Anticipatory Capacity: Leveraging Model-Based Approaches to Design Systems for Dynamic Futures

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Abstract. *The paper presents a vision for enhancing anticipatory capacity of engineering organizations, with a goal of enabling the design of systems that can deliver sustained value as the world changes. Anticipatory capacity is the capacity of an organization to continuously develop and apply knowledge acquired through a structured approach to anticipate changing scenarios as needs and context change over time, While anticipation has always had a role in designing systems; the availability of model-based methods has significant implications. Anticipatory capacity extends from three key elements: competencies, methods, and a model-based environment. The paper discusses ongoing and planned research in support of establishing anticipatory capacity in organizations by leveraging the opportunities of model-based engineering.*

Keywords – *anticipation, anticipatory capacity, dynamic, design, modeling, tradespace exploration, model-based engineering*

I. INTRODUCTION

The challenges of designing complex systems in a highly dynamic world drive the need for *anticipatory capacity* within engineering organizations. Anticipation is the ability to look forward in order to take a future decision and action, or the visualization of a future event or state [1]. Systems scientists have long recognized that humans possess unique abilities for anticipation rather than just simple reaction. Accordingly, the natural process of anticipation has always been part of design practice. We define *anticipatory capacity* as the capacity to continuously develop and apply knowledge acquired through a structured approach to anticipate changing scenarios as stakeholder needs and system context change over time, to consider their consequences, and to formulate design decisions in response. In the design of modern systems, operationalizing this capacity is not truly feasible without a model-based approach, supported by enhanced engineering abilities and an enabling environment.

Anticipatory capacity of an engineering organization is enabled by three elements. The first element is the existence of appropriate dynamic systems competencies in the workforce, such as temporal-based thinking, context analysis, and situational decision-making skills. The second element is a set of new methods for performing anticipatory thinking, analysis, and decision-making in the design of systems. An example is dynamic tradespace exploration, a value-driven, model-based approach that enables the comparison of hundreds to thousands of system designs to realize value robust systems, that is, systems that provide sustained stakeholder value delivery in the face of a changing world. Early research is demonstrating the potential for dynamic tradespace exploration to enhance the anticipatory nature of systems decision making. The third element is availability of a model-based venue to enable execution of these anticipatory design and decision practices, and facilitate the associated analysis and decision making. A vision for an enabling environment for anticipatory capacity is a multi-sensory tradespace exploration laboratory, wherein designers and decision makers can perform experimentation, and explore possible futures and decisions, not only through visual support mechanisms but also mechanisms involving other human senses. This facility will potentially enable anticipation, experimentation, learning, and decision making at both a deeper level and more rapid pace. Following a discussion on motivations, the paper will expand upon anticipatory capacity and its importance for systems design. This follows with a discussion of new methods and abilities enabling anticipation, and a vision for the enabling environment to support this model-based anticipatory practice.

II. MOTIVATIONS

A fundamental goal for systems engineering is to maximize the perception of system success by stakeholders. Success can be defined narrowly in terms of meeting performance, cost, and schedule expectations, or more broadly in terms of stakeholders perceiving benefit at an appropriate cost for having the system. This broader goal requires attention to how value is perceived by stakeholders through interaction with the system. Understanding how people perceive value is fundamental to creating valuable systems [2]. Designers do an adequate job of understanding value perception in the short run, but in order to do so in the long run, there is a need to effectively anticipate what the future will bring, and incorporate this knowledge into the decisions in the present. While designers cannot predict the future in its entirety, they can predict possible and even probable scenarios for the future, and also predict sequential orderings for these scenarios. Thus, it is possible in an engineering organization to establish the organic capability to perform anticipatory thinking as part of the system design practice, and to enable this through model-based approaches.

