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Five Aspects of Engineering Complex Systems

Emerging Constructs and Methods

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***Abstract*—This paper introduces and describes a five aspect framework for the engineering of complex systems. The framework serves three purposes: (1) characterizing and elaborating engineering methods to ensure coverage of essential aspects; (2) providing an organizing taxonomy for research initiatives related to developing methods and practices; and (3) providing a focusing framework to develop management and innovation strategies for complex systems. The framework has been useful in structuring an engineerig methods research program and assessing the balance of methods under development both within each of the aspects, as well as in combination. This paper describes the use of the framework for the first two purposes, with illustration of its use for descriptive purposes, and as applied to development of a comprehensive research portfolio for evolving advanced engineering methods.**

Keywords – engineering systems, methods, socio-technical considerations, context, temporal, perceptual

I. INTRODUCTION

The engineering of complex systems has always considered a multitude of dimensions and increasingly has involved rigorous methods and enabling technologies. The evolutionary path of engineering practice is threefold: (1) initial constructs and conceptual approaches emerge; (2) quantitative approaches are then formulated and formal methods are developed; and (3) methods are then made executable through computer-based implementation. For instance, over the past decade model-based systems engineering (MBSE) approaches have developed into relatively mature practice [1]. Foundational constructs for MBSE go back several decades in time to the constructs of structure and behavior to describe systems. In the earlier efforts, the model-based approach was incorporated to not only enhance requirements and design practice, but also as a specific means to bridge the gap between the structural and behavioral aspects of systems. Only recently has the full power of the computational environment been realized.

Contemporary engineering systems have unprecedented levels of complexity and uncertainty. Further, these systems exist in a very dynamic world and the pace of change continues to accelerate. While the structural and behavioral aspects (as evidenced in MBSE) remain at the core of the systems engineering method, there is an urgent need to more effectively address three additional aspects: contextual, temporal and perceptual. These latter three aspects are not entirely new to engineering meta-methodology [2, 3], but have not received adequate focus given their importance to engineering value robust systems, that is, systems that continue to deliver value to stakeholders over their entire lifespan in a dynamic world [4]. This paper proposes five aspects as essential for the engineering of complex systems. Fig. 1 provides a brief definition of the five aspects. The first two, structural and behavioral, are evident in the current state of the practice, while the latter three are prominent in the emerging state of the art.

STRUCTURAL *related to the form of system components and their interrelationships*	"State of the Practice" systems architecting and design, and emerging model-based systems engineering approaches
BEHAVIORAL *related to performance, operations, and reactions to stimuli*	
CONTEXTUAL *related to circumstances in which the system exists*	New constructs and methods seek to advance "state of art", for example: *Epoch Modeling* *Multi-Epoch Analysis* *Epoch-Era Analysis* *Multi-Stakeholder Negotiations* *Visualization of Complex Data Sets*
TEMPORAL *related to dimensions and properties of systems over time*	
PERCEPTUAL *related to stakeholder preferences, perceptions and cognitive biases*	

Fig. 1. Five Aspects and State of Art and Practice.

II. CHARACTERIZATION OF FIVE ASPECTS

Each of the five aspects can be characterized by specific constructs and considerations. The *structural* aspect relates to the form of the system logical and physical components, and their interrelationships. The structural aspects may include both vertical and horizontal structures, such as hierarchy and a combination of loose and tight coupling of the component systems. Methods for designing complex systems must accommodate multiplicity of scales in regard to the structural elements that comprise them.

In regard to the *behavioral* aspect, engineers must be able to model the emergent behaviors resulting from these complex interconnections in order to understand how the systems will perform. Behavioral descriptions are enabled by newer methods developed under the MBSE paradigm, including formal notations, modeling languages (e.g., SysML), and modeling constructs [1].

The third aspect, *contextual*, requires the understanding of complexities and uncertainties stemming from the external environment in which the system operates, and the relevant stakeholder needs as driven by this environment. The contextual aspect relates to understanding the system in a fixed context and needs environment. Context shifts may occur as related to political, economic, threat, cultural, policy, and market factors. Exogenous factors drive design decisions, yet are typically not fully elaborated and considered.

