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Extracting Value from Uncertainty: Proposed Methodology for Engineering Systems Design

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Abstract

Designers and managers of new investments in engineering systems look for ways to add value to their programs. One fundamental way to do this is by taking advantage of uncertainty. Although uncertainty is usually seen as negative in most investment projects, it can also increase performance if flexibility is incorporated into the system to capture upside opportunities, and reduce losses in case of downside events.

This paper introduces a design methodology that adds value to engineering systems by considering flexibility at an early conceptual stage. It provides screening tools to find areas where flexibility can be incorporated at the engineering, operational, and management decision levels. In engineering and operations, technical modifications need to be done within the system to acquire the flexibility exercisable by managers. One example is the ability to expand or contract product output as demand fluctuates. At the management decision level, no explicit modification is needed, such as the ability to abandon the project altogether. The methodology incorporates screening tools based both on qualitative historical studies (GPS, B-52, etc.) and quantitative Design Structure Matrices representing the engineering system (Bartolomei et al. 2006; Kalligeros 2006; Kalligeros, de Neufville 2006).

The design process also provides a set of quantitative tools to assess the financial value of flexibility based on Real Options Analysis and simulation models (de Neufville et al. 2006; Kalligeros 2006; Kalligeros, de Neufville 2006). These give managers and designers discriminating tools with which to choose the most valuable flexibilities to implement in the engineering system.

The methodology represents a practical procedure for understanding where flexibility can be found and incorporated into all areas of engineering system design.

Introduction

One way to capture benefits from uncertainty and add value to an engineering system is by incorporating flexibility in design. This approach capitalizes on upside opportunities, and reduces losses in case of downside events. Current engineering practice does not exploit the full potential of uncertainty, often regarding it as negative because of possible downside events.

The ability to find flexibility is important to designers and program managers in order to increase value. Design Structure Matrices (DSM) and Real Options Analysis (ROA) are useful quantitative tools for assessing the value of flexibility. The design process introduced here incorporates these tools and offers a structured way to think about flexibility at an early design stage. It allows discriminating between different sources of flexibility to implement the most valuable ones.

Methods

The design process is developed from historical studies of complex engineering systems. Systems such as Navstar Global Positioning System (GPS), Boeing B-52 Stratofortress, Convair B-58 Hustler, and U.S. Air Force/NASA Inertial Upper Stage (IUS) Program were considered. The goal is to learn engineering lessons on the sources of flexibility that added value or could have added value to these systems at the engineering, operations, and management decision levels.

These systems were selected for the following reasons. For the B-52, we suspected that flexibility inherent to the design enabled the bomber's remarkable longevity and ability to adapt to different missions. With respect to GPS, flexibility in program design and management could have been considered to serve more commercial applications. For B-58, we were attracted by the possible lack of flexibility in airframe maintenance that led to large repair costs (Kelly and Venkayya 2002). This certainly contributed to a short ten years of service compared to the nearly sixty years for the B-52. Finally, for the IUS, we considered a system that was delayed, thus incurring large cost overruns because initial design requirements changed many times before getting to final production phase (Dunn 2003).

A set of important engineering lessons called *flexible design attributes* was extracted from these studies. These attributes are qualities that may exist under various implementation forms in systems that are flexibly designed.

We hypothesize that the design methodology adds value to engineering systems design by offering a structured way to think about flexibility. This hypothesis is tested by applying the methodology to new engineering systems case studies. In a subsequent paper submitted to INCOSE 2007 (Cardin et al. 2006), the methodology is applied to the early design of Fusion Island, a facility using nuclear fusion for hydrogen production and storage for a possible future hydrogen economy (Nuttall et al. 2005).

Proposed Value Assessment Method. We propose a method based on Monte Carlo simulations and ROA to assess the value of flexibility found by applying the methodology. Tools based on financial metrics are promoted because they are more general and widely used. Net Present Value (NPV) and Value At Risk and Gain (VARG) curves shown below are examples of such tools (Figure 1). Designers are however free to use the value metric most suited to their particular context. In this case however suggested tools may have limited use.

The first step consists in assessing initial design value without flexibility. It is done using deterministic projections for the design uncertainties (e.g. variables such as demand, price, etc.) to calculate NPV of the system using standard Discounted Cash Flow analysis (DCF). This step corresponds to traditional engineering practice.

