Responsive Systems Comparison Method: Case Study in Assessing Future Designs in the Presence of Change

Adam M. Ross.[1]
Massachusetts Institute of Technology, Cambridge, MA 02139

Hugh L. McManus, [2]
Metis Design, Cambridge, MA 02141

Andrew Long, [3]
UMRobotics, Chantilly, VA 20152

Matthew G. Richards,[4] Donna H. Rhodes,[5] and Daniel E. Hastings[6]
Massachusetts Institute of Technology, Cambridge, MA 02139

In this short paper, the Responsive Systems Comparison (RSC) method is introduced. RSC is a structured method for collecting information and conducting analysis to characterize a wide variety of possible futures in order to enable the comparison of the performance of proposed systems in those futures. A case study uses the RSC to analyze a satellite radar system. The needs and expectations of a user community for such a system, the context it will operate in, and its technical basis are determined both at the present time, and with possible changes over the next 15 years. This information is used to set up an analysis that should be able to highlight systems that will deliver value under a wide variety of future situations. The case study illustrates the practicality of the method, and provides lessons for improvement and implementation.

Nomenclature

N_{epoch1} = Number of possible configurations of Epoch 1
$N_{epoch(total)}$ = Number of possible configurations of all Epochs
N_{needs} = Number of possible need sets in a given Epoch
$N_{contexts}$ = Number of possible context sets in a given Epoch
N_{eras} = Number of possible Eras
L_{era} = Length of Era in Epochs

I. Introduction

The designers and system architects of a complex system often face the problem that changes in user needs, available technologies, and political and technical contexts are inevitable during the system lifetime. These changes are often unpredictable.[1] Attempts at rigid probabilistic treatments of the future possibilities are hampered by difficulties in estimating the probabilities of various futures, and the possibility that an unanticipated factor (i.e., the "unknown unknown") may appear.[2] Attempts to enumerate many possible futures by simulation or through consideration of many scenarios have the same problems. These attempts often run into computational difficulties when a reasonable design set is considered across a large number of possible branches derived from a modest set of possible futures. Currently, designers are left with only intuition and experience, as well as abstract guidance to

---

[1] Research Scientist, Engineering Systems Division, NE20-388, AIAA Member.
[2] Senior Special Projects Engineer, 10 Canal Park, AIAA Associate Fellow.
[3] 43727 Scarlet Sq, AIAA Member.
[4] Research Assistant, Engineering Systems Division, NE20-343, AIAA Member.
[5] Principle Research Scientist, Engineering Systems Division, NE20-388, AIAA Member.
[6] Professor of Aeronautics and Astronautics and Engineering Systems, Dean for Undergraduate Education, 4-110, AIAA Fellow.

incorporate desirable system properties known as “ilities” (e.g. flexibility), which are difficult to quantify, and hence difficult to formally specify.[3]

This paper will describe a structured method for collecting information to characterize a wide variety of possible futures in order to enable the comparison of the performance of proposed systems in those futures. The method will not solve the problem of an unknown future, but will provide decision makers with information necessary to make the best possible decisions given available information. The method is referred to as the Responsive Systems Comparison Method. It is an application of tradespace analysis in general,[4] and specifically leverages the developing science of Epoch-Era Analysis of Ross.[5,6] As with tradespace exploration and Epoch-Era Analysis, the RSC method is motivated by the goal of providing decision makers with quantitative comparisons of the advantages and disadvantages of possible systems, as opposed to selecting an “optimum” system.

The method is introduced in the first half of the paper, and then a case study is explored. A notional Satellite Radar System (SRS) is the subject of the case study. Such a system has obvious utility – it can collect observation data at night, through adverse weather, and even through light cover (such as tree canopies) in ways that optical or other forms of sensing cannot. It can also be used to accurately map land features and spot and track moving objects in ways not possible with other technologies. However, US Government efforts to field such a capability have run into repeated programmatic difficulties due to immature technology, diverse and non-aligned potential users, and cost and funding risks. These difficulties indicate that it has potential as a good subject for the RSC method.

