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Quantifying Flexibility for Architecting Changeable Systems

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Abstract

The design of complex systems often, if not always, occurs in a context that is uncertain -- needs change, technology evolves, and resources are uncertain. Much recent work has focused on design of systems that are able to deliver high value over time despite uncertainty. One commonly cited mechanism for doing so is to embed flexibility into system design. The design of a flexible system is described in terms of a new framework. Change propagation analysis is extended to allow analysis of systems with heterogeneous relationships between system components. Filtered outdegree analysis is presented as a method for quantifying flexibility at the system level. Limitations of both techniques are discussed as well as their use in concert with real options analysis to arrive at a valuation of flexible system designs.

Introduction

Flexibility has long been cited as a key goal for dealing with uncertainty in the design and future use of complex systems. Modern systems engineering requires operating in an ever changing environment within which systems often need to adapt to maintain value delivery and to take advantage of emergent opportunities. This paper seeks to develop practical guidance for using different approaches for characterizing and strategizing for flexibility. Two techniques that address quantification and valuation of flexibility are explored. The first technique is Change Propagation Analysis (CPA), which looks at the components of a system and whether they absorb or multiply changes in a system. The second technique, Ross's Filtered Outdegree (f-OD), measures the degree to which a system can be changed (i.e. its changeability), under decision maker specified constraints that limit which changes are feasible. This technique is useful when

the designer has the desire to be able to change the system, but lacks specific information on which changes may be advantageous. Traditionally, authors have focused on the physical components when looking for possible change points. Using the Engineering Systems Matrix (ESM) representation and constructs developed in Dynamic Multi-Attribute Tradespace Exploration (MATE), this paper discusses using two new approaches to find useful points to insert options in the physical architecture. Real Options Analysis (ROA) has emerged over the last decade as a useful methodology for evaluating whether or not specified changes to system are valuable given a defined uncertainty about the systems future environment (or state). Once options are identified using Filtered Outdegree and CPA, their value can be assessed with ROA.

Flexibility Landscape

Before attempting the task of quantifying and valuing flexibility, two questions must be answered: "What is flexibility?" and "Why would a designer want it?". Flexibility is a subset of changeability. Changeability is defined as the ability of a system to change easily, and can be decomposed into four categories: robustness, agility, adaptability, and flexibility (Fricke and Shultz 2005). Robustness is the ability of the system to continue delivering value in a changing environment. Agility is the ability to change rapidly. Adaptability and flexibility both refer to the ability of the system to change. Adaptation is an internally initiated change, while flexibility is externally initiated. Most of the confusion about these two categories comes from the subtle distinction between flexibility and adaptability. Ross (2006) explains:

> It is important to note that the only difference between flexibility and adaptability is the location of the change agent with respect to the system boundary: inside (adaptable) or outside (flexible). Of course the system boundary could be redefined, changing a flexible change into an adaptable one, or vice versa. The fungible nature of the definition is often reflected in colloquial usage and sometimes results in confusion. If the system boundary and location of change agent are well-defined, confusion will be minimized.

Since the distinction between flexibility and adaptability relies on the designers' definition of the boundary, these two 'ilities' are quantified and valued in the same way. The reason they are separate aspects of changeability is that they are designed into a system differently. Consider the simplistic example of popcorn in the microwave. Suppose the system boundary is defined as the bag of popcorn and the microwave, with everything else external. You wish to change the system in such a way that instead of heating the popcorn for a set amount of time, you will heat it until it is done (definition of 'done' is left to the reader as a personal choice). An adaptable system could involve a sensor and shutoff switch in the microwave to stop heating when the popcorn is done. A flexible system could involve a shutoff switch that is tripped by a person standing outside the microwave listening to the popping. With this example, it is easy to see the design choices for an adaptable versus a flexible system could be very different. An adaptable system needs to incorporate the ability to decide to instigate a change, while in a flexible system the decision-making ability is exogenous to the system. For the purposes of this paper, the term *flexibility* will be used, but in what follows, the term should be viewed as representative of the broader concept of changeability.

