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Anatomy of a Change Option: Mechanisms and Enablers

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Abstract. Designing systems that can deliver value to stakeholders is more than just eliciting requirements and developing sound and efficient technical solutions. In a time when technology, policy, economic conditions, and system end uses can change on short time scales, it is necessary to better conceive and manage system changes in order to alter system form, function, or operations to continue to deliver value in spite of exogenous changes. In order to better characterize and explicitly consider "changes" in a system during its lifecycle, this paper introduces the concept of "change mechanism" and describes the essential aspects that need to be considered for intentional changeability. The links between design principles, change mechanisms, and system properties are described in order to help frame how designers can create and evaluate changeability across various system types.

Introduction

Motivation. The purpose of this paper is to discuss current progress in developing a general framework for representing the concept of "change mechanism", which is the way in which a system can change. Related concepts of "path enablers" and "real options" will be briefly addressed, as well as precursor research that inspired some of the current aspects of the change mechanism framework. A section on example change mechanisms provides illustrations of four aerospace system case studies that used the concepts of path enablers and change mechanisms in order to evaluate the changeability of alternative system conceptual designs. Ultimately this more general formulation of change mechanisms is intended to assist the broader goal of providing prescriptive design principle guidance on how to intentionally create more 'valuable changeable' (i.e. flexible and adaptable) systems. The resulting framework is intended to provide engineers with a more precise and formal way to specify and evaluate candidate system changes, and make decisions that ultimately result in a system that will be responsive to its changing stakeholder needs and environment.

Prior Work. The following section describes precursor research related to the concept of "system change in response to context and needs changes."

Change Events as Paths. The construct of "change events as paths" has been described as fundamental to a more precise understanding of a system change (Ross, Rhodes, and Hastings 2008). A system change event can be characterized with three elements: (1) the agent of change, (2) the mechanism of change, and (3) the effect of change, as illustrated in Figure 1. The *agent of change* is the instigator, or force, for the system change, and the role of the role of change agent can be intentional or implied, but always requires the ability to set the change in motion. The *mechanism of change* describes the path taken to transform the system from the current state to the future state, including, including any costs, both time and money, incurred. Some examples of change mechanisms include swapping of modular components, execution of real options. The third element, the *effect of change*, is the actual difference between the originating and destination states.

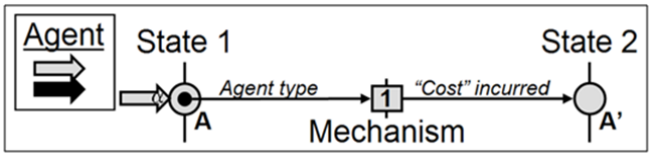

Figure 1. Change Defined as State Transition

Figure 1 shows a simple case of one particular change. In the agent-mechanism-effect representation, a particular change is represented by a path, and the changeability of a system is determined by how easily it can undergo various changes. The example in Figure 2 illustrates an expanded view. The multiple change paths available are enumerated. Using this construct to more precisely characterize change, the representation shows a change performed by a change agent external to the system is termed a flexible change, and where the change agent internal to the system is an 'adaptable' change.

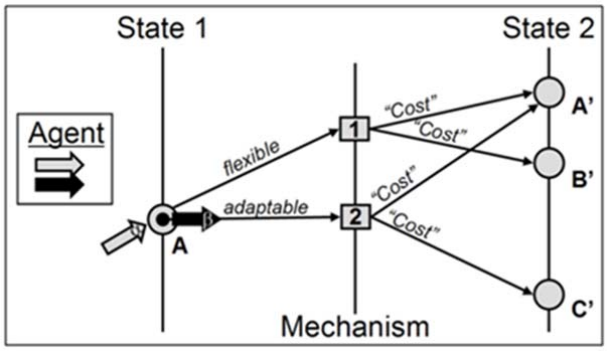

Figure 2. Multiple System Changes Depicted Using the Agents, Mechanisms, and Effects Representation

Taking this one step further, Figure 3 includes a "perturbation" as an instigator that triggers a *change pathway*: *perturbation-agent-mechanism-effect.* A perturbation can be exogenous to (outside of) or endogenous to (inside of) the system. The decision is made as to whether to execute a pathway for change.

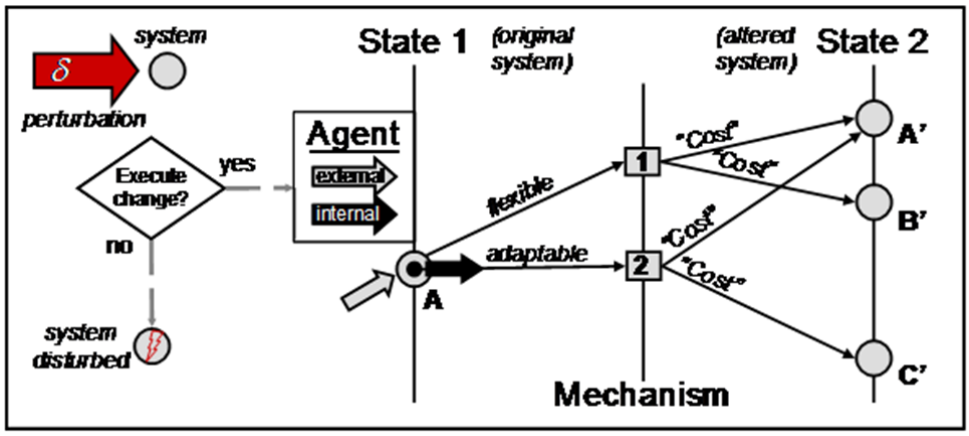

Figure 3. Change Pathway Illustrated With Perturbation Catalyzing a "Decision" by a Change Agent Whether to Execute a Change Mechanism to Alter System to a New End State (Change Effect)

Changeability Taxonomy Based on Change Pathway. The change agent location (internal or external to system) has been discussed as a useful taxonomic distinction for classifying

change **(Ross, Rhodes, and Hastings 2008)**. In the framework, if the change agent is external to the system, then the change under consideration is a *flexible*-type change in this taxonomy. The change is an *adaptable*-type change if the change agent is internal to the system. Depending on the particular change being considered, a single system can be both flexible and adaptable. The definition of the system boundary must be explicitly defined in order to remove ambiguity in characterizing a change as flexible or adaptable.