The institutional framework surrounding a notional SRS program was explored. A goal was specified – to help the leader of a SRS program select system(s) with the best chance to keep the potential stakeholders of the system satisfied over the program lifetime. Representatives from various potential stakeholder groups were then selected and interviewed. A structured method, based on applied decision theory,[7,8] was used to collect a set of current and projected needs from multiple potential stakeholders. These needs were formalized as the attributes of the tradespace study to be embedded in the RSC. The same interviews were used to elicit a realistic set of needs, contexts, and available technologies that define the possible epochs, characteristic time periods within which a SRS will operate. A structured process is used to create a parametrically-defined set of possible system designs, and transition rules that allow the designs to be responsive. The result of this effort is a fully defined RSC analysis for a SRS. Although the analysis itself is not complete at the time of this writing, the formalization of the problem serves as a proof-of-concept of the RSC method, and illustrates some of the practical difficulties of the method.

II. The Responsive Systems Comparison Method

The RSC method considers changes in 1) user needs and expectations, 2) context (or environment in a broad sense), and 3) the system itself (and its associated technology). The method is an application of Epoch-Era Analysis, which allows for the discretization of the future system timeline into a series of short run *Epochs* of fixed *Expectations* and *Context*, as shown in Figure 1. An ordered series of epochs is known as an *Era*, or system timeline. A single proposed system is analyzed for its performance in various epochs, during which expectations and contexts are assumed constant. Expectations are represented by a band capturing the range from minimally acceptable to the highest of expectations. In Figure 1, the system exceeds the highest expectations during Epoch 1 (i.e. has capacity or performance perceived to be unneeded), which enables the system to remain valuable in later epochs with increasing user expectations, changing environments, and possibly system degradation. Finally, in Epoch 5, the system no longer meets minimal user expectations. Figure 2 shows a responsive system that is capable of changing or being modified to adapt to the changes in epochs. It does not have excess capacity in the system in Epoch 1; instead, it changes (or is changed) in response to the changing epoch to continue to meet stakeholder needs. The downside of this strategy is also shown–if the system is not (or cannot be) modified, its performance may become unacceptable in later epochs. As currently practiced, Epoch-Era Analysis is used to

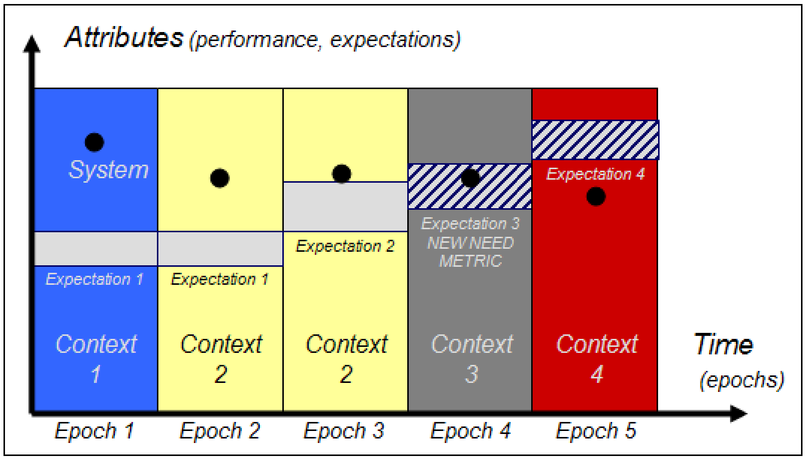

Figure 1. Example Era: Five epoch analysis of an unchanging system

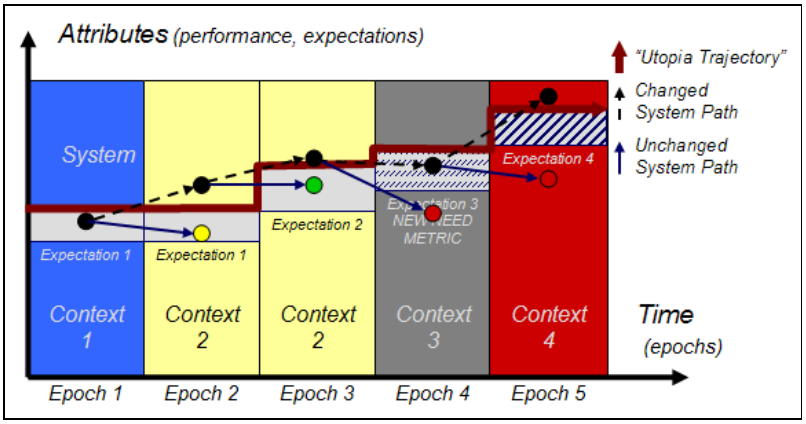

Figure 2. Example Era: Five epoch analysis of a responsive system

analyze a large number of potential systems through a small set of epochs, and to find systems that either passively or responsively deliver best value over time.