In most complex engineering systems, the desire for flexibility is based on a heuristic that more flexibility is good. This desire most likely comes as a response to uncertainty about the future. In systems design, uncertainty is often treated as synonymous with risk. Risk is defined as a measure of the downside of uncertainty in attaining a goal, objective, or requirement pertain-

ing to technical performance, cost, and schedule. Risk level is categorized by the probability of occurrence and the consequences of occurrence (Thunnissen 2003). However, the upside to uncertainty is opportunity. Flexibility has also been proposed as a way to mitigate risk inherent in an uncertain future. Saleh (2002) argues:

> Flexibility should be sought when: 1) the uncertainty in a system's environment such that there is a need to mitigate market risks, in the case of a commercial venture, and reduce a design's exposure to uncertainty in its environment, 2) the system's technology base evolves on a time scale considerably shorter than the system's design lifetime, thus requiring a solution for mitigating risks associated with technology obsolescence.

In the case of a commercial market, Fricke and Schultz (2005) contend that staying ahead in a dynamic environment requires a state of the art system throughout the lifetime of that system. To achieve that capability level, systems need to incorporate changeability throughout their life cycles within themselves and with respect to their environments.

Rajan (2004) examined flexibility in small to medium size consumer products. He says that since evolution and change are inherent in the nature of product design, products should account for these effects. In addition, the product needs to change to retain value during some unknown future. Uncertainty about the future leads to developing a design that can easily accommodate future changes—flexible designs offer manufacturers an option to reduce time to market and shortcut the evolution cycle.

The relationship between uncertainty and flexibility is described by Nilchiani (2005):

> We define flexibility as the ability of a system to respond to potential internal or external changes affecting its value delivery, in a timely and cost-effective manner. Thus, flexibility is the ease with which the system can respond to uncertainty in a manner to sustain or increase its value delivery. It should be noted that uncertainty is a key element in the definition of flexibility. Uncertainty can create both risks and opportunities in a system, and it is with the existence of uncertainty that flexibility becomes valuable.

Since unfolding uncertainty can give value to flexible designs, it is important to recognize how engineers think about future unknowns.

The authors cited above have each developed different approaches in response to the common problem of uncertainty facing designers. Overall, the problem can be understood with reference to three 'D' concepts here introduced: *Dice, Designs & Decisions,* and *Discounting,* as shown in Figure 1.

Put succinctly, the design problem under uncertainty can be stated as the following. Designers wish to develop engineering solutions that meet their needs both now and in the future. They, however, are uncertain as to what that future will be with respect to needs, technology and resource available. They therefore try to design solution that will deliver high value to them in a variety of different possible futures. They also attempt to create designs that allow them (or their customer or agent) to make changes and adjustments to the engineering solution so that they can maximize value once the future is known. Since they must make design choices now on the promise of future benefits, their decisions will be based on their perception of the value of the future benefits as seen at the time of decision.

The first 'D' of this decision problem is termed *Dice.* This represents the uncertain future within which the engineering solution will be delivering benefit to stakeholders. Various approaches to the decision problem characterize the future in different ways. For example, some take scenario-based approaches where various future states are described as members of families

of discrete possibilities. Other approaches view the uncertain future as a continuous space of possible states with probabilities assigned across the space. More complex models take a hybrid approach mixing both continuous and discrete elements. None of these are correct for all situations; the particular representation chosen by a designer will depend on the information available. Designers must be fully cognizant of the assumptions being made in choosing a particular representation and must interpret the results with these assumptions in mind. Representations should not be chosen simply for computational convenience – if a normal distribution is assumed, then that choice needs to be justified.

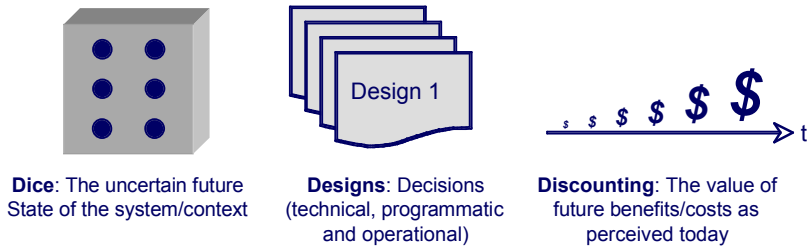

Figure 1. The "Three D's" for valuing flexibility

The second 'D' refers to *Designs & Decisions*. While the future is uncertain, designers may still have some control over current design choices and, as the design allows, over choices in the future, in response to the resolution of uncertainty. Other stakeholders may also be able to change the design in response to future events. These future decisions are referred to as contingent decisions, as they are dependent upon future environments. Decision metrics should account for this ability of stakeholders to make choices at different points in time. An example of this 'D' is the use of a modular architecture to allow deferral of module selection. The availability of alternative modules is the *Designs* 'D', while the ability to choose at a future date which modules to include is the *Decisions* 'D'. Taken together, they reflect the ability of stakeholders to influence the future of a system.

