Interactive Model-Centric Systems Engineering (IMCSE)

Phase One Technical Report SERC-2014-TR-048-1

September 30, 2014

Investigators

Principal Investigator: Dr. Donna H. Rhodes, Massachusetts Institute of Technology

Co-Investigator: Dr. Adam M. Ross, Massachusetts Institute of Technology

Phase 1 Research Team

Dr. Adam Ross, Massachusetts Institute of Technology

Dr. Donna Rhodes, Massachusetts Institute of Technology

Dr. Paul Grogan, Massachusetts Institute of Technology

Prof. Olivier de Weck, Massachusetts Institute of Technology

TABLE OF CONTENTS

OVERVIEW

PURPOSE OF RESEARCH

Model based systems engineering (MBSE) is becoming increasingly more important in the practice of SE. MBSE methods and tools are used throughout the entire lifecycle to generate systems, software and hardware products, and work towards replacing labor-intensive and error-prone documentation-based processes with model-based methods. To take advantage of model-based techniques to develop systems, it is important to improve human and technology integration to make trades and decide on what is most effective given the present knowledge and future uncertainties, as well as make logical decisions based on the availability of resources and constraints. The Interactive Model-Centric Systems Engineering (IMCSE) research program will develop the SE methods, processes and tools to improve this interaction, with the goal of accelerating the transition of SE to become a more model-based discipline.

The IMCSE research program aims to develop transformative results through enabling intense human-model interaction, to rapidly conceive of systems and interact with models in order to make rapid trades to decide on what is most effective given present knowledge and future uncertainties, as well as what is practical given resources and constraints.

WORK ACCOMPLISHED IN PHASE 1

The IMCSE research program presently involves three projects initiated in 2014. These work accomplished on the projects in this phase include:

1. Pathfinder Project. This project is investigating the current state of the art/practice in IMCSE. The research team has been conducting informal surveys and performing literature review to establish a preliminary understanding of what is being done in practice with current IMCSE-related MPTs, and what research has/is being performed. The results of this knowledge gathering will be used to inform an invited workshop, focused on identifying research opportunities, gaps and issues along with associated priorities and initial plans. The team has performed initial planning in support of the workshop, and has looked at multiple models for documenting the results of the workshop in a report.

2. Interactive Schedule Reduction Model. The research team initiated its plan for using and improving an existing prototype system dynamics (SD) model to interactively explore alternatives in the systems development process and application of resources. The model enables rapid sensitivity analysis of various factors to determine their potential impact on program schedule, and investigates new methods for human interaction with the model. The goal of this year's effort is to develop and evaluate exploratory extensions of the SD model, and to prototype an interactive interface to the model resulting in a new prototype for user testing.

3. Interactive Epoch-Era Analysis. The research team developed a strategy for extending a current approach for evaluating systems under uncertainty, Epoch-Era Analysis (EEA), through the development of an interactive capability. The goal of this year's effort is to develop a method and demonstration prototype, with a case application. This case application will serve as a pathfinder for identifying key considerations for applicability and deployability of the method for eventual DoD use. It will also inform the next phase effort to evolve to a prototype for user testing.

4. Supporting MPTs. During Phase 1, the opportunity to develop several MPTs to support IMCSE arose, including supporting infrastructure (e.g. databases), software (e.g. IVTea Suite), and methods (e.g. Value Model Trading). These supporting MPTs are essential for success in the three research projects, as well as to help with capturing and transferring knowledge gained in this research effort. The IVTea Suite software and the Value Model Trading demonstration case are described in this report.

ACCOMPLISHMENTS IN PHASE 1

The following findings have resulted from the Phase 1 effort over the 4 month period of performance:
1. Knowledge and information have been gathered in support of the pathfinder project, and alternative models for structuring the initial workshop and a resulting report were explored. The plan for the Phase 2 workshop was developed.
2. Within each of four pillars (key topic areas), several emerging IMCSE-specific considerations have been identified through literature review and discussions with subject matter experts. At the intersection of the pillars, three challenges for further investigation have been identified: tradeoff of models, visual analytics of artificial data, and perceptual and cognitive considerations in human-model interaction.
3. A six step technical approach was developed for evolving an existing early prototype of a interactive schedule reduction model to include a user interface for enhancing user interaction with the model. Three of the six steps have been implemented in Phase 1.
4. An approach for an interactive Epoch-Era Analysis capability was formulated, and supporting techniques and tools were investigated. Development of a demonstration prototype is in progress.
5. A demonstration case for value model tradeoffs has been developed for a Space Tug system, highlighting methodological considerations, with further refinement in progress.
6. The first preliminary version of Interactive Value-driven Tradespace Exploration and Analysis (IVTea) Suite software was augmented to facilitate IMCSE research and accelerate the application of techniques and case studies.

RESEARCH RESULTS

The research team has produced interim research outcomes for each of the three research thrusts in the project: foundations, fundamentals, and applications. These outcomes feed forward into Phase 2 of the project.

- The research team will be using knowledge and information gained in Phase 1 to focus ongoing efforts in Phase 2 to further explore the identified IMCSE-related considerations within four key areas, and the challenges and opportunities at their intersection.
- The pathfinder workshop plan will be finalized and the workshop will be scheduled. The workshop will be held and a workshop report will be published and released to elicit comments and recommendations. Approaches to creating a broader collaboratively-derived research agenda have been identified, and will be used to design the next steps in building a community for IMCSE research.
- A first prototype for interactive Epoch-Era Analysis will be completed and tested with a case application, along with preliminary supporting infrastructure, which will then be used to inform the design of a next version prototype. Specific next steps are described on page 47.
- The team will continue analysis of the value model trades in the demonstration case, along with developing a more complete framework and process for how to conduct value model trades more generally. Specific next steps are described on page 60.
- The IVTea Suite will continue to undergo refinement of user interface, data handling, as well as development of additional widgets that support ongoing research. Specific next steps are described on page 69.
- The extended interactive schedule reduction model prototype will be completed and made available for user testing. Specific next steps are described on page 80.
- The research team will use the results of Phase 1 to develop several publishable papers for the CSER 2015.

Year	Focus	Key Deliverables
Pre-2014	New start	
2014	Pathfinder project with collaborative research discovery; exploratory extensions to an existing development schedule reduction model; exploratory piloting and interactive extensions to Epoch-Era method	*Pathfinder Project:* Investigation of current state of art/practice. Workshop to explore issues and opportunities, with report on workshop results. Pathfinder project report, with findings of research opportunities, gaps, and issues. Out-year research plans based on pathfinder results. *Interactive Schedule Reduction Model:* Exploratory extensions implemented and evaluated. Report on exploratory schedule model. Prototype model for pilot application. *Interactive Epoch-Era Analysis:* Exploratory research to develop interactive capability, with demonstration via a mission planning support application case. Report on exploratory research and case application.
2015	Initiate multi-year research plans based on pathfinder results, including 2014 project follow-on for one or both of the exploratory research projects. Assess results individually and comparatively.	*IMCSE Project Applications:* Based on pathfinder project results, select and initiate one or more additional projects, and increase SERC member collaboration in projects. Report to document the maturation of the MPTs for each of these projects, with comparative results.
2016	Increasing maturation of IMCSE MPTs and enabling environments, leading to adoption by user community and assessment of real-world impact; extend IMCSE scope via increased collaboration of additional universities and broader user community. Exploration of further new-idea projects.	*IMCSE MPT Implementations and Impact Assessments:* Continued maturation and implementation of IMCSE MPTs, with enabling environments. Ongoing study of impacts resulting in a comprehensive report of progress, results, and opportunities.
2017-2018	Increasing maturation and synthesis of IMCSE MPTs and enabling environments, leading to adoption by user community and demonstration of real-world impact; sustain and increase collaboration of additional universities and broader user community. Step-ups of new-idea projects.	*IMCSE MPT Synthesis Impact and Effective Practice Assessments:* Continued maturation, synthesis and implementation of IMCSE MPTs, with enabling environments. Ongoing study of real-world impacts to identify successful practices. A comprehensive report of impacts and insights, with guidance on practice.

Figure 1. IMCSE Project Timeline

INTRODUCTION

The IMCSE research program aims to develop transformative results through enabling intense human-model interaction, to rapidly conceive of systems and interact with models in order to make rapid trades to decide on what is most effective given present knowledge and future uncertainties, as well as what is practical given resources and constraints.

MOTIVATION

Models have significantly changed systems engineering practice over the past decade. Most notably, model-based systems engineering (MBSE) methods and tools are increasingly used throughout the entire system lifecycle to generate systems, software and hardware products, replacing labor-intensive and error-prone documentation-based processes with model-based ones. While substantial benefits have been achieved, the most impactful application of models in systems engineering has yet to be realized. Models are needed to inform engineering decisions. Truly transformative results will only come through intense human-model interaction, to rapidly conceive of systems and interact with models in order to make rapid trades to decide on what is most effective given present knowledge and future uncertainties, as well as what is practical given resources and constraints.

As cited in the SERC 2014-2018 Technical Plan, reports have found significant insufficiencies in the current practice.

> *The National Research Council's "Human-System Integration in the System Development Process," (NRC, 2007), "Pre-Milestone A and Early-Phase SE," (NRC, 2008), and "Critical Code," (NRC, 2010) studies consistently found that the SE MPTs for integrating hardware engineering, human factors engineering, and software engineering into a scalable, unified approach were not up to the challenges of the complexity, scale, and dynamism characterizing DoD's large-scale systems and systems of systems.*

This research project addresses the SERC's Systems Engineering and Systems Management Transformation (SEMT) grand challenge:

> *Move the DoD community's current systems engineering and management MPTs and practices away from sequential, single stovepipe system, hardware-first, outside-in, document-driven, point-solution, acquisition-oriented approaches; toward concurrent, portfolio and enterprise-oriented, hardware-software-human engineered, balanced outside-in and inside-out, model-driven, set-based, full life cycle approaches. These will enable much more rapid, concurrent, flexible, scalable definition and analysis of the increasingly complex, dynamic, multi-stakeholder, cyber-physical-human DoD systems, systems of systems, portfolios of systems, and enterprises of the future.*

INSUFFICIENCIES IN CURRENT PRACTICE

Early concept decisions have always been critically important, and with continuously evolving systems of systems having long life spans, such decisions are now made throughout the entire life cycle. Soft factors become increasingly influential. For example, trust in model-based data sets and decisions are in part determined by the chosen model itself as perceived by specific decision makers. The timescale of making early architectural decisions is out of sync with the current model-based systems engineering capabilities and decision environments. New algorithms and novel modeling approaches must be discovered to accelerate technical and programmatic decision support from months to minutes. In order to effectively leverage and incorporate human knowledge and judgment, an interactive capability is needed. Much potential exists in maturing emerging novel methods for evaluating system responsiveness under complex uncertainties, to enable engineering of resilient systems.

RELEVANT PRIOR SERC RESEARCH

IMCSE will include and significantly extend the traditional focus on the modeling of system products and the use of the models. Extensions will address the modeling of system execution processes, such as operational concept formulation, and system development processes, which can also be executed to aid in the generation of system products. As emphasized in the SERC Systems 2020 Report, an additional focus on modeling the system's environment will be pursued, which is needed for performing many of the ilities tradespace and affordability analyses. Models can also improve affordability by automatically generating needed documentation, or even better by serving as the documentation itself. Further, models can reduce or avoid system overruns and performance shortfalls by enabling more thorough Analyses of Alternatives and evidence-based decision reviews. Modeling the system's dynamic operational environment remains an open area of research. IMCSE has a relationship to many of the past and ongoing SERC projects. Several of the most relevant prior SERC projects are summarized in Appendix A.