Tradespace exploration is an important approach in early system decision making, where understanding change options provides greatest value Tradespace Networks (Ross, Rhodes, and Hastings 2008). The typical tradespace plot displays the system designs on a Cost-Utility space, showing the resources required (cost) and benefit delivered (utility) for systems in a concise format. Using the tradespace plot, a Pareto Set can be identified that characterizes those "non-dominated" designs of highest utility at a given cost, across all costs, or those of lowest cost at a given utility, across all utilities. It often shows the tradeoff of cost incurred for increased value. Considering each design as a potential starting or ending state for system change, the tradespace frame suggests a mechanism for considering the changeability of system designs. In the instance where specifying design parameters (static representations of a system) designers also specify transition paths (dynamic change opportunities), a traditional tradespace can become a *tradespace network*.

A tradespace network leverages the network representation of entities and relationships, and its associated analytic techniques. A network is composed of nodes and directed arcs, with each node representing a state and each arc representing paths that link allowed state changes. In a tradespace network representation, each node corresponds to an alternative system design and each arc is a possible transition path between two alternative designs. More than one arc can link the same two designs, representing the possibility of more than one to change a design from one state to the same alternate state. Each arc has an associated "cost" for execution, which can be represented in terms of appropriate resource expenditure, such as dollars and time. Figure 4 shows a traditional static utility-cost tradespace transformed into a tradespace network after the specification of transition rules, which are used to generate transition paths between design nodes.

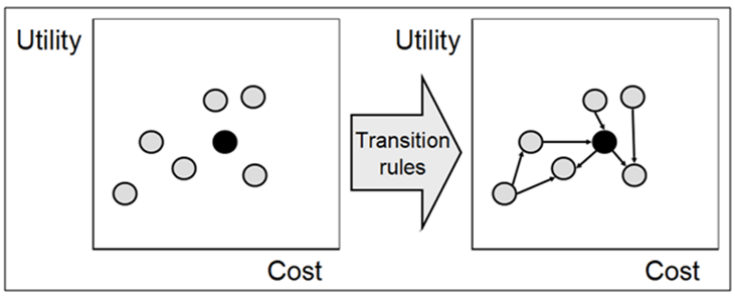

Figure 4. Specifying Transition Rules Transforms a Tradespace Into a Tradespace Network

Figure 5 illustrates that when counting paths, one includes the agent-mechanism combination as a unique path. Each path has an associated cost with it, given the mechanism that is used to move the system from one state to another state.

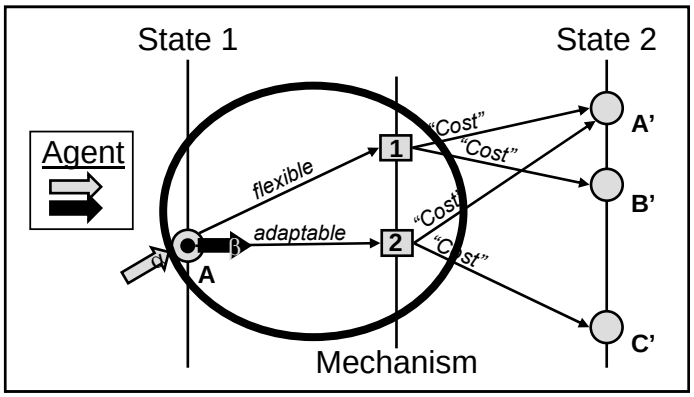

Figure 5. For Counting Paths, Include Agent-Mechanism Paths

Filtered Outdegree. The tradespace network representation provides a foundation for measuring changeability paths, given that each path will have a "cost" associated with its execution. Each decision maker will have an acceptability threshold for time or money spent for enacting change. The number of outgoing arcs from a particular design is called the *outdegree* for that design, as illustrated in Figure 8 (left). The number of outgoing arcs from a particular design whose cost is less than the acceptability threshold, $\hat{C}$, is the *filtered outdegree* for that design, as illustrated in Figure 6 (right) (Ross 2006). The filtered outdegree is a quantification of the apparent changeability for a design for a decision maker. The higher the filtered outdegree of a design, the more changeable it is to that decision maker. In the figure below, the outdegree counts the total number of change paths from a given design, state 1: A, to future designs, states 2: A', B', and C', shown with outdegree of four; (right) The filtered outdegree counts the number of change paths with acceptable cost, from a given design, state 1: A, to future designs, states 2: A', shown with filtered outdegree of two.

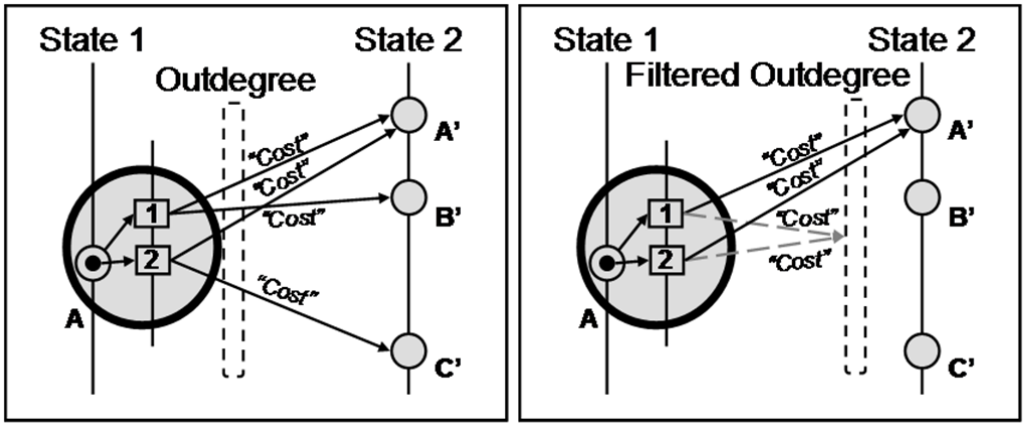

Figure 6. (left) Outdegree; (right) Filtered Outdegree

The objective, coupled with subjective nature, of the filtered outdegree captures the apparent relativity in perceived changeability of various designs: *what may be changeable to one decision maker may not be perceived as changeable to another*. The subjective acceptability threshold differentiates the results per decision maker. Acceptability threshold "cost" can be on dollars, time, or any other resource that must be "spent" in order to follow a path. The objective outdegree calculation provides a mechanism for system designers to explicitly improve the potential changeability of a system: increase the number of outgoing arcs (add new transition rules), or reduce the cost of following outgoing arcs (increase the likelihood for arcs to cost less than acceptability threshold). The subjectivity in the filtered

outdegree means that the setting of the threshold is subjective to the particular decision maker and his preferences for spending resources for change. The full outdegree, without filter, is an objective quantity upon which all people will agree, given a set of enumerated design variables and a set of transition rules.