Context is central to design, but clearly systems experience changes in regard to context over time. The system exists in a dynamic world, and particularly in the case of systems having long lifespan, there are likely to be many shifts in context and needs during the system lifetime. Often these shifts are decoupled from the acquisition phases, another temporal dimension of the engineering effort. The *temporal* aspect is necessary to characterize changes over time, as well as time-based properties such as survivability or adaptability of the system over its lifespan.

The fifth aspect, *perceptual,* relates to how the system is interpreted through the perspective of system stakeholders. This aspect considers individual stakeholder preferences, and how preferences vary across stakeholders. It also considers the changes in preferences as a response to context shifts over time as the stakeholders interact with the system in its environment. This aspect relates to cognitive limitations, biases, and preferences of the stakeholders. Fig. 2 summarizes examples of the constructs and methods relevant to each of the aspects.

aspect	Examples of constructs and considerations
Structural	• heterogeneous components and constituent systems • elaborate networks, loose and tight couplings • layers, vertical/horizontal structures, multiplicity of scales
Behavioral	• variance in response to stimuli • unpredictable behavior of technological connections • emergent social network behavior
Contextual	• many complexities and uncertainties in system context • political, economic, threat, market factors • stakeholder needs profile and overall worldview
Temporal	• decoupled acquisition phases and context shifts • systems with long lifespan and changing characteristics • time-based system properties (flexibility, survivability, evolvability, etc.)
Perceptual	• many stakeholder preferences to consider • perception of value shifts changes with context shifts • cognitive constraints and biases

Fig. 2. Five Aspects with Example Constructs and Methods.

Constructs, approaches, methods, and enabling environments for the structural and behavioral aspects of systems have evolved significantly in the last decade, yet three other aspects remain relatively less understood and enablers are presently insufficient for the challenges of complex systems. In the following sections the five aspects are discussed in more detail, with examples of emerging constructs and methods.

III. STRUCTURAL AND BEHAVIORAL ASPECTS

The structural and behavioral aspects are well understood in engineering practice. Leading systems engineering textbooks cover these foundational concepts and practices [5, 6], and more recently model-based systems engineering practices [1] provide adequate constructs and methods for these two aspects, after several decades of evolving practice.

In 1987, Karas and Rhodes [7] presented an early descriptive methodology for capturing high level system information using three types of models: the functional model and physical model (both structural models), and operational model (behavioral model). The structural models related to the arrangement and interrelationship of the logical and physical objects in the system. The behavioral model related to the response of the system to stimuli, and resulting state changes. In this work, the three model constructs were formalized in an early modeled-based method. This was followed by the introduction of an early model-based environment to enable an executable behavioral model, integrated with the structural elements (logical and physical views). A decade later Oliver et al. [8] published a prescriptive approach for engineering complex systems using the structural and behavioral systems models, which influenced modern MBSE practice.

In present day engineering practice, it is now quite inconceivable that systems engineers would fail to explicitly define the system in terms of its structure and behavior. Integrated toolsets provide the computation-enabled environments for performing model-based systems engineering, Detailed constructs and descriptions for these two aspects (structural and behavioral) are now defined in systems architecture frameworks such as the DODAF [9] and MODAF [10], with recent enhancements of these frameworks reaching toward two additional aspects, the contextual and temporal.

IV. CONTEXTUAL ASPECT

Understanding the system context has always been an important aspect of engineering practice and is well described in textbooks [5, 6]. System boundaries, external entities, and external interfaces are illustrated in system context diagrams, and also described in some detail in various documents such as operational concept documents or capability description documents [11]. While highly useful, these provide descriptive information rather than an analytic capability.

With the availability of model-based approaches, the potential for modeling the system context is made possible. Multi-Attribute Tradespace Exploration (MATE) is a value-based method that can be used to generate context specific design concepts and explore their value (utility) for cost within a full tradespace of possibilities [12].

