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Scenario Planning in Dynamic Multi-Attribute Tradespace Exploration

Christopher J. Roberts, Matthew G. Richards, Adam M. Ross, Donna H. Rhodes, and Daniel E. Hastings
Engineering Systems Division, Massachusetts Institute of Technology
Building E38-576, 77 Massachusetts Avenue
Cambridge, MA 02139 USA

Abstract— **The long time scales associated with complex system design and operation necessitate front-end systems engineering methodologies that enable consideration of alternative futures. This paper advances scenario planning techniques through a parameterization and ordering of potential future contexts and stakeholder expectations (e.g., articulated system attributes, available technology, funding levels, and supporting infrastructures). After surveying existing approaches for scenario planning, a methodology for specifying and analyzing large numbers of alternative system timelines is presented. A satellite radar case study is used to motivate and illustrate the value of this approach. Benefits of the methodology include: (1) broader and more rigorous consideration of alternative future needs, contexts, and timelines, (2) identification of gaps in traditionally-derived scenario sets, (3) identification of passively value-robust system alternatives, and (4) providing a basis for evaluating system evolution strategies that enable sustainment of value delivery across potential timelines.**

Keywords-scenario planning, epoch-era analysis, multi-attribute tradespace exploration, value robustness

I. INTRODUCTION

As complex engineering systems are increasingly characterized by long development timelines, extended operational lives, and interdependencies with other systems and infrastructures, scenario planning has grown in importance as a front-end systems engineering task [1]. Scenario planning allows the performance of alternative system designs to be assessed across representative distributions of uncertain future contexts. Rather than abstracting contextual uncertainty through implicit assumptions, this paper motivates, develops, and demonstrates an approach for internalizing time-dependent context factors within an existing system analysis framework.

The paper is composed of seven sections. Following this introduction, the second section provides a brief literature review and decomposes scenario planning techniques into two general categories: narrative and computational. In the third section, Epoch-Analysis is introduced as a computational approach for scenario analysis. The approach is demonstrated in the fourth section through a satellite radar case application. In particular, the broad parametric analysis of alternative system design afforded by Multi-Attribute Tradespace Exploration (MATE) is complemented by an analogous parametric characterization of plausible futures in Epoch-Era Analysis. The benefits of this approach for better aligning front-end design decisions with contextual uncertainties over the entire system lifecycle are discussed in the fifth section. The sixth section discusses propositions for future work, followed by concluding remarks in the seventh section.

II. SCENARIO PLANNING OVERVIEW

Scenario planning refers to a broad set of methods that organizations use to make systematic, well-informed strategic decisions through consideration of possible future contexts [2-7]. Scenario planning may be used to assess the robustness of alternative system concepts to uncertain futures by evaluating the performance of each alternative across changing stakeholder needs and contexts (e.g., technologies, policy constraints, and operational environments) [2,3,7]. Numerous scenario planning methods exist to support enterprise leaders in making strategic decisions [2-7]. Although there are many conflicting opinions regarding the merits of scenario planning approaches [3], they can be divided roughly into two broad camps: narrative and computational-based approaches [3]. Narrative-based approaches are typically informed by quantitative trends but their outputs are characteristically rendered as a qualitative and integrated story [4,6]. Computational-based approaches characteristically rely more heavily on quantitative and discrete characterizations of future states, though still often incorporate significant qualitative content [2,3,5]. Both approaches rely on domain experts but in different ways [3].

An additional complication to scenario planning is the existence of two temporal state characterizations, one for the context (exogenous) and one for the system (endogenous). In this paper, "state" refers to the state of system exogenous factors: a particular fixed set of context and needs for a system unless otherwise noted. Scenario planning approaches tend to be used to predict alternative states for the context and stakeholder expectations and label these states as scenarios, which we refer to as "state-scenarios." The value of considering these alternative state-scenarios is the ability to evaluate the usefulness of alternative system designs and configurations in these alternate futures in order to make better strategic decisions.