Change "Rules" and Mechanisms

To clarify the concept of change mechanisms and transition rules, the following describes these two concepts. A *change mechanism* is a method by which the system is changed. For example "burn on board fuel" change mechanism results in a change in satellite orbit, costing "extra ops cost" for executing the maneuver (in this case the system "state" includes the operating orbit). A *transition rule*, also called *change rule*, is an algorithm that determines whether two proposed "states" are connected through a particular change mechanism. For example: "compare two 'states' and if difference is only fuel and orbit location, then if fuel difference is equal to amount burned to achieve orbit difference, then states have directed accessibility via change mechanism for cost determined by that mechanism." The change rule is an operationalization of the concept of change mechanism in order to allow for computationally generated and evaluated alternative "paths" in a tradespace network, greatly automating the analysis process.

"Degree of" Change. One of the essential concepts related to changeability regards the number of possible system end states reachable through available change mechanisms, summarized in Figure 7. In some sense, if a design has more reachable end states, that design is more changeable. A given change mechanism may have some number of countable or uncountable end states. For example, a sleep number bed has 100 "levels" for firmness, corresponding to 99 alternative end states from a given starting state using the change mechanism of dialing the controller to inflate or deflate mattress-embedded air bladders using a pump. Alternatively, a design might have available more than one change mechanism, which also adds to the number of potential end states.

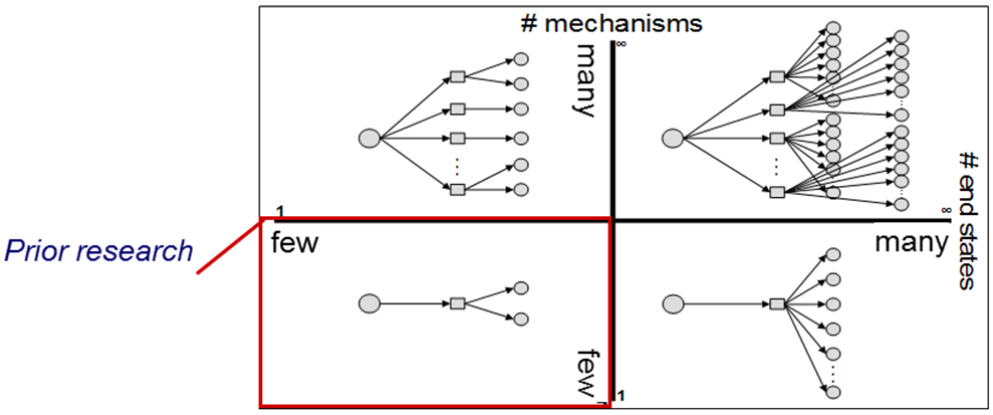

Figure 7. Degree of Changeability as a Function of Number of Mechanisms and End States

Figure 7 displays a four quadrant view of differing numbers of mechanisms and end states. Prior research focused in the lower left quadrant and a goal of on-going research is to expand to the other quadrants. Investigating the heuristic that "more end states is better" resulted in the following insights for why the number paths to end states might matter.

Mechanism blocking. One can conceive of instances where a particular change mechanism might become blocked, that is, unable to be executed. This blocking could occur as a result of a system failure, or imposed constraint, such as policy. For example a change

mechanism may require the execution of prior-arranged contract agreement, but an ensuing policy directive prevents such relationship from taking place. Or one might purchase spare parts to allow for a "repair" change mechanism, only to find that the expert knowledge for conducting the "repair" was not available when needed years later. Having more change mechanisms allows a design to retain changeability even when one or more change mechanisms are blocked.

Mechanism paring. One can also conceive of instances where particular end states may no longer be available within execution of a particular change mechanism. For example, the pump needed in the sleep number bed example from above might become mechanically degraded resulting in a smaller range of possible firmness levels from 100 to 30. Certain destination orbits for a deployed satellite might become unusable due to orbital debris accumulating later in the lifecycle, thereby reducing the number of end states for the "change orbit" change mechanism. Having more possible end states for a given change mechanism allows a design to retain some changeability even when one or more end states are pared from a change mechanism.

Uncertainty in desired goal end state. One may also recognize that the desirability of a particular end state may be context dependent. That is, the particular mission in operations may change over time and the target end state for a system may not be what was anticipated earlier in the lifecycle. Having more possible end states allows for a design to have a higher likelihood of having a "good" end state available when the definition of "good" changes over time.

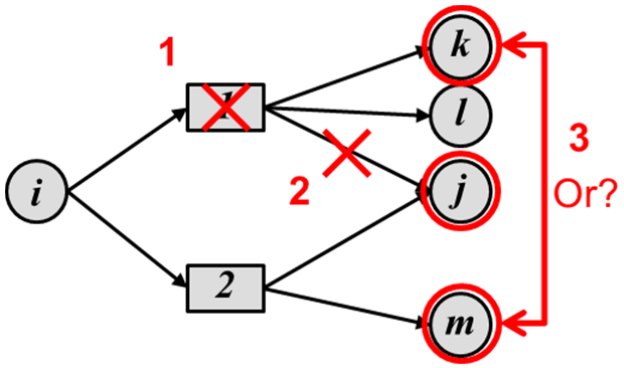

Figure 8. Justification for Need to Account for Number of Change Paths

Concept of Path Enabler. Supplementing the concept of system design state and change mechanism for switching between design states is the concept of "path enabler." Path enablers create opportunities for change mechanisms, or lower the cost and/or time for executing a change mechanism. Consideration of how individual or groups of design concepts could change is another act of design, similar in vein to initial concept creation. Change mechanisms can affect present design variables, as well as "enabling" variables that create the opportunity for change mechanisms. The transition rules are the specification of how one design can be changed into another. Each transition rule takes into account a subset of the design variables, potentially including the enabling variables as well, specifying the "cost," or resources needed, for the transition. An example of a transition path from one state to another includes "spending" down one variable in order to get an increase in another, or "spending" down an enabling variable.