Analyzing large numbers of systems is most efficiently done using tradespace exploration.[4] In this method, the system in question is represented using a parametric model, with the parameters making up a *design vector* that, when enumerated, specifies a large number of possible designs. A careful choice of design vector elements can specify a wide range of possible solutions while keeping the computational load tractable. The designs are evaluated using stakeholder-specified *attributes*, which are quantitative measures of what the stakeholders want from the system. These attributes can be technical performance measures, or programmatic measures such as schedule, cost, and risk. The attributes can be used to calculate the relative utilities of various designs to various stakeholders. Some of the utilities can be aggregated using multi-attribute utility theory. Some can or should not be; notably, cost is usually kept disaggregated, and the utilities of different stakeholders should not normally be aggregated.

The above examples assume that the progression of epochs is understood in advance. Figure 3 illustrates a set of epochs that *may* happen, and a set of possible descriptions of the era, represented by traces through possible epochs. The number of possibilities for epoch 1 is:

$$N_{epochs1} = N_{contexts} * N_{needs} \tag{1}$$

If two contexts and three sets of user needs are possible, then 6 possible epochs need to be considered. If the length of an era is L_{era} (measured in number of epochs) and later epochs have the same number of possible needs and contexts as Epoch 1, then the number of total possible epochs to consider is:

$$N_{epochs(total)} = (N_{contexts} * N_{needs}) * L_{era} \tag{2}$$

The number of possible eras that can be constructed through the epochs then increases geometrically with the length of the era:

$$N_{eras} = (N_{contexts} * N_{needs})^{L_{era}} \tag{3}$$

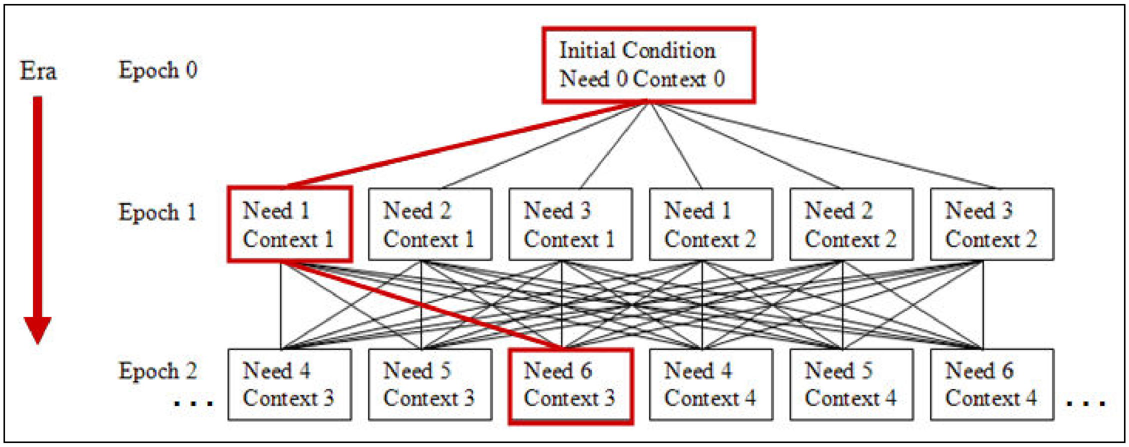

Figure 3. A small number of epochs create a large number of possible eras

More generally, the number of possible epochs for a given “Epoch i” in an era will vary, and will be path dependent, i.e., will depend on the order of epochs prior to “Epoch i”. The geometric growth of possible eras will remain, however. The growth problem has several immediate consequences. Some form of automated enumeration of possible system eras will be required, as opposed to simply defining a number of scenarios “manually.” A full enumeration would likely face computational constraints, so a sampling strategy is needed to reduce the computational burden. Finally, the problem must be partitioned such that computation is done once per epoch and can be reused when analyzing paths across eras. With a database of possible epochs, tracing many possible paths within an era that responsive systems can take can be made computationally tractable.

