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ARCHITECTING/DESIGNING ENGINEERING SYSTEMS USING REAL OPTIONS

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Abstract

Everyone concerned with engineering systems faces a common issue: How do we design systems to perform well in a constantly evolving and thus risky context? As professionals concerned with the system (rather than its individual pieces), this design issues predominantly relates to the overall configuration, the architecture of the system.

This paper presents an approach to this fundamental issue. It suggests how we could architect flexible engineering systems that can evolve optimally to meet new challenges and opportunities. It suggests that the methods of "options analysis"-- that have revolutionized thinking about investments -- can provide a conceptual basis for defining optimal configurations. When these procedures are applied to design issues, they are generally known as "real options analysis".

The fundamental result of "real options analysis" is the determination of the value of flexibility. It thus permits system designers and managers to decide which flexible design elements, that permit their system to evolve effectively over time, are worth their cost. It thus provides a clear rationale for when to design specific types of flexibility into the system.

The Problem

Learning how to define the appropriate architecture, to configure engineering systems optimally, should be a central task for all of us. At present we often to do it suboptimally. As a colleague has suggested:

> "In traditional space systems conceptual design, point designs are chosen early to pursue. This has the benefit of jump-starting downstream design efforts, but has severe detriments in terms of sub-optimization and the cost of redesign." (Hastings et al.)

How do we configure computer systems, manufacturing plants, power grids, satellite arrays and other systems to evolve optimally in the uncertain environment defined by technological shifts, changes in industry structure and market fluctuations? In short, how do we design in the right kinds and amounts of flexibility into engineering systems?

How do we guarantee that our systems are well positioned to take advantage of new opportunities, yet insured against poor performance in changed circumstances?

Arguably, this task is not only central to systems design but also urgent. If we could establish a methodology for determining the appropriate system architecture, we could avoid the 'severe detriments' Hastings alludes to, and achieve significant gains. Much is at stake.

An essential design reality is that, as other colleagues indicate:

> "A system… is not a static design---it is a dynamic process that is continually adapting to achieve its goals and to react to changes in itself and in the environment." (Leveson)

We must, therefore learn how to explore the:

> "Tradeoffs between performance, cost, risk and schedule…during architecting and design of complex engineering systems." (de Weck et al.)

We do yet not know how to define, in any rigorous way, appropriately flexible system architectures. We can deal with parts of the problem. For example, we can build in reliability for particular parts. We can also in some cases design for reasonable performance over a wide range of situations. However, we do not have a consistent engineering approach to the general problem.

Moreover, our schemes for measuring performance do not generally provide means to evaluate contingency plans. Until we develop appropriate ways to value the flexibility that we can build into our systems, we can neither make informed decisions about flexibility nor design the systems for optimal performance.

Simulation is almost certainly likely to be an essential tool to help us explore these issues. A broad range of new capabilities enables us to use this approach in ways previously unaffordable. As another colleague points out:

> "A new generation of stochastic simulation tools capable of exploring risk vs. efficiency tradeoffs in large-scale…systems…is now evolving." (Marks)

However, we will need to place such tools within a larger conceptual context. This is likely to use some form of construct that defines an optimum portfolio of system capabilities or assets. It will thus probably borrow heavily from recent developments in economics concerned with optimizing portfolios of assets. Colleagues within the Engineering Systems Division are already working on this approach. For example:

> "We have been exploring a methodology for concurrently evaluating uncertainties embedded in potential architectures and utilizing this information in the upstream conceptual design trade-offs. This methodology relies on the use of portfolio theory and the analogy that a trade space of architectures can be modeled as a marketplace of potential assets from which efficient portfolios can be created." (Hastings et al)

Conceptual Approach of Real Options

The core of the proposed general approach is the development of clear, understandable measures of flexibility. To engineer flexibility into systems, we must be able to measure alternative possibilities so that we can compare them analytically. The discipline of measuring objectively is a -- if not the -- characteristic that distinguishes engineering from other design professions.