The second step consists in incorporating uncertainty as random variables for each uncertain variable, still with no flexibility in design. It makes use of Monte Carlo simulations, and is referred to as the inflexible design valuation. Each round of simulation samples from the random variable distributions to produce one NPV for the project. Statistics such as mean NPV and standard deviation are collected by running several simulations. Those are then used to describe the design project's distribution of possible NPVs.

The third step incorporates flexibility in Monte Carlo simulations. For instance, if the flexibility is the ability to expand production as demand increases, the valuation takes into account higher revenues as capacity increases to demand.

Another interesting tool to analyze the outcome distribution is the VARG curve. The VARG is normally shown on a plot of cumulative density (or probability) function versus NPV. It is informative to senior management looking for the likelihood of getting a NPV smaller than a given value (Value at Risk) or greater than a certain value (Value at Gain). For example on Figure 1, the dotted line on the left shows there is a 10% chance of having NPV inferior to -$94M, which is the Value at Risk (VAR). The dotted line on the right shows a 10% chance that profits will be higher than $309M, or the Value at Gain (VAG).

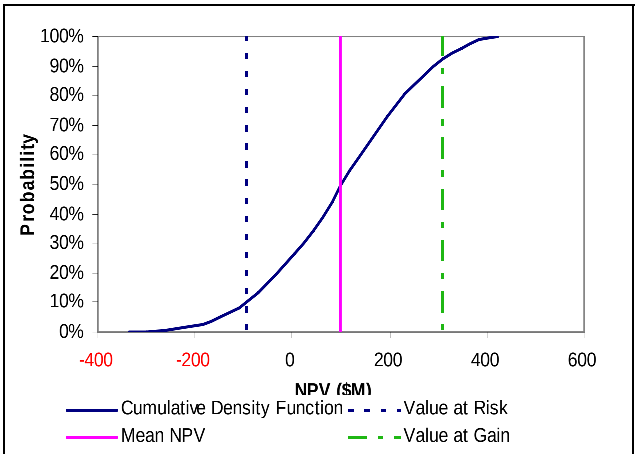

Figure 1: Example of Value at Risk and Gain (VARG) graph. The graph shows the cumulative probability density for each possible project NPV. The dotted lines give the cumulative probability for the VAG and VAR, with a 10% threshold percentage decided by the user.

Real Options Analysis. The value of flexibility is not captured in traditional DCF analyses. Hence, the NPV is usually a lower bound to the real expected NPV for a flexible project. Managers, however, need a way to quantify the value of flexibility to discriminate between those worth implementing in design.

The value of flexibility is found by subtracting the mean NPV of the inflexible design (from the Monte Carlo simulations) from the mean NPV of the flexible one. The expression for the value of flexibility (or the real option) is:

$$V_{Flexibility} = MAX[0, NPV_{Flex.} - NPV_{Non\text{-}Flex.}]$$

The MAX condition expresses that the flexibility will not be acquired if it is negative, hence a zero value.

The rationale for the method is to initially assume the cost of acquiring the flexibility to be zero. Then, $V_{Flex.}$ is found as described above. If $V_{Flex.} = 0$, designers reject the flexibility as being worthless. If positive, they decide whether it is worth implementing if the real cost of acquiring it is lower than its value.

This same exercise can be performed when many flexibilities are combined, as their individual value may not necessarily be additive. It is possible that interactions occur between flexibilities so the value of the project is not necessarily enhanced by a direct sum of each flexibility's value.

Screening for Sources of Flexibility. The process creates a variety of future states for the system (see definition below). It integrates the Invariant Design Rule (IDR) algorithm developed by (Kalligeros 2006; Kalligeros, de Neufville 2006) and based on DSMs to find potential sources of flexibility. It also uses the Engineering System Matrix (ESM), a holistic representation of a complex engineering system that shows the critical architecting elements as well as the different causal interactions between them (Bartolomei et al. 2006).

An ESM is composed of traditional architecting DSMs with the addition of two new ones: the system drivers and human stakeholders DSMs (see Figure 2). Such DSMs represent environmental and social interactions within the system's boundary.

Future States. Future states are different scenarios, missions, applications, and operational modes for which the system can be used in the future. A B-52 bomber used as a reconnaissance aircraft is an example of a future state where the system is used for a different type of mission (Dorr and Peacock 1995). A mine deploying shipping trucks on different routes to make ore extraction more efficient is an example of a different operational mode. Making use of new and evolving technology to improve overall performance and/or make maintenance easier is also a future state of the system. A new and improved aircraft engine is such an example as well. Management decisions are also future states of the system. One example is to delay investment in research and environment to gather more information about market behavior.