Needs are context dependent, and this context includes both changing environments and limited access to information. Accordingly, value perceptions of stakeholders will inevitably change as well. An important question, then, is "how systems can achieve success when the criteria for true success--delivery of value--changes over time?" One approach is to design systems for *value robustness*. It is only when designers have a good grasp of the dynamic flow of value that they can develop truly long-lasting high-value systems. The authors assert that the role of a good designer is about achieving value creation and sustainment, not simply technical achievement, and as such anticipation of dynamic futures is essential.

Value robustness can be achieved through active or passive strategies, that is, via system change or lack of system change [3]. For example, if stakeholder expectations were to increase, such as having a longer system life, a value-robust system would be able to meet those new expectations, possibly achieved via over-design (requiring no change) or through life extension (requiring a system change). Architecting value robust systems requires methods for exploring the concept design tradespace not just for today, but in considering possible dynamic futures where context changes and/or new needs arise. The authors see anticipatory capacity as a necessary ability for engineering organizations seeking to develop *value robust* systems. Previous theoretical work on anticipatory systems informs the new research in this area.

III. ANTICIPATORY SYSTEMS

The role of anticipation in design has largely been ignored [4] in comparison to topics such as learning, creativity, and innovation. This paper will not fully describe anticipatory systems and their relevance for the design of systems; but will highlight some of the important definitions and concepts necessary for discussion of the research and its relevance to anticipatory capacity of engineering organizations.

The fundamental work on anticipatory systems was developed by biologist and systems scientist Robert Rosen. In his major text, Rosen defines an anticipatory system as "a system containing a predictive model of itself and/or its environment, which allows it to change state at an instant in accord with the model's predictions pertaining to a latter instant"[5]. There are several relevant characteristics of anticipatory systems [6], including:

1. There is a double temporal nature of anticipations in that they are directed at one time and exist at another.
2. Anticipatory systems can be open, wherein they can perturb and be perturbed by states external to the system.
3. The anticipations in these systems can be facilitated by a system modelling relationship between its own output, the environment and future state input.
4. These anticipations are an organic part of the system that is doing the anticipation.

In the case of this paper, the "system" that possesses anticipatory capacity is the engineering organization that is performing system design. The doubly temporal nature of anticipation is one element of anticipatory thinking that makes it a very complex process. The engineering organization can anticipate more than one state of a system and its context at one time, and can also at multiple points in time anticipate what things will be like at another given time. This introduces such complexity that only a model-based approach can provide for the level of anticipation necessary for the world the complex engineered systems.

An important aspect of anticipatory systems is their dependence on predicted future states, and not only on past states as would be the case for purely reactive systems [6]. A *prediction* is a representation of a particular future event, and an *anticipation* is a future oriented action, decision, or a behavior based on a prediction. In the case of designing systems, anticipatory capacity provides the engineering organization with the ability to make decisions based on the predictive models it creates and utilizes during the design process. These models include the model of the system being developed, model of the environment of the organizational entity performing the system design, and model of the external environment in which the system will operate.

There are three elements that are necessary to establishing enhanced anticipatory capacity in an engineering organization. The first is the set of competencies that enable strong anticipatory thinking. The second element is the body of methods for anticipation as an integral part of the design practice. The third element is the laboratory environment in which engineers execute the design process in order to leverage the power of models in anticipation and to perform socio-technical decision making for complex system.

In biology, anticipatory systems are those that have an organic ability to build and use models of themselves and their environments to respond to change in a more intelligent manner than a simple reaction. The analogy for engineering organizations is to have an embedded group of individuals who are dedicated to the development of models of systems (that is, the systems being designed by the organization), their environments (both context in which they are developed and operated), and their possible dynamic futures. The ultimate goal of this anticipation is to design superior systems that are dynamically relevant throughout their lifespan. While system designers have always used some level of anticipatory thinking, there is a need to apply more sophisticated anticipatory approaches to address the challenges of modern systems. Advancements in model-based approaches and affordable computing power are major factors in operationalizing anticipatory capacity in designing systems.