IMCSE

Interactive Model-centric Systems Engineering (IMCSE), not to be confused with Model-based Systems Engineering (MBSE), is a research program that seeks to encourage the development of augmented complex systems thinking and analysis to support data-driven decision making.

WHAT IS IMCSE?

Systems scientists have long recognized that humans possess unique abilities for anticipation rather than simple reactive response. In order to increase the likelihood of developing complex systems that can deliver value to stakeholders across a dynamic, uncertain future, systems engineers must have both reactionary and anticipatory capacity to make better decisions. In contrast to reactionary capacity, which involves developing solutions after the fact, anticipatory capacity, as defined by Rhodes and Ross (2009), is "the capacity to continuously develop and apply knowledge acquired through a structured approach to anticipate 1) changing scenarios as stakeholder needs and systems context change over time; 2) to consider their consequences; and 3) to formulate design decisions in response[1]. Three key enablers of anticipatory capacity are mindset, methods, and environment. Models represent an abstraction of reality in order to make predictions about the future. Models can come in a variety of forms and formats, but fundamentally they are an encapsulation of reality that humans use to augment their ability to make sense of the world and anticipate future outcomes. Improvements in computation, simulation technologies, and human-machine interaction have created an opportunity to enable human-model interaction to greatly enhance anticipatory capacity. Complex, integrated models, of various levels of fidelity, can create large data sets in need of human pattern recognition skills. Interaction enables real time interrogation of the data and opportunities for model creation as well as validation and learning. IMCSE is a research program intended to leverage human-model interaction in order to transform systems engineering decision making through anticipatory capacity.

RESEARCH PROGRAM VISION

The vision for the IMCSE research program is to develop transformative results through enabling intense human-model interaction, to rapidly conceive of systems and interact with models in order to make rapid trades to decide on what is most effective given present knowledge and future uncertainties, as well as what is practical given resources and constraints.

In order to accomplish this vision, IMCSE will pursue a balanced basic and applied research approach. This will leverage the strength of the academic environment (e.g. developing fundamentals, approaching with rigor, providing a neutral third party view of the problem). Additionally, IMCSE will strive to keep the research relevant to the sponsor community, as well as enabling opportunities for knowledge and methods, processes, and tools (MPTs) transfer to

---

[1] Rhodes, D.H. and Ross, A.M., "Anticipatory Capacity: Leveraging Model-Based Approaches to Design Systems for Dynamic Futures," 2nd Annual Conference on Model-based Systems, Haifa, Israel, March 2009.

sponsors. Such knowledge transfer opportunities include workshops, teleconferences and meetings, reports, papers, collaboration with other SERC activities, prototypes, methods, processes, and tools (MPTS), government partner applications, and potential student internships.

IMCSE PILLARS – FOUR TOPIC AREAS

IMCSE is motivated by the convergence of four key topic areas: big data, visual analytics, complex systems, and model-based systems engineering. Each of these areas have associated with them large research and application efforts. This research program seeks to identify synergies and gaps at the intersection of these four topic areas, and leverage existing and new techniques in this area to create new knowledge and capabilities for systems engineering decision making. In order to focus the research program, early efforts are aimed to identify key challenges that summaries the gaps in the existing topic area overlaps.

BIG DATA

We live in a world with big data. As data storage costs have shrunk, so too has the need for purging data. Additionally data is being generated through a large and growing number of means, from sensors to users to corporate IT environments. Even "document-based" data is becoming digital as technology (including OCR) becomes commonplace for capturing physical information as digital data. No consensus currently exists regarding a formal definition on what constitutes "big data," but it is generally recognized as having a number of characteristics that make it "big." One example description, from IBM[2], characterizes big data as having challenges regarding Volume, Variety, Velocity, and Veracity. The challenge for Volume revolves around the scale of the data (e.g. how to store and recall large numbers of field entries in a database?). The challenge for Variety revolves around the different forms of data (e.g. how to store and compare data from photos, videos, blogs, articles, etc.?). The challenge for Velocity revolves around the analysis of streaming data (e.g. how to account for and parse large streams of potentially incomplete data in real time?). The challenge for Veracity revolves around the uncertainty of the data (e.g. different data sources have different degrees of trustfulness and reliability, so how to fuse data from such sources?).

The impact of big data is being felt across many fields from transportation to entertainment, education to banking, which will only increase as the benefit of leveraging such data becomes apparent. Such benefits have been recognized by a growing number of commercial organizations who are leveraging this inundation of data to gain insights into phenomena to create predictive models (e.g. of user behavior and preferences). For example, Amazon and Netflix both have sophisticated user preference models that are used to make recommendations to users based on their own (and related others) browsing and shopping/viewing history. Additionally, Netflix has used this information (and Amazon recently as well) to generate design requirements for new shows. House of Cards, produced by Netflix,

---

[2] http://www.ibmbigdatahub.com/sites/default/files/infographic_file/4-Vs-of-big-data.jpg

was partially designed based on derived preferences of its viewer base in order to increase the perceived value of the program[3].

While not necessarily generated in a similar manner, DoD has already a vast amount of data stored in documents, for example requirements documents, design documents, DoDAF, etc, which represent latent data that could be leveraged using techniques being developed in the commercial application space. What would a ground vehicle recommendation look like? How would it parse and analyze historical requirements documents and contextual information in order to predict and/or augment modern user needs? Big data is a topic area that holds promise in providing a foundation for large scale analytics to predict the future.

VISUAL ANALYTICS

Visual analytics is a topic area that has likewise been a growing area for research and application. At its core, visual analytics is about collaboration between human and computer using visualization, data analytics, and human-in-the-loop interaction. More than just visualization tools, visual analytics aims to take advantage of a human's ability to discover patterns and drive inquiry in order to make sense of data. In 2007, DHS sponsored the National Visualization and Analytics Center, which developed a research agenda called Illuminating the Path. In it, visual analytics was defined as "the science of analytical reasoning facilitated by interactive visual interfaces" that "provides the last 12 inches between the masses of information and the human mind to make decisions."[4] Application areas range from homeland security to anti-fraud, banking to insurance. One common element in much of the current visual analytics work involves case applications comparing VA-supported inquiry results to ground truth, that is, discovery of patterns in "natural" data. One consequence of these studies is that the validity of the applications can be compared to observable "truth." This allows researchers to test how well their predictive models match reality, for example, using VA to discover hackers trying to break into streams of ATM data; or discovering patterns of use in bike sharing programs as a function of time and geography. In both of these examples there are "real" processes at play and actual measurable real world data against which to validate predictions by the human-machine VA system. VA has been shown to be incredibly useful for developing models of natural data.

COMPLEX SYSTEMS

Our application domain is the development of (artificial) systems that serve the purpose of delivering value to stakeholders. By "artificial" we mean that these systems are artifacts created by humans for a purpose, to be contrasted with natural systems, which are not created by humans. Over time, the complexity of systems has tended to grow, not only due to scale and interconnectedness, but also due to increased scope in our ability to describe the system. This enhanced scope reflects realization that the success of artificial systems requires a fuller

---

[3] http://www.nytimes.com/2013/02/25/business/media/for-house-of-cards-using-big-data-to-guarantee-its-popularity.html?pagewanted=all&_r=0
[4] Jim Thomas, Director, USDHS National Visualization and Analytics Center, "*Visual Analytics: An Agenda in Response to DHS Mission Needs*," 2007

understanding of how the system is structured, behaves, performs in different contexts, performs over time, is perceived across stakeholders[5][6]. This means that to describe a complex system, one must consider all five perspectives, thereby creating a richer description of the system. Developing complex systems necessitates an approach to generate, manage, and analyze artificial data across these five aspects.

MODEL-BASED SYSTEMS ENGINEERING (MBSE)

Traditional systems engineering has been document-heavy and process-driven, resulting in many opportunities for miscommunication and mistakes during "hand-offs" between phases and teams. Models are often used during design and development in order to predict behavior or other consequences of design decisions, before the system is built or operated. In contrast to document-based engineering, "model-based systems engineering (MBSE) is the formalized application of modeling to support system requirements, design, analysis, verification, and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases."[7] Today, however, standalone models are typically related through documents. A future vision is for organizations to use "shared system model(s) with multiple views, and connected to discipline models," in order to reduce effort creating and aligning documents, and to increase synthesis and coherence across disciplines throughout design[8]. Regardless of the degree to which MBSE is employed, its benefits stem from moving to models to represent systems with less ambiguity, more parsimony, and more consistency, resulting in reduced acquisition time, enhanced reliability, etc. MBSE generates "artificial data" about systems which can be used to make decisions that impact the future and continuing success of that system.

SYNTHESIZING THE PILLARS

Each of the four topic areas above are themselves large areas of active research and development across government, academia, and industry. IMCSE in particular is interested in the intersection of these four areas with application to improving systems engineering decision making. More than just applied visual analytics, IMCSE seeks to look at data generated by models, in order to make better decisions in how to deliver sustained value to stakeholders. In particular preliminary investigation has uncovered two initial challenges for IMCSE to address.

These include:

1) Visual analytics of artificial (i.e. model-generated) data: how does this differ from VA of natural data? How to take into account the impact of various model implementations on

---

[5] Rhodes, D.H., and Ross, A.M., "Five Aspects of Engineering Complex Systems: Emerging Constructs and Methods," 4th Annual IEEE Systems Conference, San Diego, CA, April 2010

[6] Gaspar, H., Rhodes, D.H., Ross, A.M., and Erikstad, E.O., "Addressing Complexity Aspects in Conceptual Ship Design: A Systems Engineering Approach" *Journal of Ship Production and Design*, Vol. 28, No. 4, Nov 2012, pp. 145-159.

[7] INCOSE SE Vision 2020 (INCOSE-TP-2004-004-02, Sep 2007)

[8] http://www.omgwiki.org/MBSE/doku.php?id=mbse:incose_mbse_iw_2014

pattern finding and matching of mental and constructed models? How to validate predictions without ground truth available?

2) Active tradeoffs of models themselves: too often models are used without sufficient investigation into the impact of the models on the data being used for decisions; these include performance models, cost models, and value models. Model selection fundamentally impacts the patterns to be discovered in the artificial data.

Ultimately, the goal of IMCSE is *to **leverage visual analytics** applied to **model-generated "big data,"** in order to **develop a rigorous framework**, with associated methods, processes, and tools (**MPTS**), which will result in **transformative new capabilities for complex systems engineering decision making***.

IMCSE APPROACH

IMCSE uses three complimentary thrusts with different timescales, in order to have impact on the long term, the near term, and the present.

These thrusts include:

- **Foundations**: 1 year, set the stage for IMCSE for long term impact
- **Fundamentals**: multi-year, medium timescale impact, potentially broad applicability
- **Applications**: 1 year, short timescale impact, generate deployment opportunities

Current progress in each of these three thrusts will be described in the following sections of the report.