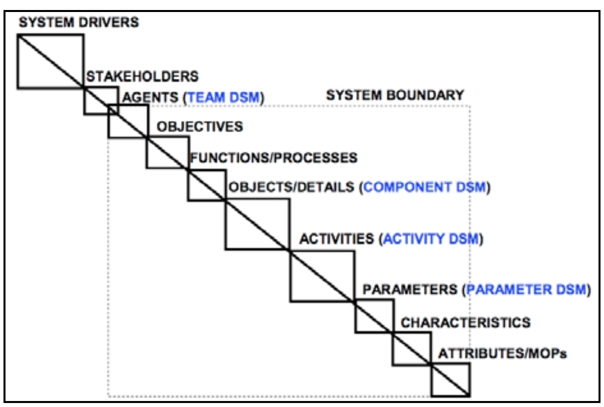

Figure 2: ESM representation. The matrix is composed of regular DSMs that represent technical aspects of the engineering system. An ESM incorporates two more DSMs that account for system drivers and stakeholders. Source: (Bartolomei et al. 2006).

Results

Flexible Design Attributes. The flexible design attributes extracted from historical studies of engineering systems are:

1) Platform-like initial design;
2) Adaptability for changing missions;
3) Adaptability for changing purpose of the system;
4) Technological evolvability and maintainability; and
5) Design modularity.

All design attributes share in common the ability to enable flexibility and adaptability in face of uncertainty. In particular, the initial necessity of a platform-like design ensures the design does not grow uncontrollably in requirements (i.e. does not oversize), which draws upon the lesson from the IUS. In addition, standard interfaces in platform designs can be used to evolve the system from one design to a subsequent one more easily (Kalligeros 2006). Flexibility can then be exploited on non-standard components. For instance, B-52's fuselage can be considered as a relatively stable standard interface from designs A to H. In contrast, the aircraft's "low-hanging" Pratt & Whitney jet engines were replaced several times over the last fifty years (Dorr and Peacock 1995). This design feature made replacements and repairs easier compared to aircrafts with engines embedded within the wing. This also represents a non-standard component where flexibility could be exploited as technology evolved, and shows how modularity in design enables flexibility.

Adaptability to different missions and purposes represent the need to think "outside-the-box" for possible uses of a system. A change in purpose is more general, such as making a system commercial while designed originally for military purposes. This contrasts with changing missions, where the overall purpose of the system may not change. For instance, the B-52 was used for high altitude bombing during the Cold War and for low altitude penetration during the Vietnam War.

This is a change in mission that remained in the military domain (Boyne 2001; Dorr and Peacock 1995). This mission change was facilitated by the huge belly that carried air-launched cruise missiles even if originally designed for heavy and cumbersome bombs (Montulli 1986).

Design Process. The design process incorporates lessons from above, as well as qualitative and quantitative tools for screening and assessing value of flexibility.

The "Holistic and Management Decision Value Assessment" step transcends the whole process and should be applied in parallel at any given time after Step 3. This ensures that designers constantly hold a value assessment ready for program managers.

Step 1: Define the immediate purpose and goals of the system. This step aims at defining the immediate purpose of the system, and its primary goal(s). It answers the general question: "What does the system accomplish?" It may rely on architectures of existing systems that offer similar functionalities so that minimal levels of technicality can be discussed in Step 2. For instance, if the system's goals are accomplished by building a parking garage, designers may rely on known designs components for such system in subsequent discussions.

Step 2: Identify the main uncertainties and brainstorm on potential future states of the system. The key here is for engineers to think freely about the following categories of future states: future purpose or mission, operational modes, maintenance requirements, adaptability to evolving technology, and management decisions. At this early stage, designers digress from the originally intended purpose of the system, and try to foresee as many commercial and non-commercial applications as possible. Regarding future maintenance, designers consider sub-components that are or will be potentially critical to the system. They also determine the relevant uncertainties inherent to the system's immediate and future environments for use in Monte Carlo simulations.

This step brings context to the flexibilities incorporated in design. Implementing flexibility without envisioning possible futures might result in over specification as in the case of the IUS.

Step 3: Develop an initial design, design representation, and deterministic value assessment. The step begins by building upon previous knowledge of similar systems (Step 1). It extends initial system architecture and interface management by suiting existing ones for a particular purpose. The preliminary design arising from this typically satisfies the system's immediate purpose (Step 1) without foreseeing too many different applications in a distant future, or possible uncertainties brainstormed in Step 2.