IV. COMPETENCIES

Engineering organizations possess competencies for performing the systems design process, however, these are typically oriented toward designing for a designated point in time (usually the window of time related to the delivery of the product or system into the hands of the user). Anticipatory thinking permits teams to model many alternative futures involving predicted future contexts and predicted changes in needs. This approach involves a significant emphasis on temporal-based thinking, that is, thinking about how systems and their operational environment may evolve over time.

System life cycle processes benefit designers in organizing the activities required to design, develop, and operate a system. The system life cycle is comprised of phases which have defined end points, and typically a phase is tied to the resources available to complete a set of phase activities. As such, the system life cycle temporality is highly ‘artificial’ and internally focused, rather than a temporal view that extends from consideration of impacts of the more ‘natural’ changes in the system’s environment or context, and stakeholder preferences. The system life cycle construct is highly useful for the effective control and management of the system elements during its life. However, this life cycle temporal view is not sufficient. Designers must have other fundamental constructs for considering temporality to design highly complex systems robust to change in contemporary contexts.

Engineers are for the most part educated to think about time in the design process using ‘artificial’ perspectives. System lifecycles are divided into phases, often using somewhat arbitrary calendar dates or increments that relate to needs of the business. The authors have proposed an adjunct view [7], involving thinking about the system in time as having natural phases and flows. Designers need to be educated to think about systems as having both ‘artificial’ and ‘natural’ influences that drive design choices and decisions.

For organizations to establish anticipatory capacity, new competencies are needed, [8] including:

1. *Ability to think deeply about systems in their context or environment.* This should include improving the ability to understand system boundaries, and how these may shift over time. Abilities include understanding how systems react to internal/external impacts, and knowledge of constructs for impact analysis and methods for decision making. Context analysis skills are necessary for anticipatory thinking involving the gathering, analyzing, and dispensing information for tactical or strategic purposes. The process involves scanning to obtain both factual and subjective information on the environments in which the entity is operating or is considering entering.
2. *Competency for anticipatory thinking includes the ‘situational leadership’ abilities.* These abilities relate to how to make decisions at multiple levels – component, system, system of systems, as well as across multiple time periods. This includes using anticipatory methods to improve understanding of the decisional trade-off process for local versus global value delivery, and understanding the environmental context in which decisions are made.
3. *Enhanced ability to think about ‘systems in time’ in a more rigorous and extensive manner*. This competency relates to how to think about systems and system interactions within and across life cycle phases, and within and across each of the timeframes where context/needs are fixed. Also important is the ability to anticipate future scenarios, and consider how decisions in present time may enable flexibility for the future.
4. *Ability for collaborative systems thinking at the team level*. This competency relates to the fact that complex systems are designed by teams and not individuals. Anticipations for this purpose require many disciplinary specialists who think about the system from multiple perspectives and with different incentives in mind. The ability to achieve a shared and coherent anticipation from multiple predictive views is necessary.

V. METHODS

Anticipation of dynamic futures of complex systems, at any significant depth, depends upon model-based approaches. Two recent research methodology outcomes are discussed in this section; the authors believe these will provide for rigorous and extensive anticipatory thinking and analysis during the system concept phase.

In early life cycle phases, designers develop and consider alternative system concepts. Traditional trade studies are insufficient for a comprehensive conceptual design effort as these consider a small number of alternative designs. Tradespace exploration [9] builds on its application by adding computer-based parametric models and simulations, enabling comparison of hundreds or thousands of potential architectures, as shown in Figure 1.