To implement the RSC method, techniques are borrowed from existing tradespace analysis methods. A front-end approach, based on applied decision theory,[5,7,8] is used to collect a set of current and projected needs from space system users. A structured process is also used to create a set of context scenarios, as well as a set of possible system designs, including transition rules that allow the designs to be responsive. The impact of new technologies on system designs and paths will be assessed in future epochs. The method will create a “tree” of future possible eras, using a set of rules to “prune” both the contingent epoch set (to filter out unrealistic orderings of epochs) and the responsive system set (to eliminate technically infeasible or prohibitively expensive system transitions).

The results of the analysis will be reduced to a set of information useful to decision makers. The basic metric for assessing a system is the difference between the path of the system through a set of epochs and the “utopia trajectory” shown in Figure 2 as a red line. The “utopian” system meets all decision maker expectations in each epoch of the era. Implied in this metric is a set of “ilities” needed by the system, such as flexibility and versatility, which help the proposed system match the utopia trajectory. The results of the RSC method will be both a quantification of these ilities for the projected futures, as well as provide emergent insights into their usefulness in handling “unknown unknowns” that are not part of an explicitly predicted future. In the end, the RSC method will empower decision makers to be able to conceptualize and strategize how investments and evolution of systems should take place in order to meet expectations over time throughout changing and even unanticipated contexts.

III. Satellite Radar System Case Study

The concept of a satellite radar system is well documented and will not be reviewed in any detail here. The basic idea is a satellite (or system of satellites) that creates and aims a pulse of electromagnetic radiation at target areas, then collects radiation reflected from the targets. This signal can be processed to resolve not only images of the target area, but also information such as the velocity of objects in the target area. Space offers a unique vantage point for such a system. There are several basic challenges however, including the extreme (4th power) sensitivity of the radar signal to range, the desire for high power transmitters and large (high gain) receivers, and the generation (and thus need to process and transmit) very large amounts of data.[9,10,11]

For this study, a SRS was postulated that would provide 24-hour, all-weather imaging and tracking of targets of interest. The purpose of the study was then defined as assessing the ability of potential space-based radar architectures to satisfy potential customers over a large range of possible future situations (epochs). This paper describes progress on the front end of the study. The system contexts, stakeholders, bounds and scope were defined. Attributes that quantify the value of the system to the various stakeholders were elicited and defined. Another set of parameters that characterize and quantify the epochs that the design(s) may have to operate in were also elicited. Finally, a set of parameters that defined a wide variety of potential designs (the design vector) were created, as were transition rules governing how designs could change or adapt to changes in epoch. The basic feasibility of the RSC method was demonstrated by this exercise, and lessons were learned about how it can be used to analyze large, complex national assets such as a SRS.

A. Satellite Radar System Context and Stakeholders

The overall context for a SRS architecture problem is depicted in Fig. 4. The fundamental question is which SRS architecture a notional SRS Program Manager should select to maximize the chances that stakeholders will remain satisfied throughout the system lifecycle (i.e. which system will provide the highest degree of *value robustness*[12]).

A SRS Enterprise itself is composed of all the key decision makers involved in the initiation, execution, operation, and retirement of a SRS system. As depicted in Fig. 4, these key decision makers include a SRS Program Office, Comptroller and Systems Integration and Engineering (SI&E) Offices, which have business and engineering oversight roles, and National and Military users which represent the users of a SRS system across a portfolio of systems that include SRS. The value definition of these four organizations must be explicitly considered and satisfied for the program to successfully meet the internal enterprise requirements. Ancillary offices, including