A. *Narrative-based Approaches*

The narrative approach to scenario planning was pioneered at Royal/Dutch Shell in the 1970's [6]. Though there is some

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diversity within the set of narrative methods, these approaches tend to strive for a few focused, thickly descriptive, internally consistent, recognizable, plausible and consequential scenarios [4,6]. Due to the limited number of scenarios generated, often narrative approaches consider extremes so that the bounds of the plausible are examined [4]. A textbook process for generating narrative scenarios involves six steps: (1) assess overall potential future stakeholder expectations and contexts, (2) identify key indicators, (3) establish the historical behavior of each indicator and analyze the reasons for past behaviors, (4) interrogate an expert panel to verify potential future events, (5) forecast each indicator, and (6) write scenarios and analyze the alternative strategies [4]. An advantage of this approach is that it may allow decision makers to consider key future uncertainties and to make more effective decisions due to the compelling nature of the constructed scenarios. However, even if the consideration of a greater number of scenarios were desired, narrative processes are prohibitively time-intensive [2,5]. The output of the narrative approach is a causal story-like scenario that accounts for how a particular future state came to be [3]. Strategies are then evaluated with respect to their performance in that scenario [3,4,6].

B. Computational Approaches

Advances in modern computing power have enabled the consideration of many different potential futures [2,3,5]. Although computational approaches generally rely on the same basic steps as the narrative approach, using domain experts for the identification of key drivers, the implementation of the scenarios is quite different. Rather than writing an integrated story-like narrative, computational approaches seek to parameterize the future stakeholder expectations and contextual factors into discrete variables more amenable to quantitative analysis [2,3,5]. This allows a more exhaustive enumeration of key uncertainties rather than a limited focus on the extremes. A major advantage of this approach has been shown to be reduction in biases and overconfidence [5]. By breaking the causal story of the narrative, it may be possible to surface consideration for counterarguments and account for counterfactual assumptions that may have gone unnoticed in the narrative scenario [3].

To differentiate between the degree of automation in the scenario generation process a distinction is made between morphological and expert-systems scenario building. Although both approaches rely on a database of enumerated potential future contexts and stakeholder expectations, the morphological approach uses experts to directly select and order these states into a cohesive scenario. By contrast, expert-systems use inferential logic to sample and order the system exogenous states into a scenario [8]. The morphological approach has been shown to provide a more exhaustive search of alternative futures than narrative approaches [5]. A key challenge for both the morphological and expert-systems approaches is managing the combinatorial expansion of potential futures [5,8]. The outputs of both computational approaches are sets of possible or plausible futures against which strategies can be evaluated [2,3,5].

III. METHODOLOGY: EPOCH-ERA ANALYSIS

An enterprise is an inter-organizational network with distributed leadership and stakeholders with both common and diverse interests [9]. Enterprises are a prevalent form of organizing work in large scale system acquisition programs. The system lifecycle is a fundamental construct that large-scale acquisition enterprises use to characterize the phases of a system during its lifespan, from initial concept to end of life. System lifecycle processes allow the enterprise to organize the numerous activities involved in design, implementation and operation of a system. The system lifecycle is typically composed of phases that have defined milestones. However, the system lifecycle does not enable the explicitly consideration of the impacts of a diverse set of changes in the dynamic value environment. Designers must have other fundamental constructs for considering the temporal view to design systems that maximize the chances that stakeholders will remain satisfied throughout the system lifecycle.