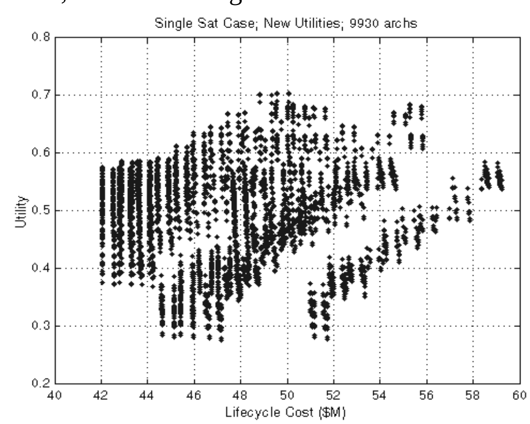

Fig 1. Tradespace Plot. Each point represents a design, and is plotted as utility (benefit) versus cost

Tradespace exploration avoids the limits of local point solution trades by providing an understanding of the underlying relationship between decision maker preference structure and potential designs. The method may be used as a quantitative tool for evaluating benefits, costs, and risks of alternative architectures, to inform the critical front-end decision making. In addition to evaluating potential technical capabilities, tradespaces aid the exploration of implications of policy uncertainties [10] and changing value perceptions [2].

Tradespace exploration can be applied to the static case; however, higher benefit is achieved through dynamic tradespace exploration, wherein the tradespace is viewed as a network. Design transition rules can be applied to consider if and how to transition from a one design to another, enabling dynamic tradespace exploration as illustrated in Fig. 2.

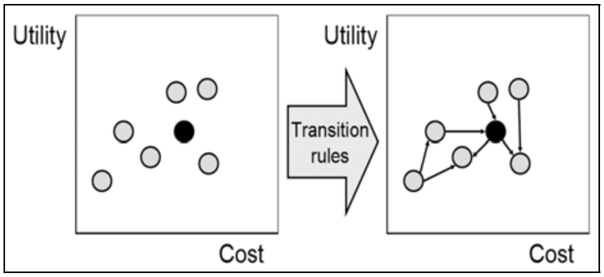

Fig. 2. Point designs in a tradespace can be linked as a network via transition rules to assess changeability.

The application of tradespace exploration methodologies provides a means to more effectively understand tradeoffs between diverse stakeholder needs and possible design alternatives. *Multi-Attribute Tradespace Exploration* (MATE) is a methodology for exploring the tradespace of possible architectures rather than settling quickly on an optimum, providing the ability to quantitatively assess many design choices very early in the design process [9]. This ability allows designers and decision makers to explore many design options, and prevents focusing on a single "point design" too early. This approach enables anticipatory thinking in regard to considering the quantitative assessment of factors such as variability in technical performance and cost, and impacts of changes in markets or policy, by allowing exploration of a large number of possible situations, including speculative ("what if") scenarios.

Extending the basic tradespace exploration method, *Dynamic MATE* [2] addresses designing for changeability to maintain delivered value in spite of system-external changes. With this type of method, designers have an enhanced anticipatory ability to consider concept alternatives in a rigorous way, not only for the present situation but also in considering futures where needs and contexts have shifted. Dynamic tradespace exploration has been shown to be suitable for extension to *systems of systems* (SoS), as it encompasses desirable qualities [11]. As the method puts less emphasis on optimization, but rather provides a set of high benefit at cost solutions, the designer can observe the changes in benefits and costs that occur when the dynamic SoS changes. It provides a useful means to study changeability characteristics of the SoS over time, and can help identify designs that are value robust to changes in constituent system membership, expectations, and contexts over time. The dynamic tradespace exploration method accommodates changed expectation levels and design concepts very easily and quickly, enabling decisions for design or redesign of a SoS while it is in operation.

Epoch-Era Analysis (Fig. 3) is a new approach that is part of the dynamic method [2, 7]. It provides insight into such decisions as when in the evolution new systems may need to be added, and when investments should be made in new technologies. With Epoch-Era Analysis, the system lifetime is divided into a series of epochs, which are defined as time periods when significant system design characteristics, expectations, and context variables are fixed. Multiple consecutive epochs can be strung together to create an era, or scenario, which represents a longer run view of the system evolution. Within each epoch, static analysis can be done to evaluate various designs. Significant changes in the system or SoS and its context (such as a new threat to the system, or a constituent system joining an SoS) can be represented by defining a new epoch. Path analysis within each epoch can help identify system evolution strategies that provide high value delivery to the stakeholders.