Designers can make use of ESM methodology as a tool to describe and represent their early system design (Figure 2). They may also take a system representation of their choosing. The goal is to provide a system representation that can be screened for sources of flexibility. Complex, Large-Scale, Integrated, Open System (CLIOS) representation is an example of another system representation tool (Bartolomei et al. 2006).

The value of the system's initial design, which is the one referred to as "inflexible design", is assessed using the approach presented in the Methods section. Different metrics and value assessment tools can be used for non-financial valuation, such as performance improvements (e.g. lives saved for a rescue helicopter system), or value-added from more flexible logistics support (e.g. efficiency improvement in operations of a copper mine).

Note: It is deliberately suggested that designers consider flexibilities for different missions and operational modes in Steps 4-6 separately from flexibilities for better maintenance, repair, and technological evolvability in Steps 7-9. Although those steps could be unified into three, it is suggested they are done separately to focus attention on the two separate but complementary sets of flexibility.

Step 4: Search and valuation of <u>existing</u> flexibilities for future applications, scenarios, and operational modes of the system. The search for flexibility begins here and aims at improving system design in a closed feedback-loop process. For instance, the search for flexibility in a positional satellite system starts from Steps 1 and 3 with an initial design (e.g. generation III GPS). Then designers concentrate on searching the design space for additional flexibility towards the future states brainstormed in Step 2.

This is where Kalligeros' methodology (Kalligeros 2006; Kalligeros, de Neufville 2006) is used to look for potential flexibilities through an ESM representation using IDR screening algorithm. If designers have opted for a different system representation, they screen it qualitatively and quantitatively for existing sources of flexibility.

The step provides a first source of flexibility within the initial design to enable future states brainstormed in Step 2. If designers wish to discriminate between flexibilities or prioritize them based on value, they use the valuation method proposed in the Methods section. Assessing the value of a particular flexibility is made by comparing the value of the flexible design with the corresponding inflexible design. The rule is to immediately reject flexibilities that have zero value, while keeping non-zero value flexibilities for further analysis in Step 6.

Designers should also consider that an inflexible design enables flexibility in operations where little modification is needed at a technical level "within" the system. For instance, an airline may decide to flexibly exploit different routes based on fluctuating regional demand, and concentrate on higher demand areas. This flexibility does not require technical modifications to the aircraft itself, but rather in the management of the system's operations. Therefore, the system's initial architecture alone creates additional value through the system's lifecycle by enabling flexibility in operations.

Step 5: Search and valuation of <u>missing and additional</u> flexibilities for future applications, scenarios, and operational modes of the system. Here designers consider other sources of flexibility not present in the current design, which are necessary to enable the remaining future states. They can use the ESM representation and screening methodology to look for such flexibilities. Once new flexibilities are found, the same method is applied for assessing value as the one presented above in the Methods section. Only positive value flexibilities are kept for final decision in Step 6.

Step 6: Incorporate additional flexibilities for future applications, scenarios, and operational modes of the system. This is the first modification to the initial design of Step 3. It can be thought of as a first feedback resulting from the brainstorm session and the search for flexibilities. Decision is taken here to incorporate the flexibilities that are worth implementing. Those modifications are reflected on the ESM or any system representation in use.

To decide whether a flexibility should be incorporated, designers select those that have positive value in Steps 4 and 5. Then they assess the real cost of acquiring that flexibility. If the cost is higher than the value of the flexibility, they reject it. If the cost is lower, value is added by incorporating that flexibility into the system.

This step is the subtlest of the methodology. Designers should be careful to not fall into uncontrolled growth of design requirements. Initial requirements should not be changed. Rather, flexibilities that make the system alterable and modifiable for different future states should be incorporated. Not doing so, with the investment project undertaken, could result in delays and large cost overruns before the system gets a final design locked-in.

Step 7: Search and valuation of existing flexibilities for better maintenance, repair, and technological evolvability. Designers consider here the first-pass design (see definition below) and evaluate current flexibilities that take advantage of evolving technology or make maintenance easier. This is also where ROA-based simulations are made to find positive-value flexibilities, as described above.

First-pass design. This is the original design modified in Step 6 to accommodate future applications, missions, and operational modes of the system.

Step 8: Search and valuation of flexibilities for better maintenance, repair, and technological evolvability. Designers consider additional flexibilities necessary to take advantage of evolving technology and easier maintenance than currently available on the first-pass design. The value of new flexibilities is assessed as previously described.