Related Research

A number of precursor research efforts directly impacted the current formulation of change representation for design and analysis. In addition to Ross (2006), Mikaelian (2008), Mikaelian (2009), and Nilchiani (2005) had a strong influence, wrapping in many concepts

related to flexibility and real options. What follows is a set of highlights and excerpts as related to "change mechanism" constructs in this paper.

Mikaelian. Mikaelian (2008) introduces the concept of "mechanism" and "option type" as a necessary tuple for specifying real options. The word choice of "mechanism" is a bit unfortunate, as it does NOT corresponds to the meaning of "mechanism" above. Rather, Mikaelian's "option type" is equivalent to "change mechanism" discussed earlier in this paper.

According to Mikaelian (2008), "real options are generally defined as the right, but not the obligation, to take an action or make a decision at a future time. At an intuitive level, real options capture the concept of flexibility." In order to generalize the concept of option from financial decisions to "real" [system] decisions, two different sets of actions were proposed: "implement a 'mechanism'" and "exercise specific 'type' of decision." The 'Mechanism' and 'Type' actions are depicted in Figure 9. Mikaelian defines these two actions as follows:

> *1. **Mechanism**: A mechanism is defined as the set of actions or decisions that either directly or indirectly enables a real option. An active mechanism is defined as a mechanism that directly enables a real option. For example, designing a modular payload bay for a mini air vehicle is an active mechanism that directly enables the flexibility to switch the type of payload. A passive mechanism is defined as a mechanism that indirectly enables a real option. For example, the decision to buy a plant is an indirect enabler of the real option to shut down the plant. It is not a direct enabler because the flexibility to shut down the plant already existed and buying the plant simply enables the owner to exercise this flexibility.*
>
> *2. **Option Type**: The option type is characterized by the set of actions or decisions that may be exercised by the owner of the real option. For example, the option to switch the payload of a mini air vehicle, the option to abandon a project and the option to enter a new market are different types of options, referred to as an operational option, abandonment option and growth option respectively. (Mikaelian 2008, 3-4)*

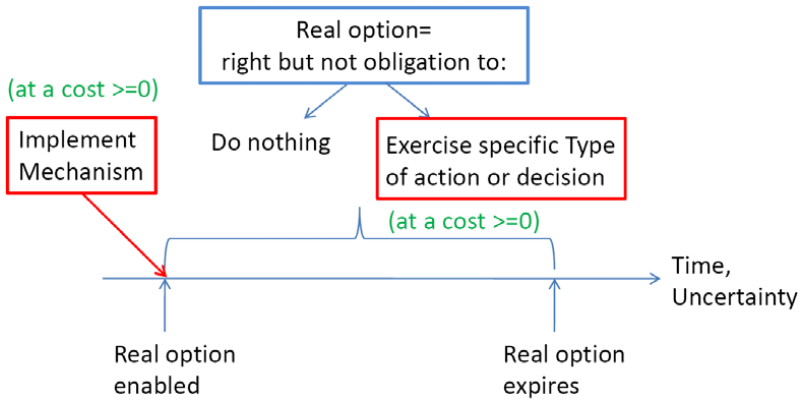

Figure 9. Anatomy of a Real Option (Mikaelian 2008)

Related to the concept of "mechanism" and "option type", Mikaelian also introduces three ilities relative to how mechanisms and option types affect the ability to achieve objectives under uncertainty. This relationship is shown in Figure 10 from Mikaelian (2009). Optionability is the ability for a "mechanism" to enable more than one "option type." Realizeability is the ability for more than one "mechanism" to enable one "option type." Flexibility is the ability for more than one "option type" to impact a given objective.

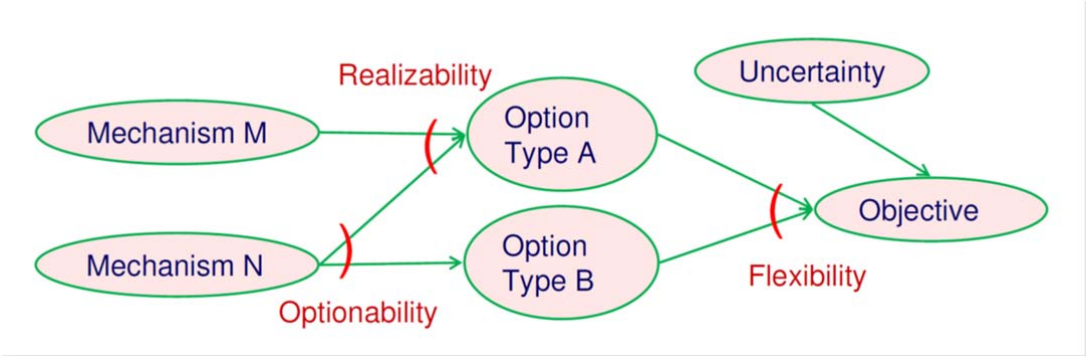

Figure 10. Optionability, Realizeability, and Flexibility (Mikaelian 2009, 33)

In relation to the framework in this paper, *optionability is the ability for a path enabler to enable more than one change mechanism*; *realizeability is the ability for more than one path enabler to enable a change mechanism*. One can see that a path enabler with high optionability may be useful if one desires a large set of change mechanisms. High realizeability for a change mechanism would be useful if there is uncertainty of availability of path enablers.