Epoch-Era Analysis is a computational scenario planning methodology that provides a structured way to analyze the temporal system value environment (see Fig. 1) [1]. An *era* is defined by a period of time corresponding to the cradle-to-grave lifecycle of a system. Eras are decomposed into epochs, analogous to the use of these terms in geology. An epoch is a period of time for which there is a fixed context and value expectation for the system. System designs can thus be evaluated within a given epoch using existing methods, such as MATE [10]. The utility-cost tradeoffs of a given system will likely change in different epochs due to the differing context and value expectations. In effect, each epoch is a "state-scenario," representing one possible configuration of the context and value expectations. In order to construct the set of epochs it is necessary to parameterize and enumerate the key contextual factors and potential system value expectations. An era is an ordered set of epochs that span the entire system lifecycle and represents the evolution of state-scenarios from current to intermediate and future states. Either morphological or expert-systems approaches can be used to construct the eras. Each era represents the unfolding of a scenario with multiple context and stakeholder expectation states (i.e., epochs).

Epoch durations are dependent on events that are exogenous to the control of the system program manager, though some feedback may exist. Each time an epoch change occurs the system operates in a different context and may need

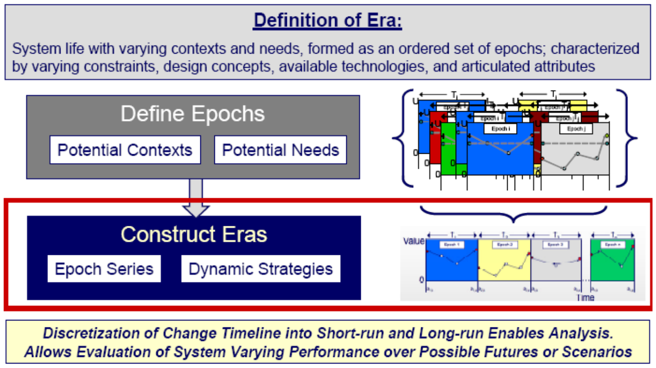

Figure 1. Representation of the Epoch-Era Analysis Process [14]

to change in order to sustain its value. An actively value robust strategy entails changing the system to maintain value given changes in context and stakeholder expectations. However, system changes may not be reversible, so this method allows short-term decisions to be viewed in terms of their long-term consequences. An alternative strategy to sustaining stakeholder value is to select designs that are passively value robust [11].

IV. CASE APPLICATION: SATELLITE RADAR

In order to demonstrate scenario planning within MATE, the method was applied to a notional Satellite Radar (SR) system. An engineering model was developed with sufficient technical sophistication to capture the key performance trades, but efficient enough to allow the parametric exploration of a large set of designs within a large number of epochs [10]. While other work has focused on the design formulation and tradespace evaluation phases of the SR case application [8], this paper focuses on the application of computational scenario planning using Epoch-Era Analysis.

Radar systems provide numerous capabilities that other forms of remote sensing cannot. These capabilities include day/night all-weather imaging, ground moving object tracking and terrain mapping. However, U.S. Government efforts to field an SR system have run into repeated programmatic difficulties due to immature technology, conflicting sets of user needs, as well as schedule, cost and funding risks [12, 13]. The challenges posed by these future uncertainties make SR a strong candidate for Epoch-Era Analysis. The application consists of three general phases (a) value-driven enterprise definition, (b) epoch enumeration, and (c) era construction.

A. Value-Driven Enterprise Definition

Previous attempts to acquire a military space radar system indicate that transitioning the radar surveillance mission to space involves a host of technical, organizational, financial and operational challenges. These challenges are not fixed, and will evolve over the course of the system development. The success of a future SR program will not only require successful execution of a program plan within a static context, but also involve aligning the system development with exogenous system drivers that change over time. Fig. 2 illustrates four types of dynamic uncertainty that are exogenous to the control of the SR program manager: mission needs (i.e., Strategy/Policy), funding (i.e., Resources), supporting infrastructure (i.e., Capital), and operational environment (i.e., Radar Product).