The third 'D' is *Discounting*. Given that the payoff of implementing a design (and making subsequent contingent decisions) will be experienced in the future as well as now, the future benefits need to measured from today's perspective in order to properly compare these time-spread benefits. Formally, future benefits and costs need to be discounted back to a common point in time--often the present, but can be any point in time–so that different design options can be compared on a common temporal basis. Various methods of valuation (e.g. NPV or decision trees) and discounting (e.g. exponential or hyperbolic) can be used. The decision maker must be cognizant of the assumptions behind the chosen method as they can lead to very different outcomes.

Valuing and Quantifying Flexibility

Various methods of dealing with uncertainty in design can be mapped to the three 'D's. For example, the classical risk matrix (see, for example, Leveson 1995) includes *Dice* in assessing the probability of hazards and *Discounting* in evaluating the impact of hazard as perceived today, but has less emphasis on active intervention by stakeholders[1]. Options based approaches, described below, include all three 'D's. Of the three 'D's, *Designs & Decisions*—finding the best set of contingent decisions to have available to respond to the resolution of uncertainty—is particularly challenging and is the goal of flexible system design. Finding the right set of *Designs & Decisions* can be looked at in two different ways depending upon the information available to the

[1] Stakeholders may use the matrix to prioritize investigation into interventions, but the interventions themselves are not explicitly represented in the matrix.

designer. If the designers know decision makers' needs as well as contexts, both now and in the future, then they can focus on choosing designs that enable valuable[2] contingent decisions to be made (formally, designs with high option value[3]). This situation is referred to as valuing flexibility since it assesses the benefit incurred at cost for having flexibility and is the problem addressed by real options analysis. Often, the designer will not know the future needs of the decision maker, but may have some sense of potential contextual changes that would suggest a preference for a flexible design. In these cases, designers may wish to maximize the number and variety of contingent decisions available in the hope that valuable decisions will be included and available when needed. This situation is referred to as evaluating flexibility since it quantifies the degree of flexibility, but does not address whether such flexibility is of value to the decision maker. Change propagation reveals likely places within a design where the ability to make contingent decisions may be useful, given a scenario-based characterization of uncertainty. Filtered out-degree provides a metric for evaluating the degree to which a given design is flexible in terms of the number of other designs into which it can transform through contingent decisions.

Real Options. Options are defined in the finance literature as the "right, but not the obligation" to take an action (e.g. deferring, expanding, contracting, or abandoning) at a predetermined cost and at a predetermined time. "Real options" are options that pertain to physical or tangible assets, such as equipment, rather than financial instruments. Real options improve a system's ability to undergo classes of changes with relative ease, which relates to the system's flexibility.

Real Options Analysis, which is the technique of determining the value of having a real option, can be applied "on" a system or "in" a system. When analyzing options "on" a system, the option is external to the physical design. Alternatively, analyzing options "in" a system requires the option be internal to the physical design.

Real options literature presents a three-phase process for applying real options "in" a system. (Wilds et al. 2007) The first phase is data collection, where designers should identify and model uncertainties and externalities that impact the valuation of designs (*Dice*). The second phase is to determine the alternative designs applicable to the problem (*Designs & Decisions*). The final phase is modeling and assessing the value, where the real options are valued using tools such as decision trees and/or lattice method to value flexible designs comparatively (*Discounting*). (Wilds et al. 2007)

One of the most significant challenges in applying real options to engineering systems is the problem of identifying potential locations within the system to create options. To identify the points of interest, systems engineers require knowledge about the physical and non-physical aspects of the system, insight into sources of change, and the ability to examine the dynamic behavior of the system. Real options analysis does not generate good decisions about where one should place options during design, but rather the results only help to determine whether one option is better to hold than another given a particular characterization of the future uncertainty.