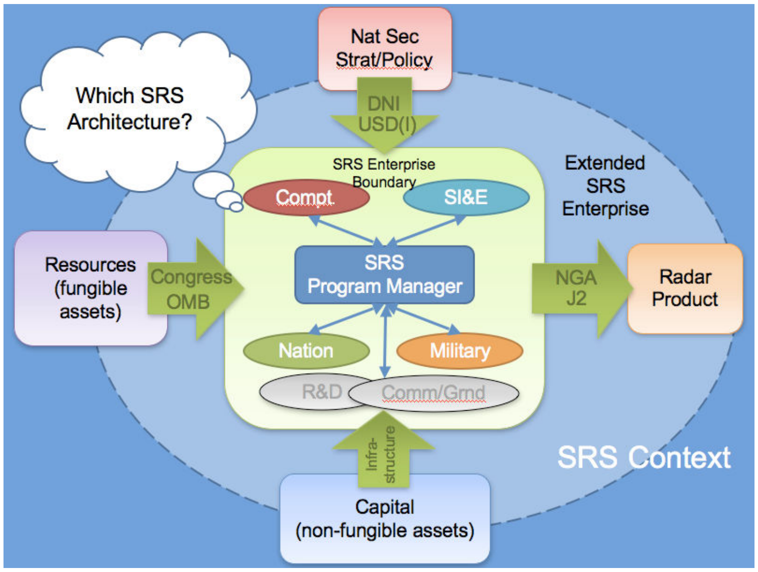

Figure 4. Satellite Radar System Enterprise and Scope Definition.

Research and Development, Systems Launch, Communications and Ground Operations offices, also play critical supporting roles in terms of the infrastructure needed to actually implement a successful system, but they do not represent core enterprise decision makers from the standpoint of having "make or break" status on the program moving forward.

Figure 4 is not intended to convey strict lines of authority or communication. Figure 4 should also not be construed as suggesting that a SRS Program Manager treats all of the interactions between the enterprise decision makers equally or in the same way. The intent is to provide a means of identifying who the decision makers are at a SRS Enterprise level, and to begin to understand the influences on these decision makers from both internal and external factors. The information elicited from these decision makers provide the basis for creating the attributes, design vector, and epoch descriptions described below.

The arrows connecting each of four external factors to a SRS Enterprise represent the organizations involved in the extended SRS Enterprise and that directly influence the value definitions of the decision makers within a SRS Enterprise. The National Security Strategy and Policy factor represents the flow down of such things as the National Defense Strategy, the National Military Strategy, National Security Space Policy, and other policy directives and mandates from such sources as the National Security Council, the Under Secretary of Defense for Intelligence (USD(I)) and Director of National Intelligence (DNI). This factor impacts a SRS Enterprise by shaping the broader goals and priorities in which a SRS Enterprise value delivery is gauged and provides the context in which cost/benefit for a SRS Enterprise is perceived.

The Radar Product factor captures the termination point at which technical performance utility is measured. For the purposes of this analysis, this termination point is the radar imagery analyst who ultimately exploits the data provided by a SRS Enterprise and who provides a finished intelligence product to the customer or "user". The interaction between this factor and a SRS Enterprise is significant in that NGA and J2 become the primary source of feedback as to the utility of a SRS architecture, and they may also provide key insight into what is required in the system performance attributes both initially and as a SRS architecture evolves. Their inputs are directed primarily through the National and Military Users but some direct lines of communication may be opened directly with a SRS Program as well.

The Capital factor is intended to represent those non-fungible assets a SRS Enterprise needs, including the materiel suppliers in the industry base, the knowledge base of the industry (from a human capital perspective), throughput or capacity, industry IRAD investment, complementary programs, etc. This factor most directly impacts a SRS Program Manager by defining the technical feasibility of a given SRS architecture.

The Resource factor represents fungible assets in terms of funding and manpower available as inputs into the program. A SRS Enterprise is influenced through direction provided by both the Office of Management and Budget and Congress with regard to this factor. The interaction is felt most keenly by the Comptroller with spin-off impacts on SI&E and the National and Military Users. These in turn translate into SRS Program constraints.