First, any SR system will be designed, developed, and operated within a complex institutional environment with multiple stakeholders and competing priorities. For example, the importance of the synthetic aperture radar (SAR) imaging mission relative to the ground moving target identification (GMTI) mission may drive the system development in different directions. Second, given the long development times of space systems, the annual funding allocations for SR are uncertain over the development lifecycle. Third, the supporting infrastructure for the SR platforms will directly impact the system value delivery. Supporting infrastructure may include the availability of technologies (typically developed and matured in research and development organizations) as well as system-of-systems considerations. For example, the future availability of the transformational satellite communications system (TSAT) or collaborative airborne intelligence, surveillance, and reconnaissance (AISR) platforms will directly affect the operational value of the SR system (i.e., tracking latency and target track life, respectively). Fourth, the operational environment of the SR system is also highly uncertain (e.g., adversary tactics) and directly impacts the value delivery of the SR system. Ref [8] provides a more detailed account of the SR enterprise boundary definition and stakeholder value network mapping process illustrated in Fig 2.

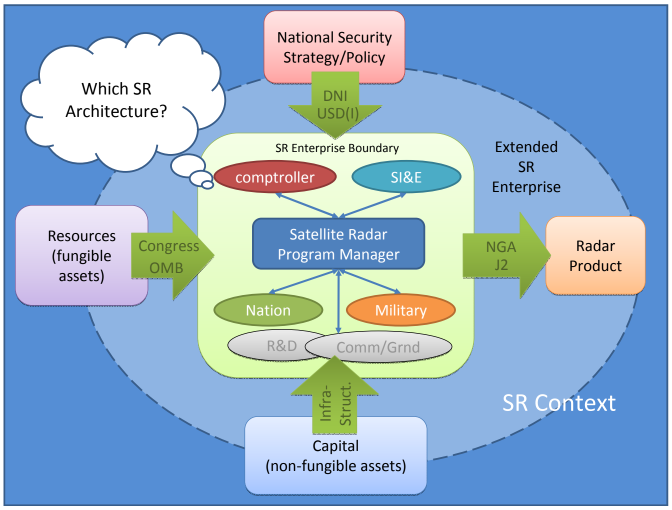

Figure 2. Satellite Radar Enterprise [8]

B. Epoch Enumeration

Given the exogenous uncertainties characterizing the context and stakeholder expectations over the SR system lifecycle, scenario planning with dynamic MATE seeks to identify value-robust designs by incorporating broad distributions of plausible future context states. In particular, rather than making static assumptions regarding each uncertainty or assuming fixed worst-case values, the future context states are parameterized using an epoch vector. In a process analogous the parametric concept generation phase in a traditional MATE system design analysis [10], each key uncertain system exogenous factor is characterized by an epoch variable. An epoch variable is a quantitative parameter that reflects an aspect of an uncertain future context. Each possible combination of epoch variables constitutes a unique epoch vector, and the set of all possible epoch vectors constitutes the set of state-scenarios. While epoch variables are not directly under the control of the program manager, the probability of some epoch variable levels from arising may be influenced by the program manager (e.g., research and development dollars on technology readiness).

When proposing epoch variables and enumeration ranges, a natural tension exists between including more variables to analyze larger sets of plausible futures and the computational limits on evaluating a larger set of scenarios. Iterative structured and unstructured interviews were conducted with

TABLE I. EPOCH VECTOR DEFINITION

Exogenous Variable Category	Epoch Variables	Number of Steps	Enumerated Range	Units/Notes
Strategy/Policy	Imaging vs. Tracking Utility Expectations	3	[1,2,3]	1=SAR<GMTI 2=SAR=GMTI 3=SAR>GMTI
Resources	Budget Constraint	na	na	Use tradespace to vary "costs"
Capital	Radar Technology	3	[1,2,3]	1=Mature 2=Medium 3=Advanced
Capital	Communication Infrastructure	2	[1,2]	1=AFSCN 2=WGS+AFSCN
Captial	Collaborative AISR Assets	2	[1,2]	1=Available 2=Not available
Radar Product	Operations Plans	9	[9,19,44,45,49,60,84,94, 103]	Lookup table of geographic region & target op. plans
Radar Product	Threat Environment	2	[1,2]	1=No jamming 2=Hostile jamming

domain experts representing stakeholders from the four areas of system exogenous uncertainty identified in the satellite radar enterprise diagram (Fig. 2). Based on those discussions the epoch variables for the SR system context were derived and are shown in Table I.