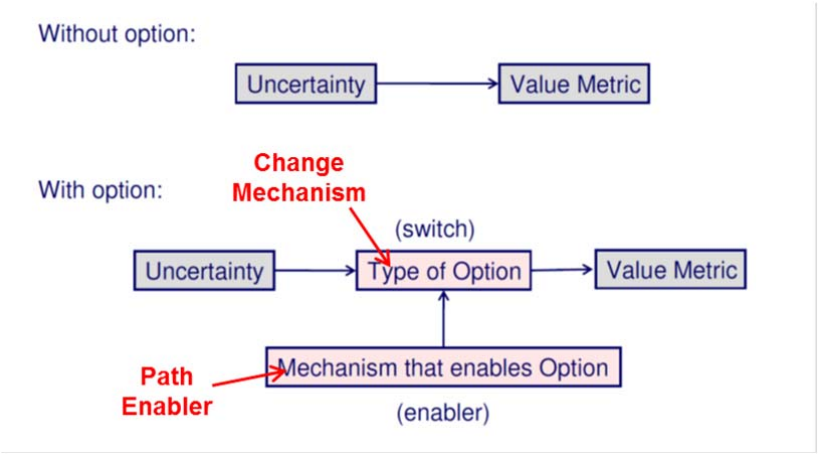

Figure 11. Option as Switch with Enabler (modified from Mikaelian 2009, 116)

Figure 11 illustrates the enabler-switch role of a real option in mitigating the impact of uncertainty on a value metric. One can see from this figure that the Mikaelian "mechanism" is in fact an "enabler" for the Mikaelian "option type" switch. In order to clarify these concepts into the framework of constructs discussed in this paper, the concepts of "change mechanism" and "path enabler" are overlaid in red on top of Mikaelian's constructs.

Nilchiani. According to Nilchiani (2005), there are six core elements in defining a "measure for flexibility" and these are:

1. *Boundary of the system to be studied*
2. *Aspects of system to which flexibility is applied*
3. *Time window in which flexibility is observed in the system*
4. *The uncertain and probabilistic nature of the future of the system*
5. *The degree of access to the system in order to apply the option or flexibility*
6. *Responses of the system to change through changes from the owner's, designer's, operator's, and user's perspective in the value delivery.*

(Nilchiani 2005, 82)

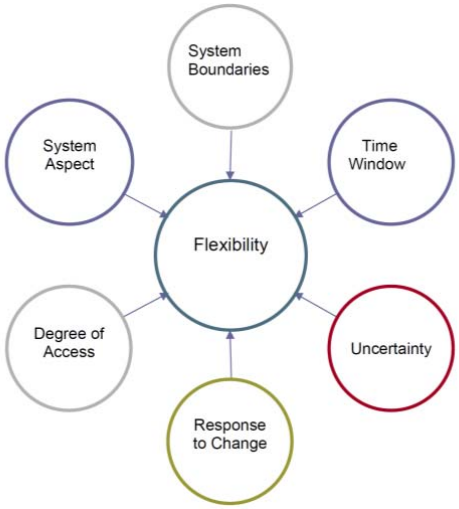

Figure 12. Six elements of flexibility (Nilchiani 2005, 82)

Based on a broad literature review of flexibility research, these elements help to suggest that many aspects of a change mechanism should be considered in order to more completely characterize and design for them. Table I provides a mapping from these six elements to related constructs in this paper.

Table I. Mapping of element to constructs (adapted from Ross 2006, 284)

Element in Nilchiani 6E Flexibility	Related Constructs in paper
System boundaries	System boundary
System aspect	Parameter to be changed
Time window	Time for transition, mechanism start/expiration
Uncertainty	Changes in context
Degree of access	Change mechanism "cost"=time/dollars/effort
Response to change	Change in system utility/cost

These six elements will impact the "aspects of a change mechanism" discussed below.

Characterizing Change Mechanisms and Path Enablers

Tying together the precursor work results in the design flow in Figure 13. One can trace from design principles to path enablers to change mechanisms to ilities analysis to ilities valuation. If one cares about "what is the value of having flexibility" one can investigate this question at the end of the flow. In order to impact valuation, one should know "to what degree one has flexibility" which can be accomplished in ilities analysis, such as calculating filtered outdegree through tradespace networks (TS networks in figure). As described earlier, in order to populate a tradespace network, one needs transition rules, which are algorithmic representations of change mechanisms that describe "in what ways a system can be changed."

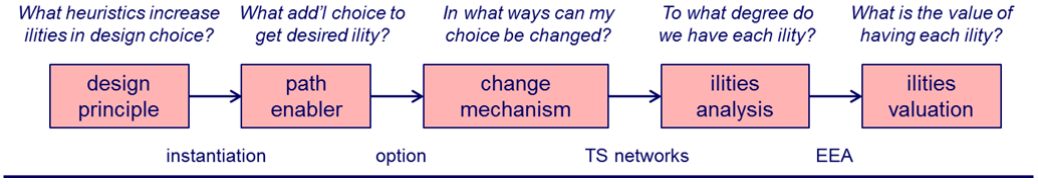

Figure 13. Relationship between Design Principles and Ilities

***Path enablers give* a system owner/designer the option to execute a change mechanism**. In order to generate path enablers, one can leverage design principles, which are generally true prescriptive statements that can be applied across a broad array of system types. Principle: "A guiding thought based on empirical deduction of observed behavior or practices that proves to be true under most conditions over time" (Wasson 2006).

In order to achieve various ilities, one must implement "path enablers", which allow for change mechanisms. On-going research will analyze the complex nature of various change mechanisms and which ilities different types of mechanisms enable. Research efforts are beginning to identify trends and emergent connections across different types of mechanisms in varying types of systems. In order to support comparisons and generation of generalizable results, a change mechanism must be characterized and identified for generic situations. Figure 14 shows how one might characterize a specific change mechanism. This representation can be viewed as a generalization of the concept of "real options." Having a path enabler gives one the "option" to execute a change mechanism at a time for a cost.