Furthermore, the measures of flexibility need to be understandable to a wide audience. To achieve major improvements in performance, it may be necessary to commit significant resources whose expenditure must be justified to the political and administrative controllers of budgets. These measures should thus be comprehensible to a financially trained audience.

The proposed "real options analysis" fits these requirements. It is, as regards measurement of value, an extension of the economic methods of evaluation that have become standard over the last generation. It essentially provides a "Net Present Value" (NPV) or "Discounted Cash Flow" (DCF) measurement of value. It is expressed in terms of monetary value and reflects the time value of resources. This is most appropriate for major systems, which evolve over many years. The time value of money is then significant and must be a central ingredient in the measure of flexibility.

"Real options analysis" moreover offers significant advantages over NPV or DCF. It recognizes the ability and responsibility of engineers and managers to shape the development of any system over time. They will make major choices along the way, dropping features that are no longer desirable or adding new ones that have proven to be essential. However, NPV/DCF analyses assume that the project and its cash flows are defined in advance. On the contrary, "real options" analysis deals operationally with the reality of many different cash flows through time. This is a crucial conceptual difference that many texts go to great effort to stress (for example, Copeland and Antikarov, 2001). Thus "real options analysis" is similar to NPV/DCF in that it is economic, but as a form of economic analysis is substantially different.

The difference between "real options analysis" and NPV/DCF analyses has deep implications for the organization of systems design and management. Real options analyses suppose a proactive process in which managers can and do revise decisions at any time in light of new information. This concept is fundamentally different from the more rigid approach that uses analysis to evaluate and choose among designs and then proposes to implement them without change. (Of course, we know that these rigid plans often do have to change, but this is typically not because this possibility was part of the original design.) As Allen and Katz indicate in another presentation to this symposium, the "real options" approach goes hand-in-hand with the notion that the development of complex engineering systems must be managed.

In many ways, "real options analysis" is similar to Decision Analysis. Indeed decision analysis may be a practical way to approximate a real options analysis in practice, as Ramirez (2002) documents and de Neufville and Neely (2001) suggest. Although the methods and the terms differ, real options analysis resembles decision analysis in that it also explicitly considers the combinations of possible choices. (Real options use lattices where paths may recombine, whereas decision analysis looks more generally at trees whose paths are distinct.)

At a deeper level, "real options analysis" differs fundamentally from decision analysis. Its special features, indeed its fundamental constructs, were what justified the award of the Nobel Prize for development of the Black-Scholes model and related aspects of options analysis. The resemblance between real options and decision analysis may be compared to the similarity between whales and tuna fish. Both are alike in that they are big aquatic creatures, but they differ substantially: whales are mammals and fish are not. Most notably, real options analysis uses the notion of arbitrage as the driving force for determining the value of assets. It ties this notion into a necessary connection between starting points of the web of choices and the possible ending points -- features that are totally absent in the structure of decision trees.

Overall, the point of using real options analysis is to calculate the value of flexibility in present value terms. This is most important information for systems designers. By comparing the value of flexibility with the cost of acquiring it, they can make an informed, analytic judgement about whether this flexibility should be incorporated into design. For example, the designers of the Iridium satellites (that Motorola developed for its failed system of mobile telephones) could have used real options analysis to calculate the value of giving the satellites the capability of handling data transmissions efficiently. They might thus have been able to justify the flexibility in bandwidth allocation to permit this use. As things turned out, they then would have been able to extract much more value from the deployment of the Iridium satellites.

A calculus enabling designers to value flexibility reasonably will have profound implications for the architecture of systems. It will transform flexibility from "something nice to have, but that we cannot include in the optimization of the system" to an important feature that can be fully valued and incorporated explicitly in the optimal design.

Formal Concepts

The concept of flexibility has been mushy in engineering, as might be expected when there is not a common, let alone an operational measure of this term. In economics and finance, however, the concept is closely tied to the specific concept of "options". It should be noted that this technical concept of "options" has a precise meaning, and must not be confused with what the term connotes in common-garden English.