The full factorial expansion of the epoch variables yields 648 potential epochs. In MATE, a parametric system design tradespace must be enumerated for each epoch. For the SR case application 23,328 unique system designs were evaluated. Due to the rapid expansion of unique designs across a large number of epochs, each epoch was assumed to have a uniform probability distribution of occurrence and a random sampling strategy was used to produce a subset of epochs to computationally analyze the system designs. This sampling strategy was chosen for its simplicity of implementation as this case application was intended to demonstrate a proof-of-concept for the method. Of the 648 epochs, a handful were purposefully selected so that eras could be constructed to resemble scenarios from the literature as a basis for comparison [13]. In total, 245 distinct epochs were evaluated – 21 hand-picked and 224 sampled – with each populated by a system design tradespace evaluated relative to the particular configuration of the epoch variables. Since each epoch is a "state-scenario," representing one possible configuration of the context and value expectations, interesting insights and system changeability metrics such as system Pareto-Trace, and Filtered Outdegree can be computed directly [14].

C. Era Construction

An era is defined as an ordered set of epochs over the system lifecycle and represents the evolution of the context from the current to intermediate and future states. Era construction involves four general steps: (1) specify era duration, (2) specify epoch durations, (3) establish epoch transition logic, and (4) implement epoch sampling strategy.

The first step is to establish the total time period for analysis (i.e., the era length). For the case application, the era was specified to be 20 years, which is a reasonable duration for the complete lifecycle analysis of a large scale space system [13]. In the second step, the enumerated epoch variables are consulted for insights into the time constants for change from one epoch to another (i.e., the clockspeeds of the epoch variables). For example, threat environments are subject to rapid change while the rate of change for major infrastructures is several years. In the third step, the epoch transition logic is determined. In the SR analysis, epoch orderings are assumed random with the sole exception of technology (which remains constant or advances over the era). In the fourth and final step of era construction, scenarios are developed based on ordered sets of epochs. For the case application, eras were constructed using a computer-augmented morphological approach [5], which entails a direct assignment of the epoch duration and ordering based on expert opinion. A total of seven eras were constructed and analyzed. However, only three eras will be discussed in the following section in order to highlight representative insights.

V. ANALYSIS & DISCUSSION

In 2007 the Congressional Budget Office conducted a study assessing alternatives for a satellite radar system [13]. The system designs and scenarios used in this report informed our modeling ,as it provides a benchmark for judging our method.

The CBO report considers four satellite designs, though in multiple constellation configurations, and two state-scenarios. The CBO scenarios were meant to provide context to evaluate the performance of a SR system in a conflict with an adversary possessing mobile missile launchers. Though the focus of the CBO study was on design alternatives for the SR system itself, assumptions regarding the availability of communications infrastructure were necessary to compute the SR performance. The only contextual variation considered was the possibility of two relay backbones. The operations plan and the user preferences for SAR and GMTI data were also fixed. Additionally, no attempt was made to consider the effects of adversary actions. We identified both epochs in our database that corresponds to the two CBO state-scenarios. One of these epochs, ID #193, is shown in Table II.

The report considered two possible radar aperture area configurations: 40 m^2 and 100 m^2. Though the radar aperture is treated as a system design variable in the CBO report, the more advanced 100 m^2 radar aperture is less mature from a

TABLE II. SINGLE EPOCH CORRESPONDING TO CBO SCENARIO

Epoch ID #193		
Epoch Variables	***Epoch Value***	***Notes/Units***
Radar Technology	1	40 m^2 aperture
Communication Infrastructure	3	TSAT+AFSCN
Operations Plans	94	Mid-latitude, small mobile targets
Collaborative AISR Assets	1	No airborne assets
Threat Environment	1	No hostile jamming
Imaging vs. Tracking Utility Expectations	1	SAR<GMTI

technology readiness standpoint. (Often advanced technology development is conducted by an enterprise stakeholder, such as a Research & Development Office, that is not directly under the control of an acquisition program manager.)