B. Stakeholder Interviews

Structured interviews were conducted with a representative cross-section of potential stakeholders illustrated in Figure 4. Personnel from a satellite program office, a satellite contracting organization, user proxy organizations, and oversight organizations were interviewed. The perspective of the Congressional Budget office was taken from a 2007 report.[9]

The interview data was aggregated and used to define, from a broad perspective:

- The overall Value Proposition of a SRS system (24-hour, all weather imaging and tracking)
- The likely end-users of the collected data
- The attributes valued by the potential end users as well as the potential program stakeholders
- The range of practical system solutions to be captured in the trade space analysis, the known or expected trades between various solutions, and known constraints
- The contexts and needs sets that define the current epoch, and how they may change in the future
- Known barriers to success, and issues and questions that represent possible future barriers

The knowledge collected in this way was used as the basis for setting up the RSC method analysis. It should be noted that this procedure represents an advance on previous (static) tradespace analyses[4] that tended to concentrate on the needs of a single stakeholder, and take their context primarily from the expertise of the analysts.

C. Attributes Definitions

The attributes derived from the interview data are shown in Table 1. These attributes are quantitative performance metrics that be used to define the utility of the proposed system. The attribute structure is more complex than typical for previous tradespace analyses. There are two major sets of technical performance attributes which correspond to the needs of two distinct users – one interested in static images for strategic purposes, and another interested in rapid acquisition and tracking of specific targets over short periods for tactical military purposes. A third potential user, interested in terrain mapping, has a small set of attributes. In general, although the utility of attributes within each set may be aggregated into an overall usefulness to that user, the utilities cannot be aggregated across the user sets. The implication is that any system will have three distinct measures of utility. In addition, the program and resource-providing stakeholders are interested in the cost and schedule of proposed systems, and the variance from nominal of these metrics if external circumstances change.

D. Epoch Structure, Design Vector, and Available Transitions

The descriptions of Epochs shown in Figs. 1 and 2 are generic. When considered in the context of a specific program, and with stakeholder-specified changes in needs and contexts, a non-generic relationship emerges between the Epochs, the system lifetime phases, and the possible transitions that the system can make in response to the Epoch changes. Figure 5 provides a depiction of the relative cycle times between epoch and system development phases for a large space system program, as well as showing feasible transitions that can be made at each stage.

The take away from this comparison is the realization that contextual and needs changes (i.e. epochs) will likely change at a faster rate than the system development phases. This is obvious on the one hand since that is exactly what induces so much turbulence in these long-lead time space acquisition programs. This time domain needs to be explicitly accounted for in both exploring what options are feasible, and more importantly explicitly accounting for

Table 1. Attributes of a Satellite Radar System

User/Stakeholder	Attribute
Tactical (tracking) data user	Data Latency (tracking)
	Target Boxes
	Minimum Detectable Velocity of Target
	Minimum Detectable Radar Cross-Section of Target
	Target Acquisition Time
	Tracking Life
Strategic (imaging) data user	Maximum Resolution
	Field of Regard
	Number of Targets Observed per Pass
	Revisit Frequency
	Geo-location Accuracy
	Data Latency (imaging)
Terrain mapping data user	Elevation Accuracy
	Geo-location Accuracy
Schedule (programmatic stakeholders)	Baseline Schedule
	Actual Schedule under Changing Conditions
Cost (funding stakeholders)	Baseline Cost
	Actual Cost under Changing Conditions

how options on the design may impact the schedule element in addition to the costs.

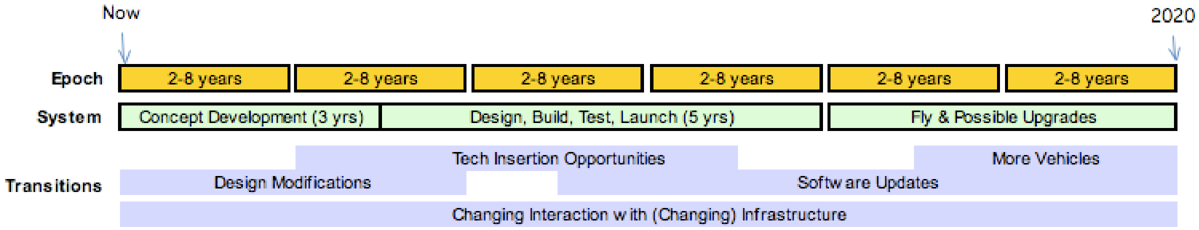

Figure 5. Natural Time Cycle Comparison.