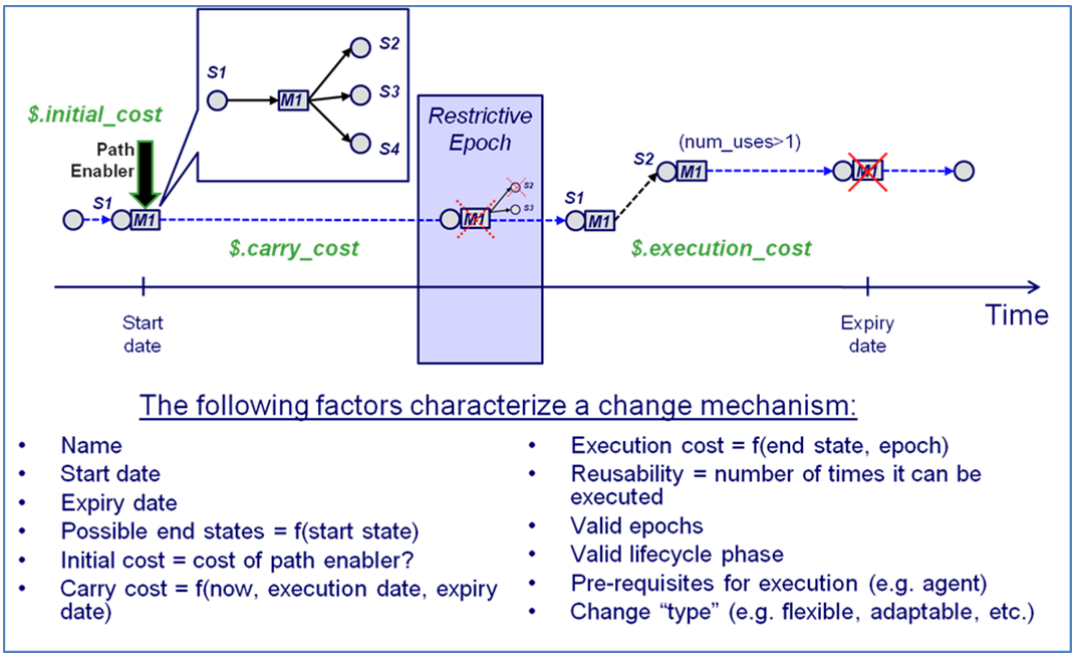

Figure 14. Characterizing a Change Mechanism

Each change mechanism will come with different types of costs. The change mechanism may have an initial implementation or design cost, a carrying cost to maintain the ability, and an execution cost when the change mechanism is used in operations. Each change mechanism will have a path enabler that allows the change to occur. The change mechanism will have an effective start time and expiration time, as well as a possible duration in how long it takes to implement or how long it has an effect on the changed state of the system.

System	State Change	Mechanism	Agent	Ility
Convertible	Closed-roof to open-roof	Button-activated automatic mechanism	Internal driver	Adaptable
Military Aircraft	Adding external fuel tanks	Universal fittings for tanks/missiles/etc	External crew	Flexible
V-22 Osprey	Vertical to horizontal flight modes	Rotating mechanism on rotors	Internal pilot	Adaptable
Parachute	Packed to deployed	Pulling release pin to deploy pilot chute	External parachutist	Flexible
Parachute	Packed to deployed	Explosive activated to pull release pin	Internal emergency AAD pull device	Adaptable
HVAC system	Change temperature	Activating heater or air conditioner	Control thermometer	Adaptable
BMW production plant	Change in car order configuration	Build-your-own vehicle online service	External buyer	Flexible
BMW production plant	Change between 5, 6, or 7 series production	Similar joining sequences and load carrying points for assembly	Factory management	Flexible

Figure 15. Example Change Mechanisms

Change mechanisms may only be useful in various lifecycle phases such as in operations or maybe even inter-lifecycle design phases. There may be epochs, periods of fixed contexts and needs, where this change mechanism is not able to be executed or requires certain pre-requisites for execution. Each change mechanism can be mapped to various ilities as in the taxonomy previously discussed. Part of on-going research is an effort to collect data on various types of change mechanisms implemented on real systems (see Figure 15 below), as well as path enablers that enable these change mechanisms. Of particular interest is the identification of path enablers that enable multiple change mechanisms. These path enablers correlate to the "optionability" concept introduced by Mikaelian (2009)[i].

Example Change Mechanisms and Path Enablers

A number of case studies have used the concept of change mechanisms (transition rules) and path enablers to evaluate the degree of changeability (filtered outdegree) of conceptual system designs. The section that follows gives brief excerpts of these case examples.

X-TOS (Ross and Hastings 2006). The first case study is a hypothetical low Earth orbit satellite mission called X-TOS, Terrestrial Observer Satellite X, whose goal is to study atmospheric density using an in-situ payload.

Table II. X-TOS transition rules

Rule	Description	Change agent origin
R1: Plane Change	Increase/decrease inclination, decrease ΔV	Internal (Adaptable)
R2: Apogee Burn	Increase/decrease apogee, decrease ΔV	Internal (Adaptable)
R3: Perigee Burn	Increase/decrease perigee, decrease ΔV	Internal (Adaptable)
R4: Plane Tug	Increase/decrease inclination, requires "tugable"	External (Flexible)
R5: Apogee Tug	Increase/decrease apogee, requires "tugable"	External (Flexible)
R6: Perigee Tug	Increase/decrease perigee, requires "tugable"	External (Flexible)
R7: Space Refuel	Increase ΔV, requires "refuelable"	External (Flexible)
R8: Add Sat	Change all orbit, ΔV	External (Flexible)

[i] One important note of caution: Mikaelian used the word "mechanism" instead of "path enabler" and "option-type" instead of "mechanism."

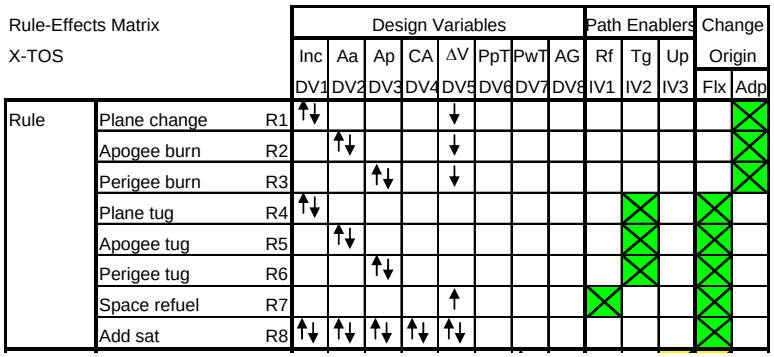

Figure 16. X-TOS Rule-Effects Matrix.

Table II lists eight proposed transition rules and Figure 16 shows the effect of the rules on design variables. The arrow direction in the figure indicates the effect of a given rule on a given design parameter (increase, decrease, or either). Path enablers are intervening parameters that reduce the cost for transition paths for a design, including creation of the path option itself. The path enablers considered for X-TOS were refuelability, tugability, and upgradeability. These three enablers were considered binary in that if they existed, the paths were allowed. The green 'X' in the cells below Path Enablers in Figure 16 means that those enablers are required in order for that change effect to be possible. The Change Origin indication keeps track of whether the rule is perceived to be motivated external to the system boundary ('Flx'=Flexible-type change) or internal to the system boundary ('Adp'=Adaptable-type change). See Ross (2006) for more details.