Allowing for changes in some of the assumptions in static tradespace analysis, in Multi-Epoch Analysis, tradespaces are modeled under a fixed set of stakeholder preferences (needs) and context assumptions, referred to as an “epoch” [4]. Deeper insights into the effect of changes in these preferences and context assumptions can be achieved through a parameterization of these epochs using “epoch variables.” Epoch variables are defined in regard to uncertainties (for example, resources, policy, technology availability, and others). Epochs are computationally generated using the possible permutations of the epoch variable set values [13]. This approach has enabled deeper analysis for assessing performance of concept designs (including multi-concepts) across multiple epochs. Fig. 3 illustrates an example of this where the same design concepts, for an operationally responsive surveillance system [14], are shown for three epochs (where epoch variables vary based on the characteristics of a context shift (different disaster situation). As can be seen, this analysis enablers design concepts (represented as dots in the tradespace) to be evaluated across the contexts.

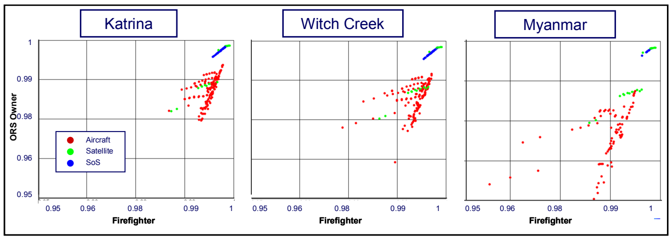

Fig. 3. Design Tradespace for Three Unique Epochs Illustrates Shift Resulting from Changes in Disaster Context source: [14]

The context of a System of Systems (SoS) is particularly complex, in that the SoS context is emergent from the interaction of the constituent system contexts [15]. As such, the context may be actively shaped to some extent through control of the interactions of the constituents.

Another example is the system shell construct, intended to mitigate impact of changing context and expectations on the system by decoupling the system from the change source [16]. The shell may take the form of a system "mask that controls how the system is seen by external context and stakeholders, or the form of a "shelter" that controls how the system sees its external context and stakeholders. The construct is proposed as a cost effective approach to deliver stakeholder value in spite of changes in context and expectations of the stakeholders.

V. TEMPORAL ASPECT

The temporal aspect of systems is critically important, but remains undertreated in the practice of engineering complex systems. The notion of temporal-based analyses as important has long been part of the theory, and while some approaches have been formalized, these have remained peripheral to systems engineering practice. Over two decades ago, Hall [2, p. 254] discussed the importance of an environmental forecast, noting "a forecast is daunting because it encompasses a comprehensive description of the environment from before the time of conception of a new system, through every period of its lifecycle, to its ultimate demise".

One temporally oriented method used by systems engineering is scenario development. Once the system boundary is defined, one or more scenarios may be developed around the system mission or purpose. For the most part, these scenarios are illustrative in nature, taking a graphically illustrated form with narrative text to elaborate. The scenarios are useful for communicating an overall picture of the system and its intended use in its environment. Advancements in the systems engineering field include the enhanced approach of Boardman's systemigrams [17] and specialized uses of scenarios such as for requirements stability assessment [18]. Monte-Carlo Simulation is useful for computational analysis under certain conditions [19]. Ritchey discusses the extension of general morphological analysis for scenario development, stakeholder analysis, analyzing risks, evaluating organizational structures, and other purposes that draw on the temporal perspective [20].

More recently, Epoch-Era Analysis has emerged as a new approach that addresses the need to consider systems (and their delivery of value to stakeholders) in context of a dynamic world [13, 21]. It provides insight into decisions such as what system concept designs will perform well across multiple contexts, or when in the evolution of an SoS new constituent systems should added [14]. It is accepted that systems have lifecycles, and these are decomposed into useful but somewhat artificially defined phases. This new approach provides complementary "natural value-centric" views of the system lifespan [13]. In Epoch-Era Analysis, the system lifespan is divided into a series of epochs (time periods when significant needs and context are fixed). Multiple consecutive epochs can be strung together to create an era, or scenario, a "long-run view" of the changing system needs and context [22]. Within each epoch, analysis methods help to evaluate various systems for the fixed set of contexts and needs. Significant changes (such as a new threat or new stakeholder need) trigger a new epoch. Path analysis across a series of epochs (an era) can then identify system evolution strategies that provide continued high value delivery to the stakeholders.