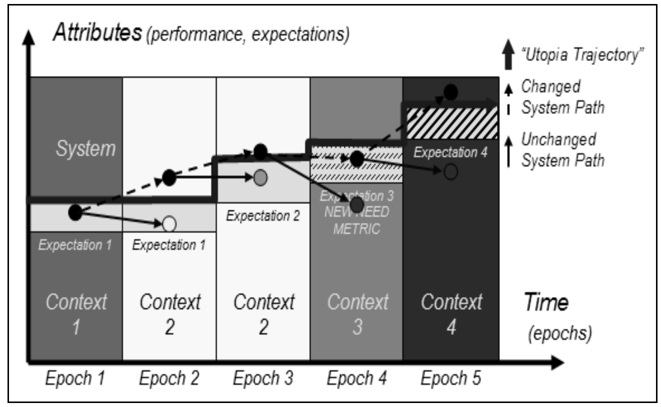

Fig 3. Epoch-Era Analysis. Each epoch has fixed context and expectations. system value may degrade in a new epoch; changing the system may restore it. Utopia trajectory is the optimal value delivery strategy across epochs.

Complex systems involve intensive decision making at multiple levels, particularly in the case of SoS. Unlike traditional systems where tradespace exploration occurs early in the lifecycle, SoS require more continuous anticipation and tradespace exploration as constituent systems enter and exit. SoS programs involve numerous and diverse decision makers, and creation of a shared value proposition necessitates a formal and rigorous approach to anticipating possible futures and assessing SoS costs and benefits. Epoch-Era Analysis shows promise as a useful method for rapidly-evolving SoS, as the analysis can be quickly redone as strategy selection criteria and epoch boundary definitions change over time. This analysis can help identify SoS designs that are value robust to changes such as constituent systems joining and exiting the SoS, and aid SoS designers in performing the sophisticated anticipations needed to devise strategies to transition to such designs [12]. Anticipatory capacity is necessary for all systems design; it is both critically important and more challenging in the SoS design case.

To summarize, Dynamic Multi-Attribute Tradespace Exploration is a method for exploring the design tradespace that considers transition paths that an individual system design may follow. Epoch-Era Analysis, as part of the overall dynamic method, provides a model-based approach for performing the complex temporal analysis of systems (with changing contexts and needs). These methods are presently being applied in several case-based studies [13], and show significant promise for enhancing the anticipatory capacity of engineering organizations. The methods can be applied with basic computing resources, however, an active area of research relates to understanding what physical laboratory and conceptual decision making environments can further enabler the power of the model-based methods.

VI. ENVIRONMENT

Anticipatory capacity within an engineering organization will be enhanced through an appropriate laboratory environment for creating models so that dynamic futures can be elaborated and their implications considered. The tradespace exploration methods described in the prior section of the paper involve comparing hundreds to thousands of possible design concepts through the use of parametric and simulation-based modeling. Very large amounts of data are created, and effectively exploring the complex relationships among the data is key to the analytic approach. Creating an environment for effective negotiations and decision making is both a physical and a conceptual challenge. There is also a challenge in effectively communicating results to senior decision makers with a goal of improving the likelihood of selecting and developing dynamically relevant, value-robust systems. The dynamic perspective informs decisions in consideration of possible future contexts and needs for the system over its lifespan.

Tradespace exploration is most effectively performed by multi-disciplinary collaborative teams using model-based laboratories as their design environment. Multi-sensory environments will enable anticipatory activities, including new approaches for representing and interacting with multi-dimensional, complex tradespace data through haptic, auditory, and enhanced visualization approaches. The ability to generate, display, and interact with multiple tradespaces simultaneously will significantly enhance the anticipatory capacity of the engineering organization by leveraging the human ability to recognize patterns in complex data.