FOUNDATIONS

The foundations research thrust is currently focused on two activities. The first is the research pathfinder project, including the initial 'setting the stage' activity of an invited workshop. Extending the results of the workshop, a more extensive effort will build a community of interest. The end result will be a collaboratively-derived research agenda. The second activity is investigating the current state practice and emerging state of the art. This includes literature review and discussions with subject matter experts. Ongoing results will inform the research agenda, and the specific projects undertaken in the fundamentals and applications thrusts.

IMCSE RESEARCH PATHFINDER PROJECT

A pathfinder project brings together the relevant stakeholders to develop a research vision and research priorities, and a roadmap to achieve them. The IMCSE pathfinder project will include one or more face-to-face gatherings of stakeholders in the research agenda, as well as specifically focused research meetings. Given the footprint of IMCSE, it would not be possible to convene a large enough community in a participant workshop for the purpose of a collaboratively-derived research agenda. Our research team is looking at various approaches that have been used, and defining pathfinder efforts to leverage the success of these approaches. The goal is to be able to engage a large and diverse community around the research agenda, and determine an approach that may include both face-to-face and virtual activities.

LAUNCHING THE PATHFINDER PROJECT

Preliminary efforts in defining a research vision and results of exploratory knowledge gathering are being used to develop the plan for conducting an **initial pathfinder research workshop**. The research team is in the process of selecting invited participants for a small initial workshop, to be held in Phase 2 of this project. The team has performed initial planning in support of the workshop, and has looked at multiple models for documenting the results of the workshop in a report. The outcome of the workshop event will be a workshop report. The goal is to identify high level research needs and questions, along with identifying gaps, issues and opportunities. The results of the workshop will be made available for review and comment, and the research report will be updated with the added information. The goal of the workshop and resulting report is to seed the larger effort to build a community of interest and undertake a more extensive research pathfinder activity.

The pathfinder activities in Phase 1 and Phase 2 of this research project will inform efforts in Phase 3 to elicit information on state of the art and practice, identify additional research stakeholders, clarify and expand the urgent research questions, and investigate priorities. The Phase 3 objective will be to establish a *collaboratively-derived IMCSE research agenda*. The ultimate goal is to build a community of interest around the IMCSE research agenda, build partnerships for research, and to foster collaboration in addressing the emerging challenges at the intersection of the four topic areas.

Each of the four topic areas (big data, visual analytics, complex systems, and model-based systems engineering) engages researchers from multiple disciplines and domains. IMCSE research seeks to encourage the development of augmented complex systems thinking and analysis to support data-driven decision making. The stakeholders who contribute to and benefit from IMCSE include government sponsors, senior decision makers, system designers, analysts, academic researchers, policy makers, funding agencies and others. Bringing such a community together around a shared research vision and agenda is a significant challenge, but there are prior exemplars.

During this phase, the research team has been investigating successful efforts in other fields to create a research agenda through a collaborative approach involving a large and diverse set of participants. A particular feature of these exemplars is the success in bringing together stakeholder from government, non-governmental organizations, academia and industry to narrow the gap between data generated in research and the information required by policy makers. One recent effort was the development of a collaboratively-derived science-policy research agenda, driven by the need for policy makers to understand science and for scientists to understand policy processes.[9] Participants were selected to cover a wide range of disciplines and constituencies. Each participant submitted a list of questions, resulting in 239 questions in the first stage. A process of voting, deliberation and further voting resulted in a final set of 40 questions, and then grouped thematically into six groups. The authors, Sutherland et al. (2012), noted the outcome is inevitably influenced by the composition of the participants and the process. While not 'reproducible, it is highly likely this approach would yield similar emergent general themes.

Ingram, et al. (2013)[10] applied the collaboratively-derived research approach of Sutherland et al. (2012) in addressing questions related to the UK food security and food system. They found it proved useful for engaging a wide range of stakeholders and helped establish a well-balanced discussion on the production system and the security outcomes, informing a research agenda from public funders and applied industry viewpoints, as well as mapping needs onto the international food security agenda. The dimensions in this work are not unlike IMCSE, where there are intertwined needs of defense funding agencies, system developers, and impacts to national/international security.

Sutherland, et al. (2011)[11] discuss methods that "maximize inclusiveness and rigour in such exercises include solicitation of questions and priorities from an extensive community, online collation of material, repeated voting and engagement with policy networks to foster uptake

---

[9] Sutherland, W., et al., "A Collaboratively-Derived Science-Policy research agenda", PLoS ONE, Vol. 7, Issue 3, March 2012

[10] Ingram, J., "Priority research questions for the UK food system", Food Sec., (2013) 5:617-636.

[11] Sutherland, W. J., Fleishman, E., Mascia, M. B., Pretty, J. and Rudd, M. A. (2011), Methods for collaboratively identifying research priorities and emerging issues in science and policy. Methods in Ecology and Evolution, 2: 238–247

and application of the results". These authors summarize eight exercises with variation on the general approach. Their work in bridging the gap between scientific researchers and policy makers is notable, as IMCSE needs to bridge the gap between the engineer/scientists and the senior decision makers and policy makers. While the authors work in a different domain of interest, their work has resulted in a set of guiding principles for generating a collaboratively-derived research agenda. The guidance covers defining the project; organizing the participants; soliciting and managing questions or issues; voting systems; and disseminating results. Experiences and effective practices in establishing collaboratively-derived research agendas provide insight and guidance, with potential to enhance the success of the pathfinder project for IMCSE.

Early in Phase 2, the research team will develop its specific approach for generating a collaboratively-derived research agenda, to build on the outcomes of the initial pathfinder workshop.

In Phase 1, the research team initiated its literature review and knowledge gathering to explore the state of the art and practice, specifically as related to the IMCSE area. The team's organizing framework for investigation is around four key topic areas, as well as the emerging challenges at their intersections. The four topic areas are (1) big data, (2) visual analytics, (3) complex systems and (4) model-based systems engineering. These four areas have an extensive and expanding landscape, and the goal of our research is not to establish a comprehensive state of the art and practice of the topic areas, but rather to discover the critical themes, challenges and questions that are directly relevant for IMCSE.

During Phase 1, three challenges at the intersections emerged: (1) tradeoff of models; (2) visual analytics of artificial (model-generated) data; and (3) perceptual and cognitive considerations in human-model interaction. feed these into the pathfinder workshop activity. During the workshop, it is expected that additional cross-cutting considerations will be identified.

In the following subsections, we highlight several of the themes within each of the four topic areas and the three intersection topics.

BIG DATA

Big data provides a foundation for large scale analytics to predict the future.

Big data provides a foundation for large-scale analytics to predict the future across domains as diverse as defense, healthcare, and urban planning. Yet as evolving technological capabilities allow for the capture, management, and exploration of increasingly large and complex data sets, researchers are also faced with new and emerging methodological questions when grappling with the forecasting implications of big data. Broadly speaking, two of the most significant issues facing researchers in the field of big data today are *trust in the data* and *representativeness of the models they engender*.

> **Overprojection of trend models.** Perhaps one of the clearest examples highlighting both the promises and pitfalls of big data driven analytics is the recent Google Flu Trends (GFT) project, which aimed to "nowcast" flu prevalence based on the real-time tabulation of query entries. In the domain of global public health, big data offers the possibility not only of facilitating the epidemiological tracking of disease, but of forecasting the spread of disease as well, thereby allowing for the effective and timely distribution of critical resources such as medication and aid workers. Yet projections offered by the GFT wildly overestimated incidence of influenza in the US, when compared against doctors' reports collected by the Center for Disease Control and Prevention. Recent analyses of this failure in big data projection have revealed systemic problems in the use of such data sets in forecasting models.[12] Specifically,

---

[12] Lazer, D., Kenney, R., King, G., & Vespignani, A. (2014). The parable of Google Flu: traps in Big Data analysis. *Science*, 343(6176): 1203-1205.

overprojection of trend models was seen to result from failures to consider the uniqueness of individual data point. In the case of the GFT, a cluster of regionalized queries probing flu symptomology could underlie a local outbreak as much as it could coincide with the theme of a district school's science fair.

Misinterpretation of a correlational relationship to mean a causal connection. In this regard, the interpretation of big data is vulnerable to one of the hallmark errors of shoddy statistics—the misinterpretation of a correlational relationship to mean a causal connection. In short, when researchers fail to consider the epistemological heterogeneity of the individual data points within a very large set—that is, the meaning underlying the behavioral actions which have been tabulated and accrued—their failure to engage with the ambiguity inherent in the data set may lead to a dangerous overfitting of their predictive models: fundamental misassumptions about the nature of the data, in turn, give rise to inaccuracies in the resulting predictions.

Reconciling big and small data. One of the central tensions revealed in this pattern is, therefore, the struggle to reconcile big and small data: how do you represent the specificity of individual points within the big-picture trends revealed by large and complex data? Data collected through social media seems to promise a wealth of insight on broad trends, social patterns, and consumer behaviors, just as cell-phone GPS data offers unprecedented tracking of commuting, mobility, and navigation patterns within the urban environment. And yet many researchers are struggling with the problem of how best to determine data validity on such a large scale. That is, how do you most effectively train algorithms to distinguish an individual user, and therefore a valid data point, from unusable data generated by bots and advertisers? How do you tell the difference between a morning commuter and an out-of-town tourist, if you are using big data forecasts to decide where to construct new highways? Do these distinctions even really matter?

Obscured origins of epiphenomenon. As reliance on big data leads to the decontextualization of individual data points, so, too, does it obscure the origins of epiphenomenon arising from the nature of the data gathering practice itself. For instance, in the weeks leading up to the recent Scottish independence referendum vote, Amazon DVD charts have recorded soaring sales of the 1995 epic *Braveheart*, which vaulted from 1074th to 454th place.[13] And yet while this phenomenon was short-lived, big data-driven year-end tabulations of DVD sale trends now run the risk of over-representing the film's general popularity, flattening at once the temporal transience of such an occurrence, as well as its significance as a social artifact of a particular historico-political event.

---

[13] Hooton, Christopher. "Scottish Independence Referendum Leads to Surge in Sales of Braveheart." *The Independent* [London] 25 Sept. 2014.

Big data offers the tantalizing possibilities of gathering unprecedented quantities of rich information in real time, increasing statistical power by orders of magnitude and providing new depth and perspective to our understanding of the operations of complex socio-technical systems. Ultimately however, these few case examples illustrate that accessing big data alone is not enough to leverage its wide-ranging potential; rather, the ability to extract meaningful forecasting predictions from large data sets relies on skillful analytics and the availability of proper tools and approaches for interactively exploring and engaging with it as well. In this respect, an understanding of the potentials, and pitfalls, of big data demands a rigorous consideration of both the capabilities of visual analytic and the nature of interactive modeling approaches.

VISUAL ANALYTICS

Visual analytics is resulting in a transformative capability, bridging human and computer analysis.

The field of visual analytics has grown extensively over the past decade, and there is a large body of knowledge on many different aspects. In Phase 1, our team made progress in finding specific work within this body of knowledge of specific relevance to IMCSE, and this will continue in Phase 2. Much of the work on visual analytics focuses on natural data and fields of interest outside the scope of this project (e.g., biomedical, marketing, etc.). Uncovering the most salient research findings is an ongoing effort.