Identifying Sources of Flexibility. To identify places for real options for flexibility, designers should seek areas in the design that can be easily manipulated and that contribute significantly to performance. Suh (2005) accomplishes this identification step using Functional Requirement-Design Parameter (FRDP) representation. FRDP maps the physical design parameters to the defined functional requirements. Bartolomei (2007) uses an Engineering System Matrix (ESM), similar to an expanded Design System Matrix (DSM), which includes the objective,

[2] As used here, value means a perceived benefit to the decision maker in return for spending a cost.

[3] Here option value means expected benefit at cost where the expectation is taken over the distribution of possible future states.

functional, and physical domains and their corresponding relationships. Recognizing early in the development process the relationships between the physical components and the resulting capability provides the designer the option to exploit the places where flexibility would likely be most valuable, especially if the functional requirements are uncertain upon design conceptualization. However, the system must be initially designed with these options to create such flexibility.

Change Propagation Method. Clarkson et al. (2001) present a framework for analyzing the propagation of change throughout a system. Because change becomes more costly as the design matures due to integration efforts (i.e., a change to one part is more likely to affect multiple additional parts), it is advantageous to understand how the system will respond to future change and, if possible, create a design that is flexible to those changes. This paper will attempt to use the Change propagation analysis (CPA) (Eckert 2004) method to assist in the formulation of real options so that the flexibility can be valued.

System Connectivity. Simon (1996) defines system complexity in terms of the connectedness of the components. Highly connected systems have highly connected components. This connectivity of the components in the system, or between systems, may result in "knock-on effects" when change is introduced to one or more components within the system, causing the change to propagate downstream and/or upstream throughout the entire system. (Eckert et al. 2004)

In their research, Eckert et al. (2004) found that the network of connections could be better represented as a change matrix, similar to design system matrix (DSM) models. (Steward 1981; Eppinger et al. 1994; Danilovic & Browning 2007) Change relationships in the change matrix are defined as a combination of the likelihood and impact of the change, as opposed to a DSM where the relationship is not necessarily quantified. (Clarkson et al. 2001) More importantly, the DSM represents a directed connectivity graph. This graph may include relationship directions according to the system flows, however those directions may be redefined depending on the change introduced and where the change is introduced in the system. Thus, a change matrix must be created for each change scenario.

In the event that the likelihood and impact of the change are not easily known, an alternative method for setting up the CPA is to develop a system DSM. The DSM includes a physical decomposition of the system to the component level. Then, different types of relationships can be defined between the components and represented as edges in the directed graph. Although this method provides less information initially, modeling the uncertainty including possible outcomes and the probability of occurrence may be delayed to later in the analysis.

Propagation of Change. Change propagates when the tolerance margins of individual parameters are exceeded. (Eckert et al. 2004) Tolerance margins often include a design buffer, or contingency margin, which is used to absorb emergent changes that are not known at the time of design. Contingency margins are often decided based on primitive assessment of future uncertainties. Therefore, the first step in analyzing potential change propagation is identifying change scenarios based on the future uncertainties. Defining the change scenario with respect to the system uncertainty is a crucial step. External uncertainties drive the internal changes within the system. Thus, change scenarios ask the question: "If component A is required to change due to resolved uncertainty, what other components will also change?" In this example, component A is the change initiator. The question is answered based on the assessment of the perceived magnitude of change required as compared to the component's contingency margin. If the margin is exceeded, then change is propagated, however, if the margin is not exceeded, then change is absorbed.

Complexity increases when a single change scenario includes multiple change initiators. Also, a single identified uncertainty may be associated with multiple change scenarios. Therefore, in a complex data set, filtering the connections that are not effected by the change scenario may reduce the computational complexity of the analysis. Filtering can only be accomplished if designers are knowledgeable about the system, and information about the change uncertainty is available. For example, an interview with a Subject Matter Expert (SME) can be conducted to determine the change initiators for each change scenarios. The SME may be asked to consider which components within the system would likely be changed in *direct* response to the particular change scenario. And furthermore, the SME may then be asked to identify which of the relationship types (i.e., energy flow, spatial, information flow, etc.) are most directly affected given the change scenario.