Figure 4 shows a possible system era of 20 years as comprised of multiple epochs of varying time of 2 to 10 years.

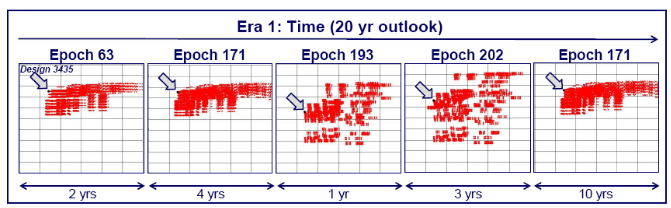

Fig. 4. Era with Five Epochs

Here a tradespace is generated for each epoch (epoch number signifies only an identifier rather than order or weight). Each tradespace contains thousands of system designs (each red dot is a unique design concept) that have been computationally generated and place on the tradespace in regard to the context specific utility (y axis) and cost (x axis). The arrow marks a promising design that will be evaluated more closely, as it occurs on the pareto front of each tradespace across the era, that is, the designs with highest value for cost.

Another area of rich research related to the temporal aspect involves designing for selected temporal system properties, or "ilities". The work of Richards provides a rich empirically-based description of system survivability using a value-based perspective. Research outcomes [23, 24] included formalized value-based definition, architecting principles and design mechanisms, and two metrics for survivability (time-weighted utility loss and availability threshold). Broad system "ilities" such as survivability can only be understood from a time-based perspective, yet these have only recently been rigorously investigated in a formal way. Ross et al. [25] describes a taxonomy of changeability, incorporating several important system ilities. This taxonomy is presently being extended for a broader set of "ilities", as well as investigating additional ilities. Trade-off of multiple ilities is also under investigation.

VI. PERCEPTUAL ASPECT

The perceptual aspect of engineering complex systems relates to stakeholder preferences, influence of perception on decision making and design, and impact of cognitive factors including biases and constraints. As systems grow increasing complex, the human-system dimensions present greater challenges. Architecture frameworks have been notably missing emphasis on human considerations; the recent work on adding a human view to the MODAF [26] is one example of augmenting these frameworks to address the shortfall.

The perceptual aspect also relates to the need to understand the 'goodness' of design concepts as a stakeholder's preferences shift over time. Exogenous factors such as economic changes, available technology, threats and other factors may influence the relative importance of what a stakeholder values. As an example, in an increased threat environment, the safety of a vehicle becomes more heavily weighted, as contrasted with comfort or convenience factors.

Figure 5 shows the tradespace of multi-concept designs in a tradespace for a set of system attributes as originally weighting and the same design tradespace when changes in preferences result in a new weighting of relative importance of these attributes. Note the shift in how the designs appear on the utility/cost tradespace.

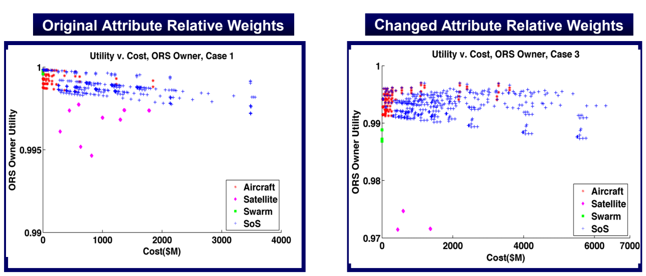

Fig. 5. Impact of Change in Stakeholder Weighting of Desired System Attributes [source: 14]

Another example is the construct of system "mask" discussed in the prior section. The mask is a mechanism that can be used to "mask" the true system to one or more stakeholders to prevent the system having to change to meet externally changing perceptions. A simple example is its use in consumer products as a strategy to address satisfying diversity of stakeholder stylistic preferences [16]. Meeting the needs of stakeholders is perceptual in that needs are subjectively judged. Formal constructs that permit the stakeholder experience as customized without changing the core system are a subject of ongoing research. Another active area of inquiry is negotiation of comprises with multiple stakeholders in decision making.