Era 1 in the case study improves upon the CBO scenario by combining an ordered set of epochs that provide the dynamic context within which a satellite radar design can be evaluated. The era begins in the following configuration: mature radar technology, a basic communication infrastructure, a mid-latitude/large target operations plan, no collaborative airborne assets deployed, no hostile communications jamming by an adversary, and a user preference for SAR imaging over GMTI tracking data. This epoch persists for two years until a new communications infrastructure becomes operational. This second epoch persists for four years until a new threat of mobile missile launchers emerges. Now there are changes in both the operations plan and the user preferences as the mission has changed from imaging large static targets to detecting and tracking small mobile targets in a different geographic region. The threatened state lasts for one year until open conflict breaks out. During the conflict, airborne assets are deployed to supplement ISR collection and, if the SR system has been designed with the appropriate interfaces, form a collaborative system-of-systems [15]. The adversary also reacts with hostile jamming, potentially degrading the performance of the satellite radar data downlink. The conflict persists for three years after which the world returns to the pre-threatened state. A summary of the era is given in Table III.

Once the era has been constructed it is possible to investigate active and passive value-robust system strategies. An illustrative example of a potentially passively value robust system design is provided in the following section.

Era 1, consisting of five epochs with associated system design tradespaces, is presented in Fig. 3 for illustrative purposes. The arrow indicates the location of design #3435, previously identified a passively value robust design – showing up at or near the Pareto optimal front (highest utility per cost) in each epoch. The axes of each system tradespace are utility (vertical) and cost (horizontal).

Because the evaluation of a system's performance is judged relative to a particular context, a number of interesting system design issues are raised by this era. First, the availability of a new communications infrastructure has the potential to increase the SR system performance by enabling more downlink bandwidth and reducing data latency. However, the SR system can only exploit the new infrastructure if it was designed with the ability to interoperate with it. This means that the program manager likely must bear a short-term cost during the design phase to purchase the option (e.g., dual transceivers, reprogrammable processors) to upgrade to the new infrastructure during the operational phase. Next a threat emerges inducing a change in the collection priorities from a more strategic focus on large targets in one region of the world to a more tactical focus on small mobile targets in a different region. System users – analysts of the radar imaging and tracking products – have different expectations of the system now that their priorities have changed. Then, with the onset of open conflict and the deployment of AISR assets to the region it may be possible to form a collaborative system-of-systems to gain an emergent technical capability. As with the communications infrastructure, it is only possible to form a collaborative system-of-systems if the appropriate interfaces are in place.

TABLE III. ERA 1: MOBILE MISSILE CONFLICT—MATURE RADAR TECHNOLOGY LEVEL

Epoch State (#)	**Epoch Duration (years)**	**Epoch Vector**	**Epoch Description**
63	2	{1, 1, 60, 1, 1, 3}	Current State
171	4	{1, *2*, 60, 1, 1, 3}	Operational status attained for an upgraded communications infrastructure
193	1	{1, 2, *94*, 1, 1, *1*}	New threat emerges – mobile missile launchers
202	3	{1, 2, 94, *2*, *2*, 1}	Conflict – AISR deployed and hostile jamming
171	10	{1, 2, *60*, *1*, *1*, *3*}	Conflict resolved – return to pre-threatened state

Eras 2 and 3 have the same structure as Era 1, however, the available radar technology is assumed to be medium and advanced respectively. As discussed previously, often the research and development of advanced technologies is not under the direct control of a program manager. Comparing similar eras with differing technology availability assumptions surfaces enterprise-level resource allocation issues between supporting existing programs versus pursuing breakthrough technologies. Additionally it may provide the program manager a way to consider the opportunity costs of waiting for "better," more advanced technology, in particular if the timescale for the technology maturation is comparable to or greater than that for the context evolution timescale (i.e., epoch durations). Observation suggests that such mismatches in context and system development timescales are a major contributing factor