Step 9: Incorporate additional flexibilities for better maintenance, repair, and technological evolvability. Designers decide whether additional flexibilities should be incorporated depending on positive value and real cost as discussed above.

Parallel/Transcending Step: Holistic and Management Decision Value Assessment. In addition to the set of flexibilities added in-design, project managers are interested in the set of management decisions that enhance value of the overall project. Those are called flexibility "on-project", as opposed to "in-project" considered in previous steps.

Much flexibility exists at the management decision level to increase a project's NPV. Most popular decisions are to abandon a project, defer investment or investment choice, alter operating scale, switch product inputs or outputs, or combine any of these (Kalligeros 2006).

Assessing the value of flexibility, its real cost, and making the decision whether to implement it is done as described above. Note that designers can go through several iterations of the process between Steps 2 and 9. This is necessary if a set of flexibility is missing to enable further future states not considered in the initial brainstorm sessions of Step 2 and discovered through the design process.

Discussion and Concluding Remarks

A benefit of this approach is to help structure designers' thinking about possible future states of the system, and consider the kinds of flexibilities that would enable such states. The process is simple, flexible for use of different engineering system representations (e.g. ESM or CLIOS) or valuation metrics, and includes a small number of steps that covers a large spectrum at the engineering, operational, and management decision levels. It also builds upon several years of complex engineering system design experience through the flexible design attributes. A benefit of using Monte Carlo simulations instead of binomial trees for valuation, as proposed by (Copeland and Antikarov 2003) is to incorporate many uncertain variables in the simulations at once and collapse them into one measured value – for instance NPV. This value assessment method integrates and models a decision rule for managers that can be valued (e.g. expand production capacity if demand is higher than capacity for two consecutive years). Decision rules can also be altered to discriminate between different managerial behaviors. One disadvantage of the methodology resides in the difficulty of application for large engineering teams that need to agree on every step. There are also easy bias values in the model with financial metrics. It is therefore recommended to use other metrics in addition to NPV, such as payback period or cost-benefit ratio. This enhances the value assessment's credibility for senior management.

We introduced a methodology that helps designer and managers of engineering systems incorporate flexibility at an early design stage as a way to extract additional value from uncertainty. It should be particularly useful in designing new technological systems in a context where financial, human, and material resources are scarce and need to be used efficiently.

Future research is directed at exploring in more details system's operations and logistics support as another source of flexibility. It explores characteristics of the methodology such as the number of iterations necessary to span the spectrum of possible design combinations. In addition, application of the methodology to engineering systems not belonging to the military domain is under way. A case study applied to the early design of a civilian commercial energy production system - Fusion Island (Nuttall et al. 2005) - was submitted to INCOSE 2007 (Cardin et al. 2006). Since the methodology presented here is based upon lessons learned from military systems, this allows assessing its validity and usefulness in civilian and commercial settings where management is also a determining factor for flexibility. Value assessments of the different sets of flexibility outlined above, and the development of more precise valuation tools are also under way.

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Biographies

Michel-Alexandre Cardin is a Science Master candidate in the Technology and Policy Program at MIT. He currently studies flexibility in engineering systems design and real options analysis. He will continue his PhD studies under supervision of Dr. de Neufville at MIT Engineering Systems Division. He holds an Honors Bachelor of Science Degree in Physics from McGill University, a certificate in Space Sciences from the International Space University in France, and a Master of Applied Sciences in Aerospace Science and Engineering from the University of Toronto.

Dr. Richard de Neufville's research and teaching focus on inserting flexibility into the design of technological systems. He is the author of five major texts on systems analysis in engineering. His work has been recognized through a NATO Systems Science Prize and an honorary doctorate from the Delft University of Technology. He received along with Dr. Tao Wang the Best Paper Award at INCOSE 2006 in Orlando for his paper entitled "Identification of Real Options 'In' Projects".

John Dahlgren is the Project Leader of the Air Combat Command Systems Engineering project, working at the MITRE Corporation's Hampton, VA site. He previously provided systems engineering and project management leadership on the Air and Space Operations Center Weapon System program, the MILSATCOM Advanced Concepts Engineering project, and on multiple projects during his Air Force career. Mr. Dahlgren has a Bachelors of Science Degree in Electrical Engineering from the University of Illinois, a Masters of Science Degree in Systems Management from the University of Southern California, and an Advanced Project Management Certificate from Stanford University.