Caution should be used when filtering the data since the exclusion of the change initiators and relationship types has the potential of limiting the analysis outcome. Failing to include a potential change initiator may result in under representation of the possible change paths. This outcome may be intended or even appropriate if the designer perceives that the change introduced through the eliminated change initiators is immediately absorbed by either the initiator or a connected component. Then, the result is a filtered outcome, giving significance to only the included change initiator, resulting in a filtered subgraph.

Responsive Behaviors. Change propagation analysis requires an understanding of the behavior of the system in response to change, including the direction of the change propagation in the system. Eckert et al. (2004) identify four types of change propagation behavior:

- "Constant are unaffected by change;
- Absorbers can absorb more change than they propagate;
- Carriers absorb a similar number of changes than they propagate;
- Multipliers generate more changes than they absorb."

Because the change propagation behavior is dependent on change flows in and out of the component, a SME can evaluate each of the included relationships by answering the question "Which direction does the change flow?" for each change scenario and relationship type. Here, it is important to note that the SME's response is dictated by the level of understanding of the overall system and each individual component. A thorough knowledge of the contingency margins within the system is ideal since the propagation of change is highly dependent on these margins. Then, using the perceived direction of change flow, a directed sub-graph can be created. This step allows the SME to explicitly document the perceived direction of change flow and provide reasoning for the elimination of any edge in the filtered graph.

Suh (2005) introduces a metric, Change Propagation Index (CPI), which measures the degree of change propagation caused by a component due to a change required on the component. The CPI represents the summation of the outward change propagating edges less the summation of the inward change propagating edges. A CPI >0 indicates a component that is propagating more changes outward than receiving inward, i.e. the component is a multiplier. Similarly, a CPI=0 represents a constant or carrier, while a CPI<0 represents an absorber.

Eckert et al. (2004) acknowledges that system components do not have a predetermined change behavior, even in the case of a similar change scenario. The change behavior can be altered by adjusting the contingency margin of the part to either absorb or propagate the change. Also, because the CPI is based solely on counting the edges, the metric does not reflect any indi-

cation of the magnitude of the change occurring across each individual edge or across the system as a whole. Instead, Suh (2005) expresses the switch cost associated with the change as the more significant attribute of the change. The switch cost is the cost of engineering design, additional fabrication and assembly tooling/equipment investment required for the design change (Suh, 2005). Accurate evaluation of switch costs is critical for valuing a flexible design.

Formulating Real Options. The CPI as a metric of the change behavior varies across change scenarios and the context in which the system is examined. For example, Eckert (2004) does not distinguish between relationship types in the classifying of the change behavior (i.e., multiplier or absorber). Thus, an aggregated CPI can be calculated by summing component CPI for each relationship type within the change scenario. This result provides an indication of which components are overall multipliers/carriers/absorbers for the change scenario, independent of the relationship type. Alternatively, another context for CPI analysis may include examining the change behaviors of the nodes for each relationship type across all change scenarios. A calculation of CPI given this context would require summing the CPI for each node in all subgraphs for a given relationship type. The variations in CPI calculations are determined by the filters applied to the data given a particular context. Using the results from differing contexts for CPI analysis, designers can create real options for flexible design.

Suh (2005) suggests looking first for change multipliers or components that the multipliers are propagating change to, and adjusting their contingency margins to absorb the change, thus making the system more robust to the change scenario. Similarly, designers could seek out change multipliers to locate where it might be good to embed flexibility in order to change the propagation paths. In the event that the change multipliers cannot be modified or if the change propagation paths are not altered by the possible modifications, then an option to modify surrounding change carriers may provide the desired outcome. While this approach to creating options is dependent on the goal/benefit of exploiting the options (i.e., to reduce the cost impact of the change on the system or to allow for the system to adopt new capabilities in the future), utilizing the results of the CPA can assist designers in: 1) identifying potential locations for options and 2) providing an improved estimate of the switch costs associated with the option due to the inclusion of the change paths.

Once real options have been formulated, they can then be valued using ROA tools. In some cases, the switch cost of implementing an option may be more than the perceived benefit of the changed design when compared to other designs, and this will be observed in the valuation of such options. Wilds et al. (2007) provides an example of the valuation of real options "in" a system using three different ROA tools. Wilds and Shah (2008) provides an extended case study applying CPA as described.