Uncertainty-Aware Visual Analytics. Correa et al. (2009)[14] discuss the growth of visual analytics as an important tool for gaining insights on large, complex data sets. The authors discuss the problem of limitations on technology and human power, making it difficult to cope with the growing scale and complexity of data, and therefore making it is seldom possible to analyze data in its raw form. The data must be transformed to a suitable representation in order to facilitate discovery of interesting patterns. However, the process of transforming raw data to abstractions and derived data is a complex network of transformations, propagating and aggregating uncertainty. As such, the authors believe when making decisions based on uncertain data, it is important to quantify and present to the analyst both the aggregated uncertainty of the results and the impact of the sources of that uncertainty, motivating their work to develop a framework for uncertainty-aware visual analytics. Figure 2 illustrates the process developed by Correa et al., which the authors describe as follows:

> *In general, visual analytics is the process of transforming input data into insight. A similar process occurs for the uncertainty. First, uncertainty modeling generates a model for source uncertainty. As data is transformed, these uncertainties are propagated and aggregated. We obtain such estimates via sensitivity and error modeling. Finally, the uncertainty on the derived data and its*

---

[14] Correa, Carlos, Chan, Yu-Hsuan, and Ma, Kwan-Liu, "A Framework for Uncertainty-Aware Visual Analytics", IEEE Symposium on Visual Analytics Science and Technology, 2009, p. 51-58

sources are mapped to visual representations, which finally populate the view used by the analyst.
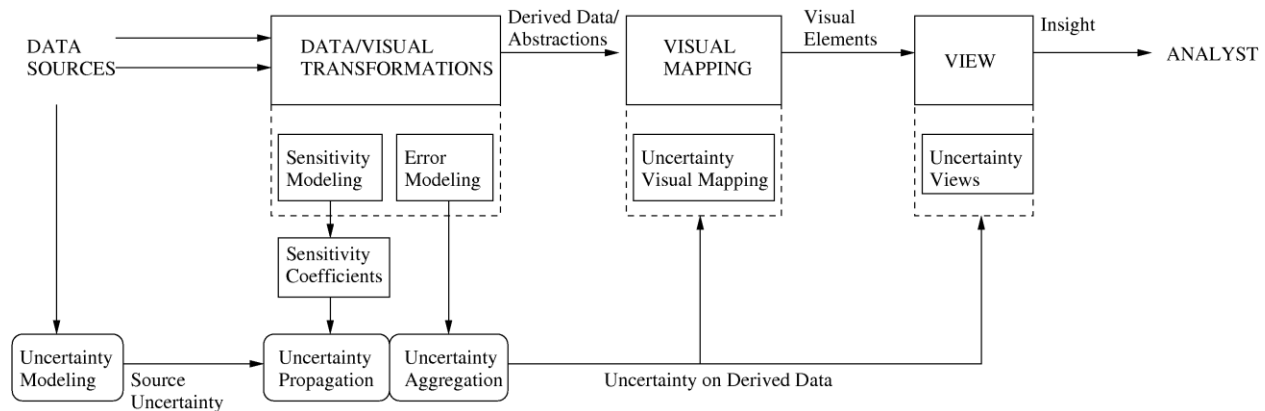
Figure 2. Uncertainty-aware visual analytics process (source: Correa, et al. 2009[14])

Visual Analytics Based Sensemaking. Vitiello and Kalawsky (2012)[15] discuss an approach that integrates a visual analytic based workflow to the notion of sensemaking. The authors describe using visual analytics to support systems thinking to make sense of complex systems interactions and interrelationships enabling rapid modeling of the systems of interest for systems engineering design and analysis processes. They state that sensemaking evolved from naturalistic decision making research, as published by Klein et al. (1993)[16]. The visual analytic based sensemaking framework described in their paper is aimed toward providing the means to rapidly gain valuable insights into the data.

Work-Centered Approach for Visual Analytics. Yan et al. (2012) present research on a work-centered approach for visual analytics. The research seeks to integrate user-centered design and data-oriented data-processing algorithms in order to reconcile human users' limited capacity to process large amount and rapid growth of information in decision making, as applied to tradespace exploration. The authors state: "After a user selects data of interest from raw data, computational algorithms are applied to build data models. The entire model building process is interactive to the user. User has the capability to control whether and how algorithms run and constructs a specific data model to fit ad-hoc problems. Visualization provides an interface between data, models and the user. It displays both source data and computational results. It also takes user's input and commands to manipulate on raw data or analysis algorithms". [17]

---

[15] Vitiello, P. and Kalawsky, R.S., "Visual analytics: A sensemaking framework for systems thinking in systems engineering", IEEE International Systems Conference (SysCon), 2012

[16] Klein, G.A., A Recognition-Primed Decision (RPD) Model of Rapid Decision Making, *Decision making in action: Models and methods*, vol 5, no 4, pp 138-147, Dec 1993.

[17] Yan, X., Qiao, M., Li, J., Simpson, T.W., Stump, G.M., Zhang, X., A Work-Centered Visual Analytics Model to Support Engineering Design with Interactive Visualization and Data-Mining, *Hawaii International Conference on Systems Science (HICSS) 2012, p1845-1854, Jan 2012*
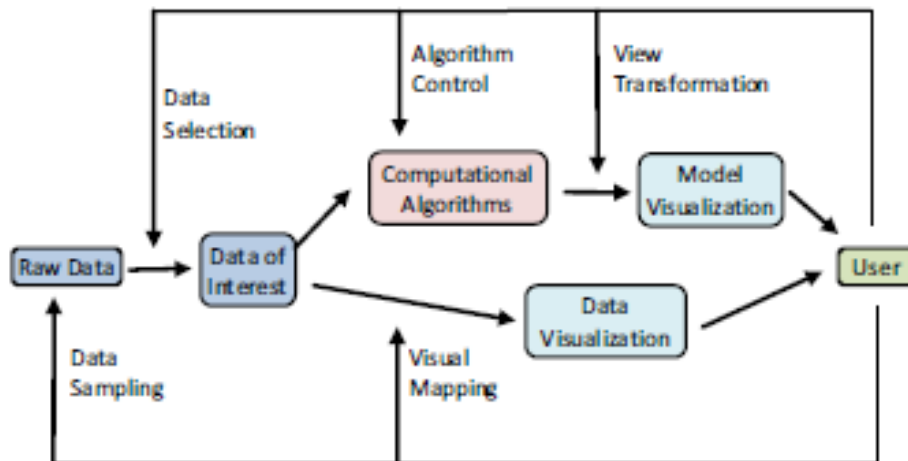
Figure 3. Framework of work-centered visual analytics (source Yan et al.[17])

Science of Interaction. Our inquiry into visual analytics necessitates looking into the "science of interaction". Pike et al. discuss the interaction challenges raised in visual analytics research, and the relationship between interaction and cognition.[18] The 'science of interaction', as defined by these authors, concerns the study of methods by which humans create knowledge through the manipulation of an interface. They state:

> *As visual analytics is concerned with the relationship between visual displays and human cognition, merely developing novel visual metaphors is rarely sufficient to trigger this insight (where insight may be a new discovery or confirmation or negation of a prior belief). These visual displays must be embedded in an interactive framework that scaffolds the human knowledge construction process with the right tools and methods to support the accumulation of evidence and observations into theories and beliefs.*

Seven key areas were identified in this 2009 paper: ubiquitous, embodied interaction; capturing user intentionality; knowledge-based interfaces; principles of design and perception; collaboration; interoperability; and interaction evaluation. Ongoing research in these areas will be explored for relevant impact as our research project progresses.

COMPLEX SYSTEMS

Developing complex systems necessitates an approach to generate, manage, and analyze artificial data across all aspects of system complexity.

The growing complexity of systems is well-recognized, and investigation of system complexity as related to engineered systems is an active subject of inquiry. Complexity, for instance, can

---

[18] Pike, W. A., Stasko, J., Chang, R., & O'connell, T.,A. (2009). The science of interaction. *Information Visualization, 8*(4), 263-274. doi:http://dx.doi.org/10.1057/ivs.2009.22

relate to the number of constituent and component interconnections, and to the necessary rapid rate of information generation and exchange. It can also relate to emergent behavior as a result of interactions of constituent systems in a system of systems.

Defining Systems Complexity. Many authors have and continue to define system complexity. Gasper (2012)[19] discusses three bodies of work than can be used as a basis for complexity definition in the context of engineering. Herbert Simon (1962)[20] proposes that how complex or simple a structure is depends critically on the way in which we describe it. Simon proposes a hierarchical approach to complexity, decomposing the system until it can be understood. Kolmogorov (1983)[21] definition of complexity asserts the more information an object has, the more complex it is. Given the system is the object, complexity can be understood as related to the other objects that interact with the system. The specification of an object is easier when another object to which this object has a relation is already specified. A third work by Suh (2005)[22] discusses the idea of information connected to the design complexity, proposing that the violation of the information axiom, to minimize the information content of the design will maximize the probability of success, will result in complexity in the system.

Types of System Complexity. Structure and behavior are the two aspects of complex systems addressed in classical model-based systems engineering [23]. Rhodes and Ross (2010)[24] propose five essential aspects for the engineering of complex systems: structural, behavioral, contextual, temporal, and perceptual. They argue that the contextual, temporal and perceptual aspects have been under-addressed in engineering methods, and have past and ongoing research efforts on advancing the constructs and methods for contextual, temporal, and perceptual aspects. Response Systems Comparison is a resulting method to address the five aspects[25]. The method has been applied in various domains and for various types of problems, for example, Gasper[19] describes the application for a conceptual ship design problem.

---

[19] Gasper, H., Rhodes, D., Ross, A. and Erikstad, E., "Addressing complexity aspects in conceptual ship design: a systems engineering approach", Journal of Ship Production and Design, Vol. 28, No. 4, November 2012, pp. 1–15

[20] Simon, H., "The architecture of complexity", Proceedings of the American Philosophical Society, 106, 6, 467–482, 1962

[21] Kolmogorov, A. N., "Combinatorial foundations of information theory and the calculus of probabilities, Russian Mathematical Surveys, 38, 4, 27–36, 1983.

[22] Suh, N. P., "Complexity—theory and applications", Oxford University Press, Oxford, UK, 2005

[23] Oliver, D., Kelliher, T., Keegan, J., *Engineering Complex Systems with Models and Objects*, NY: McGraw-Hill, 1997.

[24] Rhodes, D.H. and Ross, A.M., "Five aspects of engineering complex systems: emerging constructs and methods", Proceedings, 4th Annual IEEE Systems Conference, April, San Diego, CA, 2010

[25] Ross, A.M., McManus, H.L., Rhodes, D.H., Hastings, D.E., and Long, A.M., "Responsive Systems Comparison Method: Dynamic Insights into Designing a Satellite Radar System," AIAA Space 2009, Pasadena, CA, Sep 2009

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	

Figure 4. Five Aspects of Complex Systems[24]

Human-System Interaction Complexity. The complexity of the human-system interaction considerations is increasingly important in developing complex systems. A 2007 report of The National Academies[26] presents a discussion of the challenges, with research and policy recommendations. Many of the points brought out in this report and in subsequent work extend to understanding of complex systems. A number of the recommendations have extensions to the challenges of we see for IMCSE, and are beginning to be addressed through research. Examples include:

- Remote collaboration is difficult to participate in or observe without proper remote collaboration tools enabling interactivity of human to human, and human to model.
- Cognitive and perceptual limitations constrain the amount of information that can be considered at a point in time by a single decision maker; multi-sensory representations may allow for some loosening of this constraint and improve human-model interaction.
- Research has increasingly uncovered the important role of context effects on both systems in use, design, and on the decision makers themselves. Facilities that can represent and control for these context effects may uncover approaches for mitigating or taking advantage of these effects.