JDAM (Ross 2006). The Joint Direct Attack Munition (JDAM), developed by the Boeing Company, is a modification kit for existing "dumb" bombs enabling precision targeting and navigation through a GPS-inertial navigation hybrid system, attached strakes, and an actuated tailfin.

Table III. JDAM transition rules

Rule	Description	Change agent origin
R1: Refit strakes	Alter planform, plus software model and price	External (Flexible)
R2: Upgrade GPS	Alter navigation system, plus software model and price	External (Flexible)
R3: Upgrade INS	Alter navigation system, plus software model and price	External (Flexible)
R4: New software	Alter software model, plus price	External (Flexible)
R5: Refit for new Aircraft	Alter planform to fit on added aircraft, plus software model and price	External (Flexible)
R6: Refit for new Warhead	Alter planform, navigation and targeting system to fit on added warheads, plus software and price	External (Flexible)
R7: Replace tail section	Alter planform, plus navigation system, software model, and price	External (Flexible)
R8: Add inflight comm	Add wireless communication system for inflight communication and target updating	External (Flexible)
R9: Add laser sensor	Add laser sensor, alter navigation and targeting systems, software, and price	External (Flexible)
R10: Add wings	Add wings, alter planform, software and price	External (Flexible)
R11: Add terminal guidance	Add terminal guidance, alter navigation and targeting systems, software, and price	External (Flexible)

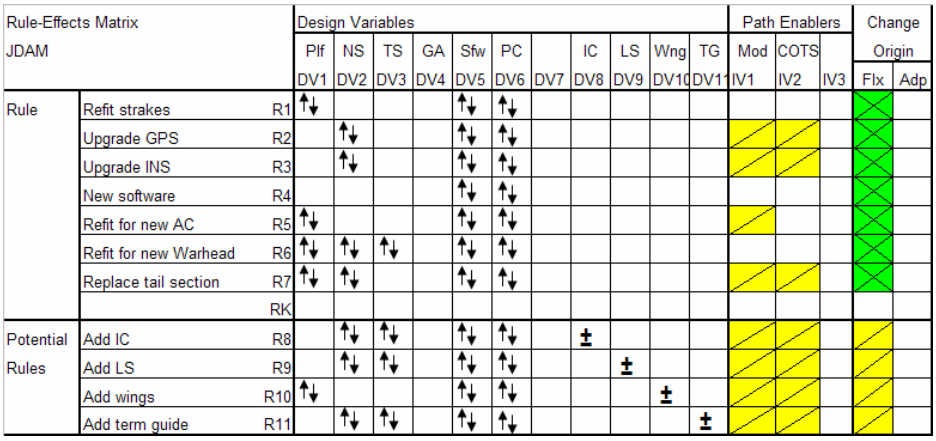

Figure 17. JDAM Rule-Effects Matrix

The transition rules proposed for JDAM case study are listed in Table III. The rules were developed in order to alter the design parameter set, both in terms of values of particular parameters and in terms of adding new parameters to the set (allowing for the enumeration of future system variants). Unlike the X-TOS rules, all of these rules were externally motivated (flexible-type changes) due to an inability to conceive of mechanisms paying down one design parameter in order to gain another. Figure 17 lists the rules and their effects on the design parameters, including the cases where the presence of path enablers may lower the cost for paths. Yellow diagonal marks in the Path Enabler columns represent their optional nature. The two path enablers considered in this case study were Modularity and COTS parts, representing design philosophies for architecture and component selection respectively. Please see Ross (2006) for more information.

TPF (Ross 2006). Now cancelled, a proposed large astronomical on-orbit observatory, the Terrestrial Planet Finder (TPF) mission was being developed by the Jet Propulsion Laboratory (JPL). The TPF mission was to discover whether life exists on other worlds through the discovery of Earth-like planets in the habitable zones around distant stars. Concepts currently being considered include an infrared interferometer and visible coronagraph. The former requires a set of smaller individual telescopes that cooperatively observe stellar light and recombine the observations to simulate a larger aperture telescope.

Table IV. TPF transition rules

Rule	Description	Change agent origin
R1: Change baseline	Expand or contract baseline	Internal (adaptable)
R2: Increase NA	Add to number of apertures	External (flexible)
R3: Change schedule	Alter observation schedule	External (flexible)
R4: Extend life	Add time to active mission duration	External (flexible)

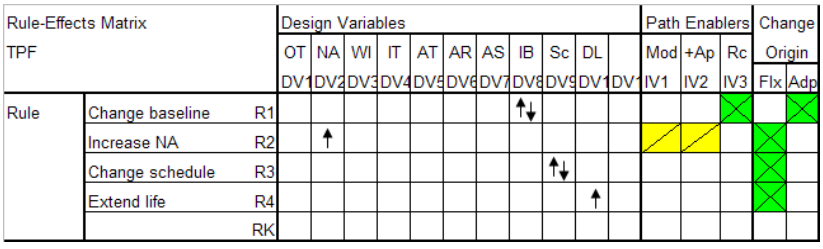

Figure 18. Proposed TPF transition rules.

The transition rules for TPF are listed in Table IV. Depending on the definition for the system boundary, the rules could be classified as either internal (adaptable-type change) or

external (flexible-type change). For the purposes of this case, the ground operations center was considered to be external to the system boundary, so changes in observation schedule are seen to be instigated by a change agent external to the system, and hence a flexible-type change. Several possible change rules are mentioned in Table IV and restated in Figure 18 showing their effects on design parameters. In particular, changing baseline and increasing the number of apertures allows for scalability of mission attribute performance (an increase in the rate and sensitivity of observation modes). In order to achieve these change types, three types of path enablers should be considered: reconfigurability, modularity, and extra apertures. Reconfigurability is the explicit ability to reposition or rearrange the physical orientation of the system, enabling the system to change its baseline. Modularity reduces the time and technical effort needed to incorporate or remove system elements. Having extra apertures reduces the dollar cost and time needed to add to the apertures in the system. With more detailed technical knowledge, additional transition rules could be readily developed.