Filtered Outdegree Method. The above discussion of CPA took a bottom-up approach to the problem of flexible system design. CPA focused on the structure and connectivity of system components and then attempted to determine beneficial modification to the structure to limit the impact (and/or take advantage of the upside) of uncertainty on future system performance and cost. Designers can also considers flexibility of the system architecture as a whole. When considering the flexibility of a system, the degree of flexibility can be reflected by two aspects: the number of possible end states for a changed system, and the transition, or "switch", costs for those change paths. In order to account for these two aspects, as well as the apparent subjective disagreement over the flexibility of a system as perceived by various decision makers, Ross (2006) introduces the concept of *filtered outdegree* (f-OD) as a quantified measure of the perceived degree of changeability of a system (Ross 2006; Ross and Rhodes 2008). The outdegree

of a system design is the number of possible end states for a design when analyzed within a tradespace network. A tradespace network is formed through the enumeration of transition rules that specify how a given design can be changed into a different design. The more possible end states for a changed system; the more flexible the system. The filtered outdegree for a system design is the outdegree filtered by the transition cost acceptability threshold, which varies across decision makers. What is inexpensive to one decision maker may be prohibitively expensive for another. The lower the transition costs for a change, both in dollars and time, the more likely a given decision maker will deem that change acceptable.

An outdegree function can be defined by varying the cost threshold for permissible transitions. The resulting graph (Figure 2) comparing OD functions of several designs aides in visualizing the trade-off between flexibility and cost to achieve that flexibility. As the cost threshold is increased, more and more transitions are deemed feasible until all possible transitions are included.

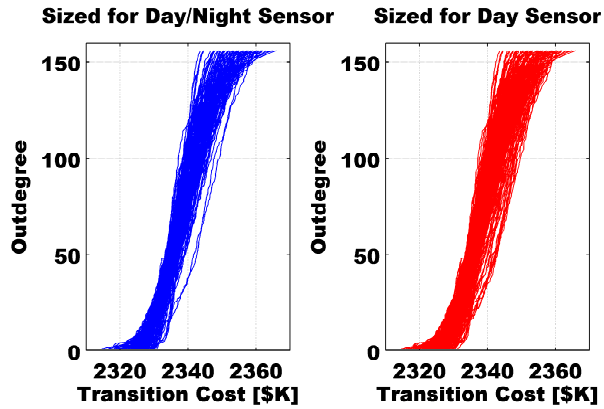

Figure 2. Outdegree function for two different micro air vehicle platforms

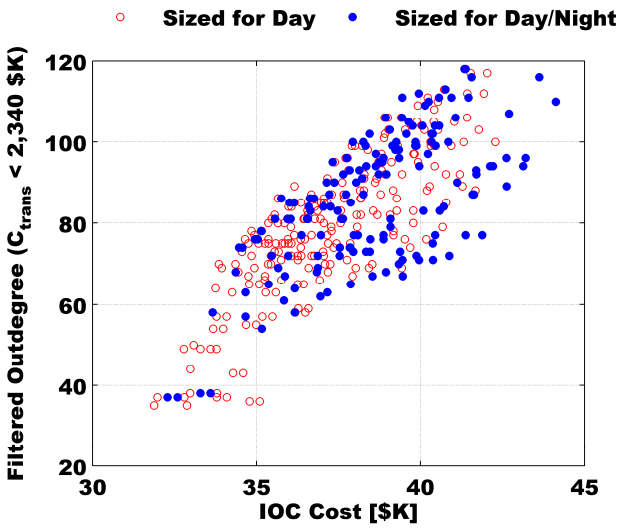

Figure 3. Filtered outdegree and initial cost

If designers find in the OD function that high flexibility is too expensive, or if the OD is not generated through sufficient variety of transition possibilities, then they can investigate embedding real options into the designs using the techniques described in the CPA section or by other means. These options serve as path enablers by reducing the cost of transition, and thereby increasing the f-OD. Of course, having these options may require additional initial expense, but that may be justified by the additional flexibility. As an example, consider the design of a micro air vehicle that is initially required to only fly during the daylight hours. Designers may wish to make the system flexible by allowing for future incorporation of a day/night sensor. One possibility is to initially design the aircraft to only work with the day sensor, and then re-design it to accommodate the day/night sensor. This strategy has the advantage of allowing optimization of the air platform (airframe, power systems, etc.) to the particular sensor in use. However, the cost for incorporating the new sensor will be high, as the air platform may need to be modified. An alternative is to size the air platform for the larger, heavier day/night sensor and allow a lower cost upgrade to day/night capability when it is available. This larger air platform may be more expensive initially, but may be more flexible as well. A