The interview data, attributes defined above, and understanding of the timeline allowed the specification of the Design and Epoch Vectors. Both are enumerated sets of parameters that are the inputs to the tradespace analysis and Epoch-Era Analysis respectively. The former defines the superset of possible systems (in any epoch) to be considered; the latter quantifies the things that change from one epoch to another.

Table 2 shows the Design Vector. The elements form three groups: radar technology used, orbit and constellation, and vehicle technologies/capabilities. Varying these parameters will define a wide range of systems. A full enumeration of this design vector would result in over 40,000 designs to be considered, a large but not impractical number assuming the modeling calculations are efficient. Consideration of synthetic apertures consisting of more than one vehicle, and consideration of non-circular orbits, were both omitted, primarily because our aim is to demonstrate the RSC method, as opposed to designing the best SRS at a high level of fidelity. These considerations could be added in with no additional complication to the methodology, although there would be a significant increase in the computational load for the modeling effort.

Table 3 shows the Epoch Variables. In the SRS case study, epochs are characterized by changes in needs, measured in both changes in priorities between the various users and changes in specific target types; changes in infrastructure, specifically the availability of other systems that a SRS can work synergistically with; and changes in available technology for a SRS system. Fully enumerating the possible Epochs would result in over 5000 Epochs and a very large number of possible Eras. This is clearly impractical. Ongoing research seeks to develop an automated strategy for selecting a subset of reasonable Eras given the large Epoch set. The current approach is to quantify existing evaluation scenarios in terms of a sequence of Epochs with the epoch variables selected to match the scenario description. The set of Eras are, in effect, the possible future scenarios of interest to the customer. This not only helps reduce the computational load on the problem, it also provides a concrete way of tying the results of the analysis back to a framework the customer understands and is comfortable with from a validation standpoint.

An interesting question is whether it would be appropriate or possible to create an assessment of the degree to which the existing scenario sets saturate the potential future outcomes enumerated by the epochs. An approach for developing this type of metric would need to be developed before a heuristic could be applied for measuring this aspect of the "scenario completeness" across the entire Era space.

Table 2. Design Vector for Satellite Radar System

Variable types	Parametric Design Variable
Radar System Definition	Peak Transmitted Power
	Center Frequency
	Bandwidth
	Antenna Area
	Electronically Steerable vs. Mechanical
Orbit/Constellation	Altitude
	Constellation (inclination and Walker parameters)
Satellite System Definition	Communication Link Type
	Tactical Communication (Y/N)
	Processing Power on-board
	Maneuver Capability
	Design for Servicing

Table 3. Epoch Definition Vector for Satellite Radar System

Variable types	Parametric Epoch Definition Variable
Need Changes	Relative Priority change between different uses/users
	Target Radar Cross Section
	Target Velocity
	Box Size
Available Infrastructure	TSAT communication system available (Y/N)
	Airborne Radar System available as a complement (Y/N)
Technology Available	Antenna Mass per unit area and/or power
	Signal Processing Capability
	Efficiency of Spacecraft Systems (power in particular)
	STAP Technology available
Funding	Resource changes

IV. Discussion

The Responsive System Comparison method is introduced. It builds on the strengths of Tradespace Exploration (for systematically examining a wide variety of solutions to design challenges), Value-based Decision Theory (for evaluating solutions in terms of their utilities to multiple, possibly diverse stakeholders) and Epoch-Era Analysis (for organizing and quantifying changing contexts, needs and systems). The goal is to systematically create knowledge that decision makers can use to select systems that are most likely to provide best value to multiple stakeholders under changing conditions.