Perceived and Descriptive Complexity. Project complexity has been defined in many different ways. In the Applications section of this report, we hypothesize that perceived and descriptive complexity are correlated and constitute a tradeoff between design-efficiency and design-robustness (refer to page 71 for the detailed discussion).

---

[26] National Research Council (2007), *Human-Systems Integration in the System Development Process: A New Look*, Committee on Human-System Design Support for Changing Technology, R.W. Pew and A.S. Mavor, Eds., Committee on Human Factors, Division of Behavioral and Social Sciences and Education, Washington, DC: The National Academies Press.

MODEL-BASED SYSTEMS ENGINEERING (MBSE)

Model-based systems engineering generates "artificial data" about our systems which we use to make decisions that impact the future/continuing success of that system

Systems engineering is rapidly becoming model-based in nature. It is recognized that MBSE offers significant potential[27] but many challenges remain in realizing the full potential of using models throughout the lifecycle in numerous ways. It is recognized that the current MPTs are inadequate, and much research and development is ongoing to address this. A few IMCSE-related challenges we highlight are: integration of MPTs, executable artifacts, issues in trusting models and need for ontologies.

Inadequate MPTs. The SERC's *System 2020 – Strategic Initiative Report*[28] states: "Existing systems engineering tools, processes, and technologies poorly support rapid design changes or capability enhancements within acceptable cost and schedule constraints. Their focus on point solutions makes ad-hoc adaptation cumbersome in theatre. To increase development efficiency and ensure flexible solutions in the field, systems engineers need powerful, agile, interoperable, and scalable tools and techniques". The study concluded that "the purpose, affordability, and interoperability, as well as scalability of the computer-aided design (CAD) and SE tools available to DoD were weak with respect to the complexities of future DoD missions and net-centric systems of systems." These findings underscore the motivation for evolving model-based systems engineering MPTs to enable users to interact with models in a more effective manner.

Executable system architecture artifacts. According to the recent study by the Systems Engineering Division of NDIA[29], "Model Based Engineering (MBE) is an emerging approach to engineering that holds great promise for addressing the increasing complexity of systems, and systems of systems, while reducing the time, cost, and risk to develop, deliver, and evolve these systems". The study assessed the current state of MBE and identified potential benefits, costs and risks within the DoD acquisition lifecycle context.

According to a recent SERC study:[30]

> *"Modeling and Simulation (M&S) technology are essential to understand the behavior of the target system and/or to evaluate various strategies for the operation of the system before it is actually built. In many cases, simulation models reflect the design of the final system in great detail and can take the place of architecture documentation. In an ideal*

---

[27] Zimmerman, P., A Review of Model-Based Systems Engineering Practices and Recommendations for Future Directions in the Department of Defense, 2nd Systems Engineering in the Washington Metropolitan Area (SEDC 2014) Conference, Chantilly, VA, April 3, 2014

[28] SERC-2010-TR-009-1, Boehm, B., System 2020 – Strategic Initiative, Systems Engineering Research Center, Final Technical Report, August 26, 2010.

[29] NDIA Systems Engineering Division, Modeling and Simulation Committee, Final Report of the Model Based Engineering (MBE) Subcommittee, Feb 10, 2011.

[30] SERC-2012-TR-024, zur Muehlen, M., Integration of M&S (Modeling and Simulation, Software Design and DoDAF, RT 24, Systems Engineering Research Center (SERC), April 9, 2012

scenario, system architecture artifacts should be directly executable and could be leveraged for simulation purposes".

Creating requisite process and data models, as well as use case descriptions can facilitate the transition from requirements engineering to simulation, and to implementation. The transition from design to implementation, however, is not seamless. Differences in tool-specific standard implementations hamper the seamless transition of model information, increasing the burden on the user.

Trust in Constructed Models. A recent SERC study sponsored by the Naval Air Systems Command (NAVAIR), *Introducing Model-Based Systems Engineering: Transforming System Engineering through Model-Based Systems Engineering*[31] assessed the technical feasibility of creating and leveraging a more holistic MBSE approach. The vision for "doing everything with models" depends on a common lexicon for MBSE including model levels, types, uses, and representations, and a significant degree of automation. The sophisticated model-based process and enabling environment that are envisioned offer the potential for a very powerful transformation of systems engineering through MBSE. A very significant challenge in realizing such a vision is trust in constructed models[36], as we discuss below.

Ontology for Human Systems Integration. A recent publication by Orellana and Madni (2014)[32] discusses the importance of creating the ontology for human systems interaction, interfaces, and integration. An ontology, according these authors, will "extend current system modeling capabilities that will enable the human element to be analyzed as part of the overall system development process. As posed in this paper, the role of the human as system operator is evolving to that of agent, placing greater demands on system architects and engineers[33]. The ontology, when developed, will "extend current modeling capabilities and allow the human element to be analyzed as part of the overall system from system conception to system disposal[32].

EMERGING CHALLENGES AT THE INTERSECTION

Across the four topics areas, we've identified several emerging challenges at their intersection with regard to IMCSE. The insights and techniques being developed in each of the four topic areas have particular additional considerations when used to support systems engineering and decision making. Each of these challenges will now be briefly described. We anticipate using these challenges to help orient and motivate some of the research activities within IMCSE.

---

[31] SERC-2014-TR-044, Blackburn, M., Transforming Systems Engineering through Model Based Systems Engineering, Technical Report, Systems Engineering Research Center (SERC), March 31, 2014

[32] Orellana, D. and Madni, A., Human System Integration Ontology: Enhancing Model Based Systems Engineering to Evaluate Human-System Performance, Conference on Systems Engineering Research, 2014, Procedia Computer Science 28 (2014) 19-25

[33] Madni, A., Integrating Humans with software and Systems, Technical Challenges and a Research Agenda, Systems Engineering 2010, 13 (3), 232-245

Tradeoff of Models

Central to most analyses are models. Since every model is an abstraction from reality, it is important for any model user to understand the implications of embedded assumptions. Sensitivity analysis is a step often performed during analyses where the stability of results is investigated, as a function of (often parametric) assumptions (Feuchter 2000)[34]. "Sensitivity analyses should be performed whenever time and resources allow, with an emphasis on alternatives that survived early screening processes" (OAS 2008)[35]. In practice, many studies are resource constrained and therefore only cursory (if any) sensitivity analysis is conducted. Since the assumptions in the models impact the results of those models, not only are choices of model parameters important from a "within" model sensitivity perspective, but also the choice of the model itself can have large ramifications on the results. IMCSE will seek to address the challenge of performing broad sensitivity analysis, in terms of model choice, as part of a given study, so that it is not relegated to a later activity that is subject to omission when resources are short.

Some preliminary research was done to trade "within model" sensitivities in value models, investigating the potential for interaction in refining value model parameter choices (Ricci et al. 2014).[36]
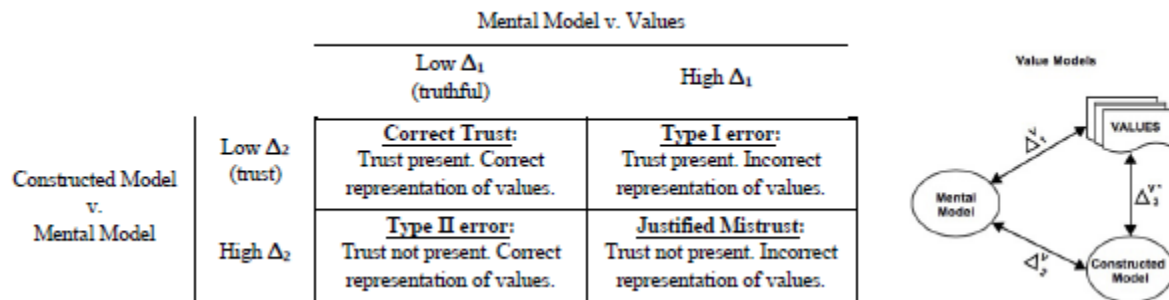
Figure 5. Trust and truthfulness in value models (Ricci et al. 2014)

IMCSE will continue to develop techniques and frameworks for conducting trades on models themselves and not just within the data generated by the models. One example exploratory project is described in the "Value Model Tradeoff" section later in this report.

Visual Analytics of Artificial (Model-generated) Data

Much of the visual analytics literature highlights particular computational and user interaction techniques, or supporting infrastructure, or applications to particular cases. Validation of proposed techniques and supporting infrastructure typically hinges on matching user-generated insights and predictions to "ground truth" in the data. This means that the particular

---

[34] Feuchter, C.A., "Air Force Analyst's Handbook: On Understanding the Nature of Analysis," Office of Aerospace Studies, Air Force Materiel Command (AFMC) OAS/DR, Kirtland AFB, NM, www.oas.kirtland.af.mil, January 2000.

[35] Office of Aerospace Studies (OAS), "Analysis of Alternatives (AoA) Handbook: A Practical Guide to Analyses of Alternatives," Air Force Materiel Command (AFMC) OAS/A9, Kirtland AFB, NM, www.oas.kirtland.af.mil, July 2008.

[36] Ricci, N., Schaffner, M.A., Ross, A.M., Rhodes, D.H., and Fitzgerald, M.E., "Exploring Stakeholder Value Models Via Interactive Visualization," 12th Conference on Systems Engineering Research, Redondo Beach, CA, March 2014

data set being explored via VA tends to be rooted in natural (i.e. empirical) data, where "ground truth" has meaning. Once this is the case, visualizations for pattern matching by humans is more likely to be uncovering actual patterns in the data, rather than artifacts. (Artifacts may still exist due to data errors, sensor errors, or data abstraction and aggregation effects, for example. However, these effects can be managed if a valid (i.e. "true") dataset is available.) An example, of this dynamic is displayed in the MIT Big Data Challenge. In this contest, a large data set of historical taxi data and other related data sets are provided to competitors. Competitors must develop predictive models of number of taxi trips as a function of location. The scoring of the predictive models "will be computed as the root-mean-squared error of [the] predictions against the ground truth."[37]

Since the goal of visual analytics is to generate insights into relationships and patterns in the data, the existence of potentially confounding artifacts in the data makes it especially challenging when ground truth is no longer available. This is essentially the difference between exploratory modeling and consolidative modeling (Bankes 1993)[38]. Consolidative modelling includes "techniques in which known facts are consolidated into a single model" in order to generate explanatory relationships of existing data (Kwakkel and Pruyt 2012).[39] While in exploratory modelling, the intention is to "generate artificial data" that "can inform modelers and decision makers of the ramifications of various sets of assumptions, as well as provide consistent communication" (Schaffner 2014)[40].

In IMCSE, models will tend to be of exploratory nature and therefore additional considerations must be taken into account when generating and visualizing the data in order to properly interpret the results.

Perceptual and Cognitive Considerations in Human-Model Interaction

In considering the form of visual analytics to represent big data, and the structure of model-based approaches to forecasting the evolving complexities of large-scale system, it is crucial to also consider the perceptual and cognitive capabilities of human beings at the center of these exploratory efforts.