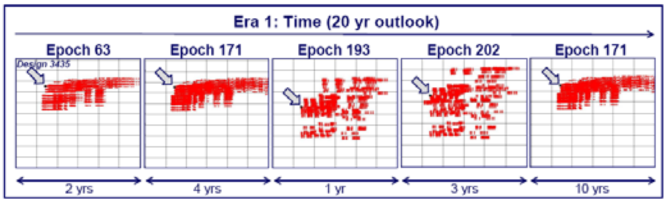

Figure 3. Illustrative Example of a Design Point within the Era

to “requirements creep.” Using the natural value-centric timescales of the context evolution to structure the system design and lifecycle activities in a dynamically relevant way is a key contribution of this work.

VI. FUTURE WORK

Scenario planning within MATE using Epoch-Era is an emerging methodology with several areas for refinement and extension. This section discusses three propositions for future work: (1) advanced epoch sampling, (2) expert-systems era construction, and (3) enterprise strategy.

First, future research should relax the assumption of a uniform probability distribution of epoch occurrence. This research should couple empirical data collection with design-of-experiments techniques to more efficiently formulate and sample large sets of future epochs.

Second, the morphological approach pursued for era construction in this paper should be compared to the expert-systems approach. While some path-dependencies in epoch sampling are incorporated into the state transition logic (e.g., maintenance or advancement of TRL over time), it would be valuable to better understand the costs and benefits associated with implementing a general Markov state transition model across a wide range of epoch variables.

Third, the SR system case application demonstrated the high degree to which enterprise considerations interact with the system lifecycle value delivery. In particular, the interdependencies between the system and numerous non-fungible factors such as technology development, communication infrastructures, and the increasing prevalence of collaborative system-of-systems suggest that deliberate enterprise architecting strategies are needed to ensure visibility to enterprise-level opportunities and vulnerabilities. This is particularly necessary for managing the inter-organizational complexity and coordination entailed in implementing collaborative system-of-systems. Furthermore, there is growing recognition that designing a system to have the technical ability to adapt to changing contexts is a necessary but not sufficient condition for actively value robust system strategies. Enterprise authorities and processes must be in place to sense changing contexts, to adjudicate between competing stakeholder interests, and to implement the system changes on timescales much less than those of the evolving context. Future work should extend this modeling approach to account for such enterprise architecture considerations, including field work to establish an empirical basis for modeling enterprise-system architecture interactions within the dynamic value paradigm.

VII. CONCLUSION

Scenario planning in dynamic MATE using the Epoch-Era Analysis methodology has been shown to enable the evaluation of thousands of potential system designs over hundreds of potential future states. This allows a far broader set of assumptions about the potential future contexts and stakeholder values to be tested. The analysis was executed for 23,328 system designs over 245 epochs, and seven eras were constructed.

Using a contemporary scenario-based analysis as a benchmark [13], we demonstrated a broader and more rigorous consideration of alternative future needs, contexts, and timelines, identifying gaps in traditionally-derived scenarios. This includes the consideration of changes in available technology, communication infrastructure, operating plans, adversarial actions, and collaborative system-of-systems. The identification of a passively value-robust system design was illustrated. Finally, this paper provided the basis for the identification of system evolution strategies that enable sustainment of value delivery across potential timelines, including the explicit recognition of enterprise architecture issues such as competing stakeholder interests and authorities.

While the satellite radar analysis generated prescriptive technical insights for the system of inquiry, the key contribution of this paper is a structured process for characterizing time-dependent contextual uncertainty. Although exogenous to the enterprise boundary and beyond the control of system developers, system analysis methodologies that internalize contextual uncertainty are better equipped to identify the dynamic relevance of alternative designs.

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