plot such as Figure 3 can be presented to a decision maker demonstrating the tradeoff between higher upfront cost and future flexibility. In this example, the air platforms sized for Day/Night tend to have higher outdegree. There is little difference in cost between the optimized and flexible design. This is because the bulk of the cost of the air platform is internal components that are common to both the optimized and flexible design. Wilds and Shah (2008) documents in full detail the micro-air vehicle example summarized above.

Thus far, transitions have only been evaluated in terms of the cost incurred when taken. The end points of different paths also deliver different benefits. If sufficient information is available to measure these benefits, then each path can be valued using real option analysis and paths that do not generate sufficient value to justify their transitions costs can be eliminated.

Summary, Discussion and Future Work

Base upon a review of literature related to system flexibility, the *Dice, Designs & Decisions, Discounting* framework was developed. This framework articulates the key features of the decision to allow for contingent choices to be made in designing and managing systems. A distinction is then drawn between the quantification and valuation of flexibility. Quantification refers simply to the degree to which changes can be made to design in response to future events. Valuation, on the other hand, considers whether the cost of having access to particular set of possible changes is justified. CPA and f-OD can be used to aide in developing flexible (in terms of quantification) systems. When combined with ROA, valuable flexibility can be identified. Integrating the methods described here with ROA to address the valuation question is the next goal of the overall research effort.

CPA, as extended from the cited work, allows the designer to investigate how possible changes will impact the structure and behavior of a system design. The method outlined can aid designers in identifying system components that have some likelihood of changing. Designers can focus efforts on reducing change costs and impacts by embedding options into the design. Using the multipliers and carriers as guides, designers can develop potential options for inclusion, and then use ROA to determine which options generate sufficient benefits to justify costs.

CPA does have some limitations, however. CPA results are highly sensitive to the particular set of change scenarios considered. If changes cannot be well represented or characterized, the analyst may miss identifying the change initiator or incorrectly propagate the change. CPA also relies upon representation of a system as a static graph of interactions between components (the DSM). Complex systems that change structure or behavior in response to changing contexts, i.e. self-modifying or intelligent systems, may not be easily represented using such a construct. Furthermore, traditionally DSMs only represent binary relationships between components. In complex systems, there may be multiple types of relationships between components. For example, two components may be physically connected, as well as exchange electrical energy. In different change scenarios, one type of relationship may result in change propagation, while the other does not. System representation that explicitly includes multiple relationship types, and filtering by those types when analyzing changes, helps to mitigate this issue. However, dealing with change scenarios that involve multiple relationship types is an ongoing research challenge.

Filtered OD analysis allows the designer to consider change at a system level by identifying designs that are most amenable to being changed given decision maker specified constraints. The f-OD metric quantifies the degree of flexibility of a system design. It is limited however, in that it does not address the value of being able to reach particular end states. Determining the value of having flexibility requires consideration of both changes in needs, as well as context in

which those needs are being expressed. Follow-on work to this paper is focused on bringing structure to and developing methods for addressing this issue of valuing end states.

CPA and f-OD can be used in concert to increase flexibility at a system level. Designers can use change scenarios to motivate system transition options or paths, and use f-OD to find system designs that are more flexible. The OD function can provide decision makers with a visual representation of the tradeoff between cost incurred in exercising transitions and the variety of transitions available from which to choose. Since the cost of transition is directly related to the changes in the system that occur during a transition, CPA can be used to determine where in the system those costs are being incurred, and to identify portions of the system that could benefit from redesign (e.g. through the addition of options) to reduce transition costs and/or to increase the variety of transitions available at a given cost. Taken together, CPA and f-OD can be used to help guide designers to generate and place real options to enable valuably flexible systems.

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