in two flavors: those that are

- "On" projects, in which the engineering system is treated like a black box. The analysis treats the piece of technology as given (the power plant, for example) and adapts the standard financial analyses to the nature of the uncertainty and data associated with the project.
- "In" projects, which provide flexibility by incorporating special features into the design of the project (just as a spare tire on a car provides the flexibility to deal with a flat). These analyses generally require engineering knowledge to design appropriate options.

MIT has been a center of work of real options "on" projects. Much of that work is associated with the Sloan School of Management: Prof. Myers is widely credited with naming the concept; Prof. Pindyck (with Dixit) wrote a standard textbook on deferral options. The MIT Press is one of the leading publishers of work in this area (for example, Trigeorgis (1996) on Real Options). None of the above work, and indeed practically no work anywhere, has been concerned with real options "in" projects.

Working with colleagues elsewhere, the Engineering Systems Division has the opportunity to develop the methods that apply real options analysis "in" projects, that is, that incorporate this approach into the design process. We have several advantages:

> access to the basic knowledge about options analysis, strengthened by our collegial relationships with leaders in Sloan School;

> the engineering capability that enables us to apply the principles of options analysis to actual engineering challenges; and

> we have embraced the challenge of improving the performance of engineering systems through collaboration with specialists in management who can collaborate with us in shaping the paradigm shifts in engineering practice that are likely to be needed.

Some of us believe this is one of the major contributions we could make over the next decade.

THE TASKS AHEAD

To achieve an impact in this area we first need to do the research on how to apply options thinking to the design of engineering systems. The prime issue in this connection is that the standard financial methods do not apply directly. Most obviously, the right kinds of data are not available. Indeed, the financial analysis of options assumes that quantities of data (such as the prices for stocks or commodities over an extended period) and the value of the underlying asset on which the option is based (such as the price of commodity or stock) are both readily available. For real projects, these assumptions are not met: we do not have historical data on innovations, for example; nor can we assume that the value of a project such as a communications system is easy to define at any time. Thus, the application of real options to engineering systems requires a range of approximations. We need to determine, presumably by analysis of actual systems, which approaches are most useful under which circumstances.

Our second task in this connection is to disseminate the procedures we develop. This will require more than writing papers. Because the real options approach involves a new way of thinking, papers written in this area do not easily complement existing texts (in contrast to how advances in linear programming might complement existing LP texts). It is likely that we will have to prepare new courses and new textbooks to make these contributions accessible and known to a wide audience.

As of now, it appears that several ESD faculty are already actively engaged in these tasks. Doctoral theses are being written. A major textbook is being prepared. The future is encouraging.