Within the context of options analysis, an "option" has a specific definition:

> *An "option" is the capability or right to take some action, without the obligation to do so.*

For example, one form of financial option is a "call" on a stock: the right to buy the stock at a specified price over a period of time, without any obligation to do so. Holders of such options cannot lose money: either the value of the stock rises above the agreed sales price (so the holders of the option can pocket the difference) or it does not and they have not lost anything. Companies often provide employees with such call options on their stock, hoping that the potential gains will motivate them to raise the price of the stock.

It is important to stress the difference between the formal concept of an "option" and its meaning in everyday language. In daily usage, the word "option" is generally synonymous with "alternative". This is what we mean when, in speaking to a friend about supper, we ask about the "options for take-out". We're then asking whether we'll have Chinese, Indian or some other cuisine. However, from the perspective of options analysis, the word "option" has a different connotation. This is unfortunate because the whole discussion of "options analysis" requires us to set aside our ordinary notion of the meaning of the word. It would be convenient of we could use a different term in options analysis. Unfortunately, the technical community concerned with options analysis is so set in its language that there seems to be no possibility to change the term. We must focus instead on the specific formal concept of an option.

The phrase "real option" is used by practitioners to indicate that the "options" being considered concern the operation or management of "real" things that have a physical form -- such as mines, power plants, factories, etc. The "real" label distinguishes these options from those that are purely financial, such as contracts to buy or sell stocks or commodities such as oil, grain, foreign exchange, etc. By definition then, systems designers should be interested in "real options".

Options thus formally represent the ability to do something, to be flexible about design. For example, the designer of a car who includes a spare tire allows the driver the flexibility to respond to changed circumstances, specifically to a bad tire. Formally, availability of the spare tire gives the driver the "right but not the obligation" to change the tire whenever it suits. It provides insurance that allows the holder to get out of the consequences of a bad situation.

Being "rights but not obligations", options have a remarkable feature: their values are asymmetric. Thus, the value of the call option is 'all gain, no pain'. The owner of the option can only gain if the price of the stock rises above the agreed upon sales price; if the stock goes down, the owner does not have to pay anything. Note carefully however, that people can lose lots of money in trading options! The option can end up having no value, so that people buying an option can lose everything they paid for it. Likewise, the holder of an insurance policy may end up not collecting money and be out the full cost of the insurance. This reflects on the difference between the price paid for an option and the actual value obtained -- not on the asymmetric value of the option itself.

Because of the asymmetry of value, flexibility has a further remarkable characteristic: the more uncertain, the riskier the situation, the more valuable the option or flexibility becomes. This is not the usual situation for projects. Normally, projects appear to be less valuable as risk increases. Thus NPV/DCF analysis often use higher discount rates to reflect greater volatility of the assets, and thereby discount or reduce the future benefits of a project. However, options and flexibility only pay off when special circumstances occur -- the higher the probability these may happen, the more valuable the option.

The fact that flexibility is worth more when there is greater risk should be obvious on reflection. If the designers of Iridium could have been absolutely certain of the future of satellite-based telephony, there would have been no value for the provision of the flexibility to reorient their satellites for data transmission. Not having omniscient knowledge of the future markets for their products, they should have incorporated substantial flexibility in the design. Flexibility in design has value precisely because and to the extent of the risk and uncertainty in the future conditions.

The great value of flexibility and options in risky situations underlines their value in systems design. Engineering systems notoriously exist and perform in complex, changing environments. They face uncertainties and changes in technology, in the market, and the needs of their buyers. For example, aircraft designs such as the Boeing 747 persist over decades. Over its lifetime, technology has changed, the market has been largely deregulated permitting different routes and favoring smaller aircraft, and the airlines have merged and reoriented their activities toward cheaper fare travelers. Because of all these kinds of causes of uncertainly, the effective configuration of engineering systems needs to recognize the great value of flexibility and incorporate into design processes.