There are many considerations in human-model interaction, and relevant research crosses multiple disciplines. For example, recent neurocognitive investigations offer some insight into three behavioral phenomena related to decision-making which may provide a structural framework for guiding these considerations: 1) the behavioral over-reliance on cognitive biases

---

[37] http://bigdatachallenge.csail.mit.edu/prediction [accessed 9/29/2014]

[38] Bankes, S. (1993), "Exploratory Modeling for Policy Analysis," *Operations Research*, 4, pp: 435-449, doi:10.1287/opre.41.3.435.

[39] Kwakkel, J.H., and Pruyt, E., "Exploratory Modelling and Analysis, an approach for model-based foresight under deep uncertainty ", Technol. Forecast. Soc. Change (2012), http://dx.doi.org/10.1016/j.techfore.2012.10.005 .

[40] Schaffner, M.A., *Designing Systems for Many Possible Futures: The RSC-based Method for Affordable Concept Selection (RMACS), with Multi-Era Analysis*, Master of Science Thesis, Aeronautics and Astronautics, MIT, June 2014.

in choice behavior; 2) the tendency towards ambiguity aversion; and 3) the limitations of affective forecasting when making projections about future needs and desires.

Behavioral Over-Reliance on Cognitive Biases in Choice Behavior. Broadly speaking, cognitive biases arise from a maladaptive overreliance on heuristics, a series of cognitive 'short-cuts' human beings recruit to reduce the complexity of day-to-day decisions, and thereby decrease cumulative cognitive loading.[41] Heuristics allow individuals to extrapolate from the consequences of previous decision-making events to inform future choice behavior. Yet when individuals become overly reliant on such strategies, at the exclusion of considering novel, situation-specific information, they become biased, and often demonstrate impaired decision-making abilities. However, research has suggested that cycles of cognitive bias can be broken through training and self-monitoring, and that the effective visual presentation of information may reduce a reliance on biased strategies and promote thoughtful consideration of salient data points, leading in turn to better and more informed choice patterns.

Human Tendency towards Ambiguity Aversion. A second important neurocognitive consideration is the processing of information regarding risk and ambiguity. Recent studies investigating the neural correlates of decision-making have shown distinct patterns of brain activation in response to uncertainty.[42,43] Behaviorally, it has been well established that a risky option of known probability—even when the odds are poor—is often favored over one where the decider is ignorant of the precise degree of risk, a phenomenon termed 'ambiguity aversion.'[44] Broadly speaking, these findings point to a general human intolerance for ambiguity and a preference for information seeking. In this regard, one of the advantages of big data driven, model-based forecasts is to reduce ambiguity by extrapolating future patterns from previously observed occurrences, thereby generating new and useful information for decision-makers.

Limitations of Affective Forecasting When Making Projections. Finally, efforts in experimental psychology to probe human abilities to 'affectively forecast'—that is, to make accurate projections about their future wants, desires, and emotional states— have revealed that, on average, people are in fact quite inaccurate in determining the emotional consequences of future events, often overestimating the amount of future satisfaction a given set of events will bring them.[45] To this end, model-based forecasts

---

[41] Tversky, A., & Kahneman, D. (1974). Judgement under uncertainty: Heuristics and biases. *Sciences,* 185(4157): 1124–1131.

[42] Brand, M., Labudda, K., & Markowitsch, H. J. (2006). Neuropsychological correlates of decisionmaking in ambiguous and risky situations. *Neural Networks*, 19(8), 1266-1276.

[43] Huettel, S. A., Stowe, C. J., Gordon, E. M., Warner, B. T., & Platt, M. L. (2006). Neural Signatures of Economic Preferences for Risk and Ambiguity. *Neuron,* 49(5), 765-775.

[44] Fox, C., Tversky, A., 1995. Ambiguity aversion and comparative ignorance. *The quarterly Journal of Economics*, 110(3), 585-603.

[45] Wilson, T.D.; Gilbert, D.T. (2003). "Affective Forecasting". *Advances in Experimental Social Psychology*, 35: 345–411.

which project future states by examining current and past trends may prove essential to aiding decision-making about the future which may otherwise be tainted by inaccurate assumptions of impending affective state.

When taken together, these three streams of neurocognitive research highlight the ways in which a fundamental understanding of people's perceptual and cognitive capabilities allows for rich, human-centered design in the presentation of visual analytic displays and engaging, interactive models which facilitate exploration and discovery. At the same time, work from these fields also illuminates ways in which visual analytic approaches and model-based projections may serve as effective aids for complex, real-world decision-making.

FUNDAMENTALS

The fundamentals thrust presently includes three areas: Interactive Epoch-Era Analysis project, Value-Model Tradeoff, and Supporting MPTs.

INTERACTIVE EPOCH-ERA ANALYSIS

Epoch-Era Analysis is a framework that supports narrative and computational scenario planning and analysis for both short run and long run futures. This project is performing exploratory development of interactive Epoch-Era Analysis, including human interface and reasoning considerations for epoch and era characterizations, as well as single and multi- epoch/era analyses.

BACKGROUND

Epoch-Era Analysis (EEA) is an approach designed to clarify the effects of changing contexts over time on the perceived value of a system in a structured way (Ross 2006[46], Ross and Rhodes 2008[47]). The base unit of time in EEA is the *epoch*, which is defined as a time period of fixed needs and context in which the system exists. Epochs are represented using a set of epoch variables, which can take on either continuous or discrete values. These variables can be used to represent any exogenous uncertainty that might have an effect on the usage and perceived value of the system; weather conditions, political scenarios, financial situations, operational plans, and the availability of other technologies are all potential *epoch variables*. Appropriate epoch variables for an analysis include key (i.e., impactful) exogenous uncertainty factors that will affect the perceived success of the system. A large set of epochs, differentiated using different enumerated levels of these variables, can then be assembled into *eras*, ordered sequences of epochs creating a description of a potential progression of contexts and needs over time. This approach provides an intuitive basis upon which to perform analysis of value delivery over time for systems under the effects of changing circumstances and operating conditions, an important step to take when evaluating large-scale engineering systems with long lifespans.

Encapsulating potential short run uncertainty (i.e. what epoch will my system experience next?) and long run uncertainty (i.e. what potential sequences of epochs will my system experience in the future?) allows analysts and decision makers to develop dynamic strategies that can enable resilient systems. Key challenges in application of EEA up to this point involve eliciting a potentially large number of potential relevant epochs and eras, conducting analysis across these epochs and eras, and extracting useful and actionable information from the analyses.

---

[46] Ross, A.M., "Managing Unarticulated Value: Changeability in Multi-Attribute Tradespace Exploration," MIT Engineering Systems Division PhD thesis, 2006.

[47] Ross, A.M. and D.H. Rhodes, "Using Natural Value-Centric Time Scales for Conceptualizing System Timelines through Epoch-Era Analysis," INCOSE 2008, 2008.

Schaffner (2014)[48] showed that the number of potential eras to consider grows very quickly, becoming computationally infeasible.

Potential era space = $(\prod_{i=1}^{v} L_i)^n$, where L is the number of levels of epoch variable i, v is the number of epoch variables, and n is the number of epochs in a given era. As an example, a model of 5 epoch variables with 3 levels each and an era of 10 epochs, would result in 3^{50}, or $\sim 10^{24}$ different eras.

This means that for many problem formulations it is not feasible to evaluate systems across all or even a large fraction of potential eras[49]. As described earlier in the four pillars of IMCSE, big data and visual analytics both have led to techniques that could be leveraged to mitigate these challenges. It is hypothesized in this research that adding interactivity to EEA will fundamentally enable new capabilities and insights to be derived from an EEA, resulting in superior dynamic strategies for resilient systems. In particular, we have three informal hypotheses regarding interactive EEA (iEEA):

1. iEEA will enable the elicitation of more broad/complete set of possible epochs:
   a. Infrastructure that enables iEEA could include databases of epoch variables, which could be leveraged in future iEEA studies
   b. Explicit implementations in an interface will provide repeatable and more understandable elicitation experiences, resulting in more epoch variables
2. iEEA, through human-in-the-loop implementation, will help to intelligently limit the potentially unbounded growth in the potential epoch/era space:
   a. Using visual analytic techniques such as filtering, binning, pattern matching, human with computer iEEA can be used to effectively manage multi-epoch and multi-era analysis scale growth
3. iEEA will enable the development of superior intuition, buy-in, and insight generation for decision making:
   a. Through getting people to "experience" (i.e. "see" and "interact with") epochs and eras, they will better understand and accept the impact of context and needs changes on systems and therefore how resilience can be better achieved

Earlier work demonstrated promise for such capability and insight improvement when interactivity is added to tradespace exploration. Ross et al. (2010)[50] introduces a method, applied to two aerospace cases in order to explore the potential for interactive tradespace exploration to support stakeholder negotiations. Preliminary results indicate the method to be

---

[48] Schaffner, M.A., Designing Systems for Many Possible Futures: The RSC-based Method for Affordable Concept Selection (RMACS), with Multi-Era Analysis, Master of Science Thesis, Aeronautics and Astronautics, MIT, June 2014.
[49] Schaffner 2014 suggested several possible mitigations to this problem, including human in the loop era tree pruning, which will be investigated in this research project.
[50] Ross, A.M., McManus, H.L., Rhodes, D.H., and Hastings, D.E., "A Role for Interactive Tradespace Exploration in Multi-Stakeholder Negotiations," AIAA Space 2010, Anaheim, CA, September 2010

a rapid and beneficial technique, which generated compromise alternatives, guided the elicitation of previously unarticulated information, and resulted in increased confidence and solution buy-in of participating stakeholders. Interactive tradespace exploration analyses allowed negotiation processes to proceed quickly. Proposed compromises can be assessed by each stakeholder in real time, and what the stakeholder is gaining or losing in the compromise is immediately visible. An open area of research is to incorporate Epoch-Era Analysis into the interactive tradespace exploration.

INTRODUCTION

The development of engineered resilient systems (ERS) was identified as a science and technology (S&T) priority for the DoD by the Secretary of Defense in April 2011. Since that time several researchers and practitioners have begun to develop methods, techniques and tools to assist designers in the early system concept selection phase. Many of the techniques in development require analysis of vast amounts of data to quantify the effectiveness of large numbers of actionable alternatives across large numbers of possible futures in order to select the best possible decision. Recognizing that some human-in the-loop techniques that are being pioneered in studies of visual analytics and big data analysis may assist in solving this problem, this research seeks to leverage and expand upon those techniques. The challenge this research seeks to address can be described as: "how can one balance System, Context, and Expectations over time, during engineering design, evaluation and selection, given human cognitive and perceptual limitations?" (Ross 2014)[51]

The development of complex engineering systems using traditional engineering design techniques can lead to point designs optimized for a fixed operating context or set of stakeholder needs. This can reduce system performance if future uncertainty resolves in a way other than predicted. This is especially true if the system is not resilient or robust to change. As an example, consider modern spacecraft, which have long development timelines of 5 to 10 years or more that makes them susceptible to changes in mission and technology before they even reach orbit. They must also have a significant amount of redundancy built in because a replacement system could take years to develop and launch if they fail. Reducing such susceptibilities to changes in context was a key goal of DARPA's System F6 program. A shift in stakeholder needs for which the system is not resilient can also limit its value delivery. A noteworthy example is the Iridium satellite constellation that suffered from a shift in the consumer market to land-based cellular towers before it reached initial operating capability (IOC) (Curry 2014)[52].