SRS (Ross et al. 2009). For this study, a satellite radar system (SRS) was proposed as a solution to the problem of providing 24-hour, all-weather imaging and tracking of targets of interest. The purpose of the case study was defined as assessing the ability of potential satellite radar system architectures to satisfy potential stakeholders over a large range of possible future situations (epochs). The overall value proposition for the case study was "to determine which SRS architecture a notional SRS Program Manager should select to maximize the chances that stakeholders will remain satisfied throughout the system lifecycle" (i.e., which system will provide the highest degree of *value robustness* (Ross and Rhodes 2008)).

A tradespace network is formed by proposing transition rules that can be followed by system designs during different phases of their lifecycle. For the SRS case study, the lifecycle was partitioned into four distinct phases: Design (D), Build (B), Test and Integrate (T), and Operate (O). Given these phases, the design vector was inspected and possible mechanisms for transitioning from one design vector state to another design vector state were brainstormed. Eight example transition rules were proposed and used for the case study. These rules are listed in Table V.

Table V. SRS transition rules

Rule	Description	Change agent origin	Phase allowed
R1: Redesign (D)	Redesign in Design phase	External (flexible)	Design
R2: Redesign (B)	Redesign in Build phase	External (flexible)	Build
R3: Redesign (T)	Redesign in Integrate and Test phase	External (flexible)	Test
R4: Alter const (add sats)	Alter constellation through adding satellites	External (flexible)	Operations
R5: Alter altitude with onboard fuel	Alter constellation altitude through burn with onboard fuel	Internal (adaptable)	Operations
R6: Alter altitude with tugging	Alter constellation altitude through tug by external vehicle	External (flexible)	Operations
R7: Alter const (change incl.) with onboard fuel	Alter constellation inclination through burn with onboard fuel	Internal (adaptable)	Operations
R8: Alter const (change incl.) with tug	Alter constellation inclination through tug by external vehicle	External (flexible)	Operations

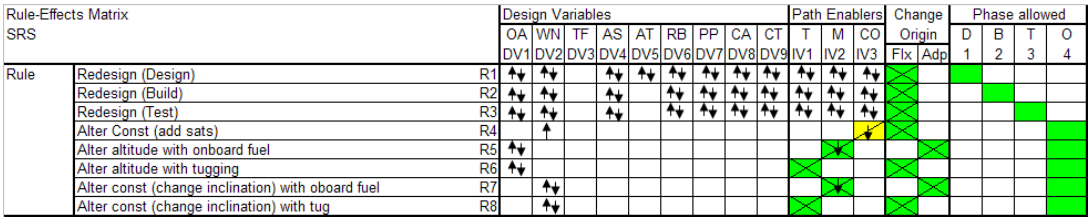

Figure 19. Rule-Effects Matrix for Satellite Radar System case.

A Rule-Effects Matrix, shown in Figure 19, lists the eight transition rules and the qualitative effect that executing each one would have on the design variables. The effect can be to increase, decrease, or increase/decrease a design variable value. *Path Enablers* are extra design variables in the design vector whose purpose is not to drive attribute performance, but rather to allow for the execution of transition rules at lower cost (e.g. buying spare satellites in advance lowers the cost of Rule 4: add satellites to constellation). The *Change Origin* column indicates whether the change mechanism can be considered to be a flexible-type or adaptable-type change, which is determined by the instigator of the change: if done by the system, it is adaptable-type; if done by a system-external force, it is flexible-type. The *Phase Allowed* column indicates that these rules are only available during specific phases in the system lifecycle.

Motivation for Continued Change Mechanism and Path Enabler Research

The appeal of formalizing the flow described in Figure 13 is strong as initially identified in Ross (2006).

As discussed in the JDAM case application, modularity, use of COTS parts, and simple, excess capacity interfaces all increased the changeability for the system. The TPF case application added the concept of reconfigurability, while the X-TOS example suggested serviceability, tugability, and refuelability as path enablers. A reasonable question to ask is whether these path enablers are part of a set of generic path enablers that would be applicable across a large range of systems. Having such a set would not only simplify a designer's efforts, but also reveal insight into the relationship between architecture and structural and operational strategies and changeability in general. (Holtta and Otto 2005) discusses specific types of modularity that increases product flexibility (read: changeability). Other research, such as (Baldwin and Clark 2000) can be used to better understand the cost lowering or path increasing properties of modularity. The potential exists to unify an analysis that can address why modularity, simple interfaces, network architectures, independence, and other path enablers increase system changeability. (Ross 2006, 278)

The ultimate goal of having a "designer reference book" for intentionally creating valuable change mechanisms in design requires the kind of research and constructs described in this working paper. Ongoing research seeks to flesh out the design flow from design principles to ilities valuation. This research includes formalizing the concept of "change mechanism," a taxonomy to distinguish among different ilities, metrics for helping to evaluate the degree to which a design has a given ility, approaches and metrics for valuation of given ilities in order to help justify investment decision-making, and an empirical investigation of change mechanisms implemented on real systems to identify patterns in design and operations choices. The holistic, end-to-end perspective put forth here seeks to organize the myriad heuristics, and experienced-based solutions that many engineers have offered as the approach to generating flexibility, for example. Instead of focusing on popular, or salient solutions, such as pursuing "modularity" or "platform-based design," this research will not only include those approaches (path enablers?), but also highlight when and why

those approaches provide the desired ilities, as well as when alternative approaches may perform better.

The most difficult part of creating systems that "match change with change" is that the problem is inherently complex, with many moving parts, many components and interfaces and interactions to consider. Compounding this difficulty is that there exist insufficient methods, constructs, and tools for characterizing and analyzing the dynamic design problem. It is no wonder that many engineers are frustrated by the modern world with changing needs, technologies, policies, and competitive environments; their methods are inherently biasing them to find the "optimized" solution for a static world that no longer exists.

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Biography

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Donna H. Rhodes is the director of SEAri and a Senior Lecturer in Engineering Systems at MIT, where she is also a principal research scientist. Her research interests are focused on systems engineering, systems management, and enterprise architecting. Dr. Rhodes has 20 years of experience in the aerospace, defense systems, systems integration, and commercial product industries. Prior to joining MIT, she held senior level management positions at IBM Federal Systems, Lockheed Martin, and Lucent Technologies in the areas of systems engineering and enterprise transformation. Dr. Rhodes is a past president and Fellow of INCOSE, and the 2005 recipient of the INCOSE Founders Award.