Procedure for Valuing Flexibility

The overall concept for architecting/architecting engineering systems using real options analysis is straightforward. The design team needs to:

- value the various kinds of flexibility they could include in the architecture of the system;
- compare these values to the cost of including each kind of flexibility, so that the designers can include the elements that add value overall, and exclude those whose cost exceeds their potential contribution; and
- specify how the system can and should evolve over time to make best use of the flexibility designed into the system.

The crux of the procedure lies in the estimation of the value of the flexibility, of the value of the real option. This is because the estimation of the cost of acquiring the flexibility is relatively simple. If not actually simple, it is at least part of the existing design processes. For example, engineers optimizing the performance of the Iridium satellites for voice traffic could have used these same analyses to determine both the loss of performance for voice traffic and the cost associated with building in the capability to handle data traffic efficiently. Therefore, although it may take considerable effort estimate the cost of incorporating a "real option" into design, this is part of the set of procedures already in place. The assessment of the value of the flexibility is the novel part that requires extra thought and new procedures.

The estimation of the value of flexibility has three major elements. It requires:

- estimation of the risks associated with the project without the options or flexibility -- this volatility is the essential driver of the value of the flexibility;
- calculation of the value of the options by one of the several methods available as indicated below; and
- identification of the strategies for exploiting the options, to permit the best use of the flexibility built into the system.

Estimation of the basic risks: Designers will almost certainly find that it is easiest to define the risks associated with a system by simulation of possibilities. This is because other measures of uncertainty are not available. For new systems being designed, there is no historical record of its performance. There may be historical records relevant to the design, such as rainfall records that are key to the proper understanding of a water supply system, but these do not define the actual behavior of the physical system.

In this respect, the analysis of "real options" differs from conventional options analysis used in financial markets. Financial markets typically have extensive records of past transactions in all the major commodities -- such as oil, gas, and foreign exchange -- on which options are traded. These data thus provide distributions of performance, in particular the so-called "beta" measures of volatility. However, this kind of information is not available to systems designers. Therefore, they will have to use some other procedure, such as simulation, to define the risks associated with a project.

Fortunately, recent hardware and software developments greatly simplify the simulation of complex systems. Faster equipment of course makes it possible to process thousands of runs in seconds or less. Additionally, standard programs now exist that permit analysts to draw upon many different distributions and run the calculations through standard spreadsheet programs. Thus Crystal Ball ® and @Risk ® are inexpensive add-ons to Excel ®. In some circles, these have already become the basic tools of real options analysis.

For example, Ramirez (2002) has recently estimated the basic risks associated with the design of the water supply system for Bogota, Colombia, as part of her real options analysis of how they should develop this system in the future. Copeland and Antikarov (2001) illustrate how this can be done generally for all kinds of systems. Thus, the general outline of the way ahead appears clear. Nonetheless, much work needs to be done in this area.

Calculation of the Value of the Flexibility: The theory for the calculation of the value of options is well developed. For example, see Dixit and Pindyck (1994) and Luenberger (1998). However, when it comes to specific situations, the theoretically correct procedures may not be practical. Moreover, even if mathematically tractable, they may not be acceptable to the intended audience. Indeed the formal methods of options analysis are often highly mathematical and thus incomprehensible or otherwise unacceptable to the intended managerial audiences. The standard procedures suitable for financial options may thus not be best for real options.

Many real options analyses may thus use adaptations of the theoretical procedures. These alternatives are likely to incorporate various forms of decision analyses, which can have the great advantage of being more intuitively obvious. The decision analytic approach is demonstrably inferior from an economic perspective, but it is not evident to what extent the differences in result are significant from the perspective of systems design. The approximate analyses will give different values than the theoretically correct procedures. The question is whether these differences are significant, and that is an open question. Its answer appears to depend on the type of system, its context, and the nature of the options for flexibility. For example, Ramirez (2002) conducted a comparative analysis of procedures, and concluded that a decision analytic evaluation of the real options was more effective for the analysis of the water supply system for Bogota.