A case study, applying RSC to a notional Satellite Radar System, provides an initial demonstration that it is practical to set up such analyses, and illuminates aspects of the method. Some lessons learned to date:

- Most complex systems have a complex, interlocking stakeholder set, which can change through the system lifetime. The SRS stakeholder set discussed here is typical of large government programs.
- The complex stakeholder set results in a more complex attribute set than found in most static tradespace or trade-off studies, which typically concentrate on a single “user” or “customer.” The SRS example was reduced to 3 “user” stakeholders and 2 programmatic ones; each had multiple attributes that they cared about. Typically, utilities cannot be aggregated across multiple stakeholders, so the output of the SRS example will be a more complex set of utilities than that of earlier tradespace studies.
- There will be multiple changes in needs and contexts (multiple epochs) over the lifetime of systems such as a SRS, and the ability of the system to respond to these changes is limited. Indeed, “chasing” the needs of the latest epoch can lead to “thrashing,” where cost escalation and schedule slip due to changes overwhelm the program. The mismatch between the system responsiveness and the epoch changes simplifies the RSC analysis (by restricting system changes), while greatly magnifying its value to decision makers. Understanding the best choice in system, and best (limited) responses to a range of future possibilities is much more valuable than responding only to immediate, unstable needs and problems.
- The component analyses within the RSC need to be set up concurrently. In the SRS example, a tractable subset of the possible design parameters was found that is responsive to both the static performance needs of the stakeholders (the attributes) and the possible changes with changing epochs. Concurrently, the possible future needs and contexts were quantified with a set of epoch variables, selected such that they could be used to affect the inputs, context, or outputs of the tradespace analysis, and hence quantify the effects of the changes that come with each epoch. In a SRS case, however, this set of variables defined a space of future possibilities that was too large to fully innumerate – it was not practical to check “all” possible futures.
- As a strategy for both handling this problem, and transitioning decision makers from existing ways of looking at future possibilities they are currently comfortable with, existing evaluation scenarios will be quantified using the epoch variables. This will define a finite set of eras (ordered sets of epochs) for the RSC analysis. The completeness of this limited set of “possible futures” will be evaluated by comparison with the full enumeration of the epoch space.

In conclusion, although the RSC analysis has not yet produced results at the time of this writing, the work to date shows that an analysis of a complex system such as SRS is practical. Insights have already been gained that will further the development of the practical application of the method.

References

[1] McManus, H., and Hastings, D., “A Framework for Understanding Uncertainty and its Mitigation and Exploitation in Complex Systems,” *IEEE Engineering Management Review,* Vol. 34, No. 3, 2006, pp. 81-94.

[2] Thunnissen, D., “Uncertainty Classification for the Design and Development of Complex Systems,” 3rd Annual Predictive Methods Conference, Newport Beach, CA, June 2003.

[3] McManus, H.M., Richards, M.G., Ross, A.M., and Hastings, D.E., “A Framework for Incorporating “ilities” in Tradespace Studies,” AIAA Space 2007, Long Beach, CA, September 2007

[4] Ross, A.M. and Hastings, D.E., “The Tradespace Exploration Paradigm,” INCOSE International Symposium 2005, Rochester, NY, July 2005.

[5] Ross, A.M., “Managing Unarticulated Value: Changeability in Multi-Attribute Tradespace Exploration,” Doctoral Dissertation, Engineering Systems Division, Massachusetts Institute of Technology, Cambridge, MA, 2006

[6] Ross, A.M., and Rhodes, D.H., "Using Natural Value-centric Time Scales for Conceptualizing System Timelines through Epoch-Era Analysis," INCOSE International Symposium 2008, Utrecht, the Netherlands, June 2008.

[7] de Neufville, R., *Applied Systems Analysis: Engineering Planning and Technology Management*, New York, McGraw-Hill Co., 1990.

[8] Keeney, R.L., *Value-Focused Thinking: A Path to Creative Decisionmaking*, Cambridge, MA, Harvard University Press, 1992.

[9] Congressional Budget Office, *Alternatives for Military Space Radar*, January 2007.

[10] Davis, M. E., “Space Based Radar Technology Challenges,” IEEE AC paper 1073, December 8, 2004

[11] Martin, M., Klupar, P., Kilberg, S., and Winter, J., “Techsat 21 and Revolutionizing Space Missions Using Microsatellites,” 15th Annual Small Satellite Conference, paper SCC01-1-3, Logan UT, August 2001

[12] Ross, A.M., and Rhodes, D.H., “Architecting Systems for Value Robustness: Research Motivations and Progress,” 2nd Annual IEEE Systems Conference, Montreal, Canada, April 2008.