The existence of a laboratory environment is not a prerequisite for anticipatory thinking since it can be performed with simple predictive ideas and manual sketching. Yet, if the engineering organization is engaged in large scale and complex systems design, low-end methods will no longer suffice. A laboratory designed to enable anticipation for systems design serves several important purposes. Such an environment provides the physical collaborative venue for bringing together the relevant set of stakeholders, analysts, architects, and decision makers. The laboratory provides the computing power and toolsets needed to enact the anticipation methods, and also to effectively portray the anticipatory analysis results with the involved participants.

Presently, the authors are investigating the development of affordable venues for performing complex tradespace analysis since traditionally these types of experimentation laboratories can only be established with a significant level of capital investment. Thomke has discussed the problem of cost of experimentation as a typical limitation of innovation, but notes that “technologies-including computer modeling and simulation promise to lift that constraint by changing the economics of experimentation” [14]. Laboratory environments designed to support anticipatory methods for systems design will enable new levels experimentation to permit anticipation in an experiential manner.

VII. DISCUSSION

There are several areas of inquiry and new research directions the authors are pursuing in the area of anticipatory capacity and systems design. The first of these is further investigation into various methods that are presently used, or could be used for anticipation in systems design. Many different fields use approaches to perform anticipatory practice. One example is *environmental scanning* in the field of management, involving the aacquisition and use of information about events, trends, and relationships in an organization's external environment, the knowledge of which would assist management in planning the organization's future course of action [15]. Other examples include *morphological analysis* [16] which has been applied in military strategic planning, and *scenario planning* used in business development and sustainable development planning [17]. Research on generation of product design concepts through model-based approaches, for example *subjective objective system* [18], is another example. Such methods and empirical studies of anticipatory behaviour in other fields may inform the understanding of anticipation in regard to systems design.

An active area of research is how to display the complex models and information of a multi-temporal nature in a manner that enhances decision making. As anticipatory analysis is multi-level and of a doubly-temporal nature, the challenge to provide results that can be cognitively processed and result in good design decisions is significant. Performing empirical studies on this topic in an experimental laboratory environment is planned future research.

A third research area of interest is to study the rate of anticipation and learning in the systems design environment. In particular, a multi-sensory tradespace laboratory provides for discovering what types of information presentation accelerate anticipation, and helps to discern cognitive limits in the ability to absorb and process this type of information. Further, a fundamental research question is whether or not a multi-sensory environment increases the anticipatory capacity of individuals, teams and organizations beyond the use of more classical mechanisms such as simple scenario planning or morphological analysis.

A fourth area of research builds on current research on collaborative systems thinking [19], examining how systems thinking emerges in design teams as distinct from individual systems thinking in engineers. In regard to anticipatory capacity, there is research needed to discover how anticipations occur in teams, and whether a team-based environment can foster anticipatory capacity. Research is needed to understand how the origination and fusion of individual anticipations lead to a team level anticipation. The current research on this process in system design will provide foundational knowledge for exploring this topic.

Finally, a very rich area of ongoing research involves applying Dynamic Multi-Attribute Tradespace Exploration with Epoch-Era Analysis [7] to the enumeration and exploration of possible futures of complex systems. Further research is needed to understand how these methods effectively enable anticipation and to understand the contributions and limits of such methods to discovering dynamically relevant designs.

VIII. CONCLUSIONS

The design process inherently involves anticipation about the product or system in reference to its existence at some future time. The capacity for anticipation within engineering organizations is becoming increasingly important as the complexities of systems and their environments expand. The authors believe that anticipatory capacity can be enabled by three areas: new competencies, model-based methods, and enabling environment. Ongoing research has identified competencies of importance to anticipation, and new methods have been developed to perform anticipatory thinking and decision making. Model-based systems approaches are essential to establishing anticipatory capacity in engineering organizations engaged in the design of complex systems.

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