VII. INSIGHTS FROM COMBINING ASPECTS

The five aspect framework offers a means to consider useful constructs, methods, and enablers relevant to the individual aspect under consideration. An even more powerful use of the framework is the potential for methodological innovations at the intersection of combining aspects. Intentional combinatorial approaches have been shown as sources for innovation. For example, research on a value-based design attribute classification framework has demonstrated how new sources of value to stakeholders can be uncovered through considering combinations of attributes [27].

As a framing mechanism, methods developers benefit from considering how to address the challenges inherent across two or more of the five aspects. Recent research provides an example; the challenge of effectively displaying information to decision makers who must select a preferred concept design for a system that will experience expected by uncertain context shifts over its lifespan.

Consider the case where effective display of the value for cost of design of a satellite radar system (represented using a tradespace) also incorporates time-based information on the survivability of the system as it experiences possible finite disturbances over its lifespan. In this case, the methodological construct is multi-aspect in nature. The perceptual aspect (ability of a decision maker to cognitively process complex tradespace information) and temporal aspects (effective display of time-based impacts) must be effectively combined. Amount of information and complexities within a set of information are challenges, in that human cognitive limits for processing the visual display must be considered, as well as mechanism to compute and display the synthesis of temporal analysis.

The system survivability work of Richards [28] includes an innovative construct addressing the above challenge. Fig. 6 shows a visualization construct developed in this work, as a four-dimensional tradespace plot where utility of the design is plotted against cost, color is used to show the threshold availability of the system, and length of the "tail" of each design shows the time-weighted utility loss. This representation permits decision makers to assess system designs based on temporal-based metrics, on a three-dimensional pareto surface of cost, utility, and utility loss.

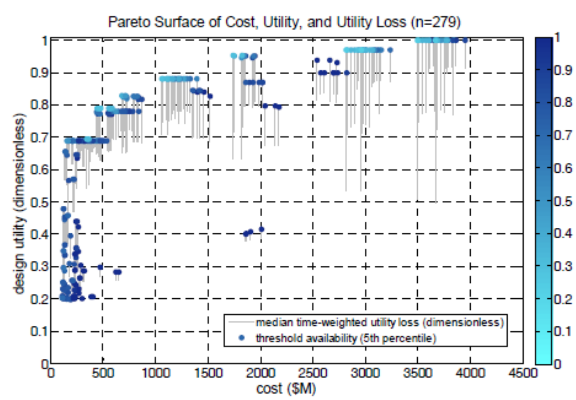

Fig. 6. Visualization of Complex Tradespace [source: 28]

Ongoing research in the systems community continues to explore useful representation graphics and techniques for systems engineering analyses such as tradespace exploration. There is also active research in the visualization community to develop approaches to multi-aspect information display [29].

VIII. SYNTHESIS OF MULTI-ASPECT METHODS

The five aspect framework provides a comprehensive landscape for evolving diverse constructs, methods, and enablers. Combination of multiple aspects is a source for further methodological innovation. Synthesis of multi-aspect methods can be used to develop robust methods for engineering complex systems. An example is now discussed.

The Responsive Systems Comparison (RSC) method is a seven process method for system concept generation, evaluation, and selection. The method consist of seven processes: (1) Value-driving Context Definition; (2) Value Driven Design Formulation; (3) Epoch Characterization; (4) Design Tradespace Exploration; (5) Multi-Epoch Analysis; (6) Era Construction; and (7) Lifecycle Path Analysis. The method has been developed using recently evolved constructs and methods, and is described in detail in [30, 31]. RSC's seven processes are used to conduct a tradespace exploration study to assess a large number of design alternatives on a common value-centric basis across changing contexts and needs. The goal of the method is to generate knowledge about tradeoffs, compromises, and risks to a system development project, and identify system concepts that are actively and/or passively value robust. The strength of the method is that it enables dialogue and knowledge building among system designers and stakeholders.