The definition of what is or is not a resilient system is not universally agreed upon. One definition is that a resilient system has "the ability to circumvent, survive, and recover from failures to ultimately achieve mission priorities even in the presence of environmental

---

[51] Ross, A.M., "Interactive Model-Centric Systems Engineering," Presentation to the 5th Annual SERC Sponsor Research Review, Georgetown University, Washington, DC, February 2014.

[52] Curry, M., "Presentation: Application of Epoch Era Analysis to the Design of Engineered Resilient System", 17th NDIA Systems Engineering Conference, Springfield, VA, October, 2014.

uncertainty" (Madni 2012)[53]. Yet another definition of resilience (called system "survivability" elsewhere, adding to semantic confusion) is "the ability of a system to minimize the impact of a finite duration disturbance on value delivery, achieved through either (1) the reduction of the likelihood or magnitude of a disturbance; (2) the satisfaction of a minimally acceptable level of value delivery during and after a finite disturbance or; (3) timely recovery from a disturbance event" (Richards et al. 2007)[54].

More recent work has generalized this concept into something called *value sustainment* (Beesemyer 2012[55]). Value sustainment is defined as "the ability to maintain value delivery in spite of epoch shifts or disturbances." Figure 6 below summarizes this concept and reflects how we will consider notions of resilience in this research effort. In this figure, the nominal value delivered by a system is (potentially) impacted by a perturbation (characterized as either a disturbance or a shift). A *disturbance* is a short duration, likely to revert imposed change on the design, context, or needs for a system, while a *shift* is a long duration, unlikely to revert imposed change on the design, context, or needs for a system. A "resilient" system is one that either is not impacted, or maintains value above the indicated threshold, and restores that value delivery to a higher acceptable level after a threshold period of time. What is common to most of the definitions suggested for resilient systems is an acknowledgement that complex systems must be designed to continue to deliver sustained value to their stakeholders even if uncertainty exists about the way a system will be required to operate in the future.
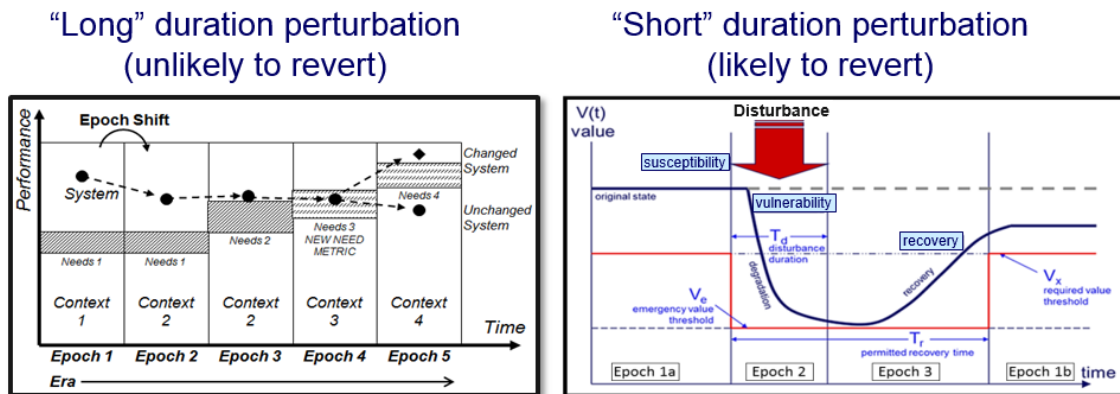
Figure 6. Temporal representation of system over time and two perturbation types: epoch shifts and disturbances

EEA AND DATA CHALLENGES

Traditional tradespace exploration and multidisciplinary design optimization techniques typically assume as fixed the needs of the stakeholders, the context in which a system will be

[53] Madni, A., "Affordable, Adaptable and Effective: The Case for Engineered Resilient Systems," Engineering Resilient Systems Workshop, Pasadena, CA, August 2012.
[54] Richards, M.G., Hastings, D.E., Rhodes, D.H., and Weigel, A.L., "Defining Survivability for Engineering Systems," 5th Conference on Systems Engineering Research, Hoboken, NJ, March 2007.
[55] Beesemyer, J.C., Empirically Characterizing Evolvability and Changeability in Engineering Systems, Master of Science Thesis, Aeronautics and Astronautics, MIT, June 2012.

operated and the future state of the system itself. To design resilient systems we must consider situations in which these can all vary with time. One framework for evaluating such possibilities is Epoch Era Analysis (Ross 2006)[56]. EEA conceptualizes the effects of time and changing context on a system by modeling combinations of future context and stakeholder needs on perceived system value (Ross and Rhodes 2008[57]; Fitzgerald et al. 2011[58]; Schaffner et al. 2013[59]). A time period over which the stakeholder needs and the context in which the system must operate are fixed is referred to as an *epoch*. A series of epochs can be strung together to form *eras* that can be used to model the long-run value delivery of a system and take into account temporal path dependencies between epochs. Such eras can be generated through narrative (i.e. story-driven) or computational means (i.e. algorithm-generated) enabling consideration of a broader set of possible short and long run scenarios than commonly considered using traditional scenario planning techniques (Roberts et al. 2009)[60].

Broadly speaking, EEA be described as the following activities (roughly sequential and depicted in Figure 7):

0. Problem Definition: identify decision to be made, relevant constraints, stakeholders, and potential contexts

1. Design Formulation: generate potential design alternatives to be evaluated in the analysis; can be generated via inheritance, creative brainstorming, value-driven methods, or other means; identify preliminary criteria for their evaluation.

2a. Epoch Characterization: identify key exogenous uncertainties and parameterize via epoch variables; can be accomplished via era deconstruction or proposing possible short run scenarios.

2b. Era Construction: generate various long term descriptions of possible futures via epoch sequencing, or proposing long run scenarios (e.g. via narrative or computational means).

3. Design-Epoch-Era Evaluations: develop and execute appropriate models that can evaluate designs in epochs in eras.

4a. Single Epoch Analyses: conduct analyses of the designs within particular epochs, determining performance and cost of alternatives and difficulty of achieving success within particular periods of fixed context and needs.

---

[56] Ross, A.M., Managing Unarticulated Value: Changeability in Multi-Attribute Tradespace Exploration, Doctor of Philosophy Dissertation, Engineering Systems Division, MIT, June 2006.

[57] 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.

[58] Fitzgerald, M.E., Ross, A.M., and Rhodes, D.H., "A Method Using Epoch-Era Analysis to Identify Valuable Changeability in System Design," 9th Conference on Systems Engineering Research, Los Angeles, CA, April 2011.

[59] Schaffner, M.A., Wu, M.S., Ross, A.M., and Rhodes, D.H., "Enabling Design for Affordability: An Epoch-Era Analysis Approach," Proceedings of the 10th Annual Acquisition Research Symposium- Acquisition Management, April 2013.

[60] Roberts, C.J., Richards, M.G., Ross, A.M., Rhodes, D.H., and Hastings, D.E., "Scenario Planning in Dynamic Multi-Attribute Tradespace Exploration," 3rd Annual IEEE Systems Conference, Vancouver, Canada, March 2009.

4b. Single Era Analyses: conduct analyses within particular eras to determine the impact of time-dependent effects on system success, along with cumulative path-dependence on the system over time.

5a. Multi-Epoch Analysis: conduct analysis across multiple (or all) epochs to determine sensitivities of designs to epochs; gives insight into short run value of active and passive strategies for system resilience.

5b. Multi-Era Analysis: conduct analysis across multiple (or all) eras to determine sensitivities of designs to eras and patterns of path dependence; gives insights into long run value of active and passive strategies for system resilience.
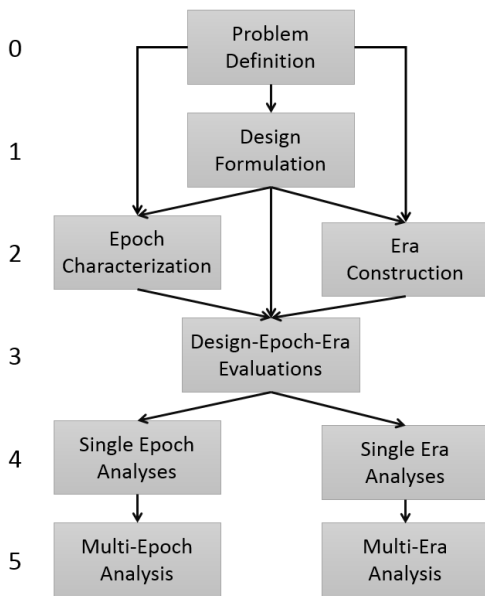
Figure 7. Activities in Epoch-Era Analysis

Figure 8 illustrates the era-tree approach to era construction via paths through the epoch space. Each epoch is defined as a particular context-need pair and duration.
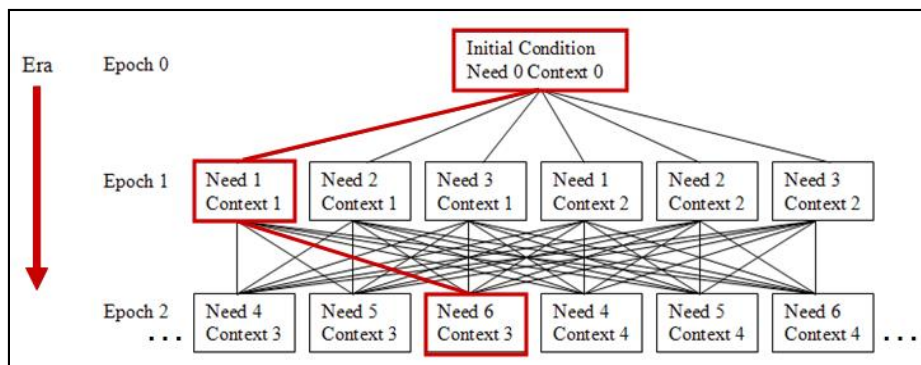
Figure 8. Eras generated as path through possible epoch space (from Ross et al. 2008[61])

---

[61] Ross, A.M., McManus, H.L., Long, A., Richards, M.G., Rhodes, D.H., and Hastings, D.E., "Responsive Systems Comparison Method: Case Study in Assessing Future Designs in the Presence of Change," AIAA Space 2008, San Diego, CA, September 2008

Schaffner (2014) introduces useful terms when constructing eras. A *frame* is a particular slot within an era that consists of an epoch and a duration. This allows an EEA user to specify era of varying number of slots in a less ambiguous manner. For example, a 5 frame era consists of 5 slots, each with a particular epoch and duration. The same epoch could appear in more than one frame. A second useful concept is that of a *clip*, which is a subset of a full era, comprised of an arbitrarily small number of frames. Using this nomenclature, one can speak of 3-frame clips, for example, which might appear in multiple different eras. When looking for patterns, such a unit of analysis may be useful.
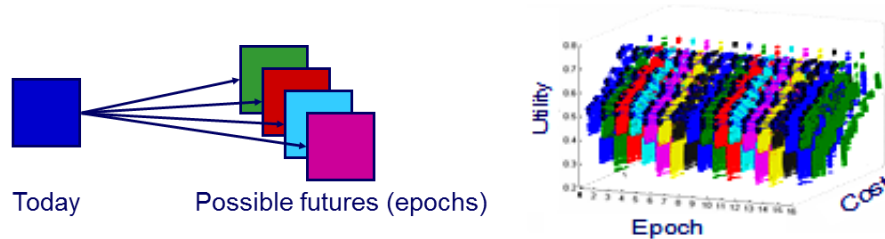
Figure 9. Epochs as Alternative "Point" Futures (l) and Multi-Epoch Analysis (r)

Figure 9 illustrates epochs as alternative (point) futures, and multi-epoch analysis as a cross-epoch activity looking for designs that perform well across the alternative future space.