<u>Definition of Development Strategies</u>: To obtain the value of flexibility, it is necessary to know when to use it. In financial cases, it is generally easy to identify the profitable circumstances because the value of the option is clearly tied to the prices for exercising it. Thus, it is easy to tell if the option on buying a stock is profitable: all one has to do is to compare the market price with the price specified in the option. If you have the right to buy at $40 a share a stock that now sells at $50 a share, the option is profitable. In systems design, the issue is much less clear. It is not at all obvious, for example, how the growth rate in consumption of water defines the desirability of exercising the option to build an addition to municipal waterworks.

An important part of the use of real options analysis in systems design may well lie in the identification of suitable markers that indicate when option should be exercised. As designers, we need to know both if an option is valuable (and thus should be included in the design) and when it should be exercised. From an engineering perspective, one of the advantages of a decision analytic approach to the evaluation of real options is precisely that this approach provides guidelines on when, or under what circumstances, to exploit flexibility built into the system.

Research Agenda

The introduction and full use of flexibility in the architecting and designing of engineering systems will require great effort. We need to develop both a suitable set of techniques <u>and</u> to reorient concepts of engineering design and practice. Full exploitation of the value of flexibility requires new techniques, new processes and new frameworks for the development of engineering systems.

The research agenda should thus comprise several elements:
- investigations into detailed technique;
- definition of practical integrated procedures for real options analysis; and
- exploration of the strategic implications of the exploitation of flexibility for architecture and the design of engineering systems.

Technique: An extended program of research is needed to create appropriate procedures for applying real options analysis to engineering systems. We need, through theoretical analyses and practical applications to numerous cases, to adapt the financial methods of options analysis to the reality of engineering systems. If successful, the resulting concepts and procedures could fundamentally alter the way we think about engineering systems design. The resulting approach for defining system architecture could provide a core methodology for engineering systems analysis.

Experts in finance have proposed possible approaches (see for example Brennan and Trigeorgis (2000), Trigeorgis (1996)). However, these do not seem adequate. One issue is that many of the technical assumptions central to the options analysis in the financial context do not apply to engineering systems. Specifically, with regard to engineering systems:
- Historical data on the volatility of the risks are generally unavailable; and
- Decision points at which the exercise price of the "real option" is known may also be unavailable.

There is a need to develop a range of specific techniques for doing various bits of the analysis.

System Studies: Moreover, we need to develop suitable procedures for analyzing specific types of systems. As a practical matter, we may want to use various forms of standard options analysis in combination with approximate methods such as decision analysis. The most suitable combinations are likely to depend on both the natures of the system and its technical and market context. We thus need to explore the possibilities by carrying our example real options analyses on a range of situations.

A series of systems studies in this area may prove most fruitful. These would consist of applications of real options analysis to a wide range of systems situated in different contexts. These would serve the two roles. Individually, they would provide educational examples showing how real options analysis could be done and why it increases the efficiency and effectiveness of systems design. Collectively, they would help define which procedures were more useful in which circumstances.

Strategic Design Issues: We need also to investigate the extent to which an appreciation of the value of flexibility might shift some fundamental concepts of design. It might well impel us to adopt new strategic concepts. For instance:
- We might also come to different conclusions about how we distribute productive or controlling capabilities in specific systems. To what extent should they be centralized, as common in electric power generation and the telephone system? To

what extent should they be distributed, an arrangement that typically costs more at the beginning but that provides substantial flexibility.

- It is possible that a correct assessment of flexibility would impel us to the increased use of modular designs, much as Baldwin and Clark (2000) have proposed.

Outlook

Options theory and analysis has revolutionized thinking about investments. It has transformed it from an art to a science, as Luenberger (1998) suggests. The management of risk through options has been a, perhaps the, major development in financial circles of the last generation. There is strong reason to believe that suitably modified options analysis will also have a major impact on investments in physical things, on systems design in particular.

The fundamental element of options analysis is indeed the determination of the value of flexibility. When we can satisfactorily measure the value of flexibility, we will be able to determine the optimal kinds and amounts to incorporate into the system architecture. We will then be able to translate systems design from a focus on static or "point" designs to an ongoing dynamic process.

Achieving this possibility is a great challenge, worthy of our sustained attention.

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