RSC strongly addresses the contextual, temporal, and perceptual aspects, and ongoing research seeks to further these elements as briefly illustrated in Fig. 7, as well as multi-aspect constructs and approaches discussed previously.

aspect	Research outcome example	Ongoing research example
Contextual	Epoch Characterization: in the method each fixed period of context and needs (an epoch) is modeled by characterization and parameterization of exogenous uncertainties	Continuing research includes empirical studies to understand the driving epoch uncertainties across different domains including space, aerospace, transportation, and energy
Temporal	Multi-Epoch Analysis: once epochs are modeled, analysis is performed to assess how designs perform across multiple epochs	Continuing research includes investigating how viable ordered sequences of epochs can be generated/used in temporal-based analysis
Perceptual	Visualizing Complex Tradespaces: complex data sets are generated using RSC, researchers have developed several effective constructs given human cognitive limitations/preferences	Continuing research includes investigation of how to present analysis results to different types of stakeholders such as senior decision makers and legislative aides.

Figure 7. Research on contextual, temporal, and perceptual aspects of RSC

In developing comprehensive methods such as RSC, there is a need to draw from multiple constructs and individual methods and techniques resulting from a portfolio of research. The five aspects framework provides a mechanism for classifying individual elements of the research program and considering synergies of these in order to construct a multi-process method such as RSC. The framework helps to encourage new research questions, as well as look for relevant research and findings from external sources. Multiple views of a university research portfolio are useful, and the framework provides one such approach to understand and elaborate research efforts. The framework appears to be useful in evolving and constructing advanced methodological approaches that provide coverage for each of the five aspects.

IX. DISCUSSION AND CONCLUSIONS

The five aspects framework provides distinct viewpoints for understanding the considerations that are necessary for engineering of complex systems. It has proven to be an enabler for identifying appropriate advanced methods within the aspects, as well as considering effective combinations of these to achieve synergies. The framework also shows promise as a focusing mechanism for establishing a comprehensive research portfolio and discovering related research of interest. Several areas of further inquiry and research are suggested given the current experience with the framework. The first area regards the further testing and validation of the five aspects, as well as how effectively synergies are achieved through combining two or more aspects. While these five aspects appear to offer comprehensive considerations for complex systems, it is possible that additional aspects will emerge, or that alternate characterization of the aspects will be more useful.

A second area of inquiry concerns looking at the research landscape using the framework as a means to classify relevant work. Several constructs and methods relevant to the aspects have been identified in this paper for illustrative purposes. In using the framework as an investigative frame, a number of works from other domains have been identified that can be classified using the aspects. For instance, investigation of the context aspect has uncovered similar inquiry in other domains. For example, research in the field of organizational behavior noted the importance of understanding influences of external environment on individuals to understand organizational behavior [32]. In the field of computer science, an empirical study of 150 participants identified external contextual factors of importance that induce change in information systems [33]. Studies from the other domains can uncover context factors not previously considered, and validate the importance of thinking about context in system design. Through classifying research using the framework, there is opportunity to seek similar research within and across domains, and to combine research outcomes within aspects, across aspects and through broad synthesis. Use of an organizing framework for this purpose seems to enable research discovery and synthesis.

A third consideration is that the suite of methods across the five aspects, when fully implemented, involves significant amounts of information and computational power. Dealing with dynamic factors and information is effort intensive. As an example, the RSC method discussed previously has been implemented using a newly developed multisensory laboratory. Early efforts show analyses, previously taking months to perform, able to be accomplished in minutes when computationally aided. Research is ongoing to further develop this capability, along with the methodological guidance and software assets to transition it to other organizations. A key goal in this effort is to understand how to create an affordable laboratory for implementation of analysis covering five aspects [21]. Presently, the newer methods described in this paper are undergoing trial use within real-world programs in government and industry. As such, the practicality of their implementation and ultimate contribution to system success is not fully understood. In regard to implementation, both computationally intensive and "back of envelope" approaches are being studied and assessed. The relative importance of each of the aspects for the complex systems engineering challenges are yet to be demonstrated.

Several examples of research as framed by the five aspects have been described using a framework highlighting areas of importance in engineering complex systems. The paper seeks to encourage further dialogue on the aspects, and input from the systems community on conditions under which resulting research outcomes can further the state of art and practice.

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