A practical challenge in implementations of EEA is the large amount of data that may need to be evaluated in order to thoroughly characterize possible system alternatives and their potential for value sustainment across a wide variety of futures. In EEA, large numbers of possible alternatives may need to be generated by evaluating many possible combinations of design variables using performance models. Evaluating large numbers of designs is common tradespace exploration challenge, especially if performance models take a nontrivial amount of time and resources to evaluate. The problem is further exacerbated by the need to evaluate each possible design alternative in each possible future context and across many future stakeholder value models. This can quickly turn into an intractable problem with millions or billions (or more) of data points that must be analyzed as part of the decision problem. Techniques from visual analytics may allow a human-in-the-loop to more quickly identify patterns in the data and filter, sort and aggregate data more efficiently than "canned" or automated algorithms, enabling a more effective tradeoff of evaluation "completeness" versus insights gained.

As previously noted, applying EEA to some system design problems may lead to vast amounts of data. New techniques that allow a decision maker to interact with their data to gain insights may improve the systems engineering decision making process. Liu et al. (2013)[62] and Heer and Shneiderman (2012)[63] point out that "interaction is essential to exploratory visual analysis", but their work primarily focuses on visualization. Note that interaction, as used here, is not

---

[62] Liu, Z. Jiang, B., Heer, J., "imMens: Real-time Visual Querying of Big Data," Eurographics Conference on Visualization (EuroVis), 2013.

[63] Heer, J., and Shneiderman, B., "Interactive Dynamics for Visual Analysis," ACM Queue, 2012.

intended to be strictly limited to the data visualization component, but also the interfaces, processes, and methods that allow a user to gain insights from their data. Interfaces may require use of sensory stimuli other than visual-only, including touch and/or sound. Processes could include custom workflows such as those described in Sitterle et al. (2014)[64]. Methods for sorting and filtering data may include, but are not limited to, interactive brushing and linking of multiple simultaneous visual displays.

The problems that may arise when scaling up to larger decision problems with traditional EEA could be placed into four categories:

1. Data size increases which creates a storage and data transmission problem.
2. Data size increase also creates a separate problem related to cross-filtering across large numbers of data dimensions. Human cognitive limitations make comprehension of high-dimensional data difficult so datasets must be "sliced" or cross tabulated across dimensions before rendering them as 1D, 2D or 3D visualizations.
3. Larger data sets require increased amounts of processing time to manipulate.
4. Rendering problems arise when large amounts of data must be visualized simultaneously.

A FRAMEWORK FOR INTERACTIVE EPOCH-ERA ANALYSIS

The current vision of Interactive Epoch-Era Analysis (iEEA) leverages humans-in-the-loop as well as supporting infrastructure in order to manage challengers associated with the large amounts of data potentially generated in a study, as well as sense making of the results. Figure 10 below illustrates three insertion points for interactivity to directly address the three hypotheses outlined earlier (improved elicitation, improved analyses, improved decision-making).

---

[64] Sitterle, V., Curry, M., Ender, T., Freeman, D., "Integrated Toolset and Workflow for Tradespace Analytics in Systems," INCOSE International Symposium, Las Vegas, NV, 2014.
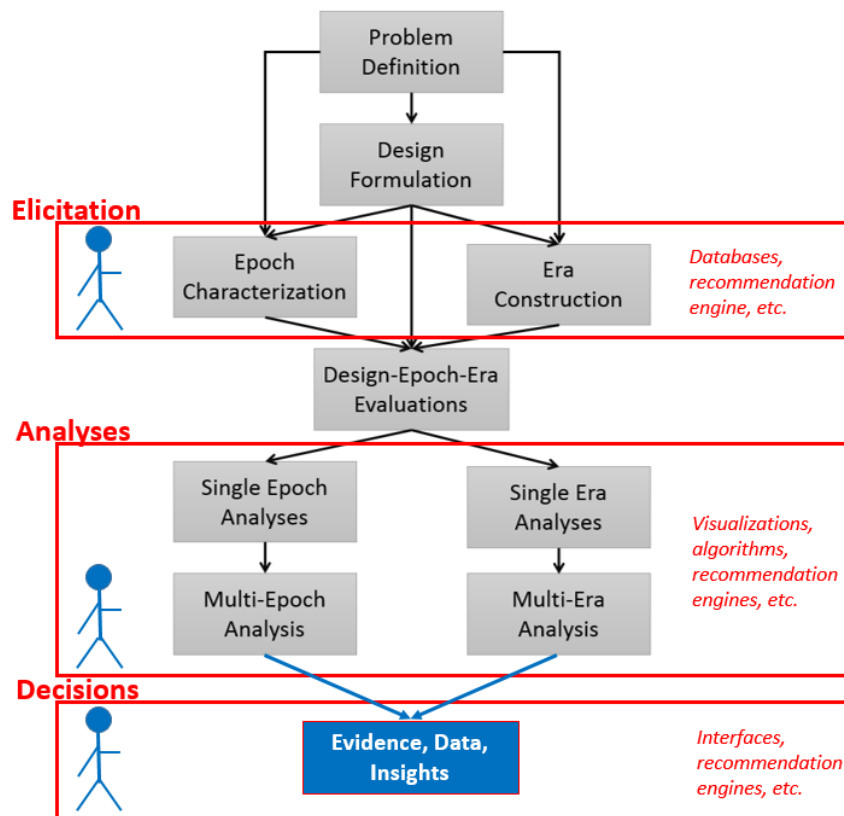
Figure 10. Interactive Epoch-Era Analysis leverages humans-in-the-loop and supporting infrastructure

iEEA seeks to combine several techniques to address the problems described above. These problems can be resolved or mitigated by using a hybrid approach that combines techniques from parallel computing, online analytical processing and visual analytics. Problems with rendering and the scalability of visualizations and other encoded visual information can be improved upon using techniques that do not require every single data point to be drawn. Liu points out that, "Perceptual and interactive scalability should be limited by the chosen resolution of the visualized data, not the number of records," and summarizes several techniques past researchers have applied to reduce the pixel density of visualizations (Liu et al. 2013)[65]:

1. Data reduction through filtering
2. Data reduction through sampling
3. Binned aggregation
4. Model-fitting

Implementation of iEEA demonstration tools and methods may need to draw on a combination of the techniques described above. This means that iEEA needs to take into account the practicality of representing large amounts of data effectively view scarce communication

---

[65] Liu, Z. Jiang, B., Heer, J., "imMens: Real-time Visual Querying of Big Data," Eurographics Conference on Visualization (EuroVis), 2013.

resources (e.g. limited spatial or temporal resolutions due to hardware or software constraints) (Keim 2000[66]). Given the volume and complexity of the data that will need to be analyzed, iEEA should allow a decision maker to manipulate their viewpoint into the data in real-time. Their viewpoint can change both in level of abstraction and information type as shown in Figure 11 below. One possible analogy is to compare iEEA techniques to those used to interact with web-based map applications such as Google Maps. When zooming in and out (level of abstraction) of the default road map the scale of information displayed to the user changes automatically as roads, city names and other feature are enabled or hidden. Attempting to view all available data from the top zoom scale could create a cluttered visualization that is not constructive or helpful for allowing the decision maker to reach a conclusion.

It is also envisioned that with iEEA the user could also adjust the layer of information they are looking at (information type) to make their decision. Depending on the type of decision they are making they may need to switch across various types of displays or variables at the same zoom level. The information they need may be a satellite image, terrain map, traffic map, public transit map or some hybrid combination. Clearly the visualizations needed for the types of decisions iEEA supports will likely not be maps, but the analogy of how users will make a large data set manageable for making decisions through interactive techniques is appropriate.
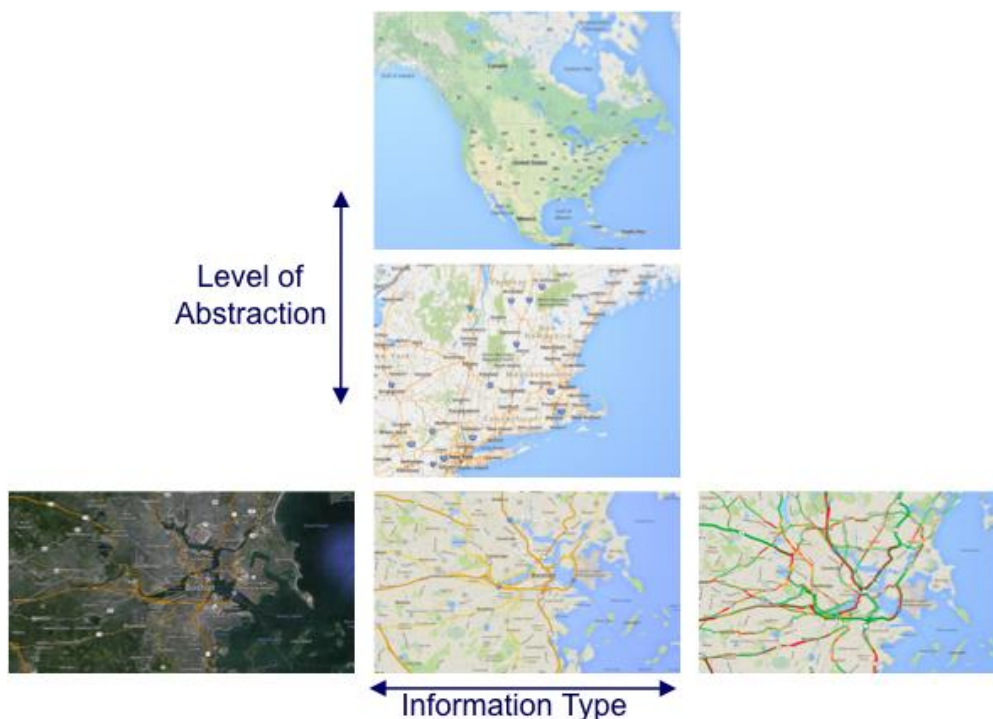
Figure 11. Level of abstraction versus information type for map data (individual images from maps.google.com)

---

[66] Keim, D.: Designing pixel-oriented visualization techniques: Theory and applications. IEEE TVCG 6, 1 (2000), 59–78.

Preliminary Work Exploring Techniques from VA and Big Data with Applicability to EEA

In order to develop an effective framework for interactive Epoch-Era Analysis, this project has pursued an initial set of exploratory prototype mini-projects. These have focused so far on leveraging techniques from big data as applied to EEA in order to manage the data scale challenge potentially faced during iEEA. These prototype accomplishments include:

1. Example of massive parallel processing that takes advantage of Amazon cloud computing services to generate very large design/epoch spaces.
2. Example web-based tools that integrated interactive D3-based[67] graphics with a database driven backend. This prototype showed that we could create an interactive visual interface that was driven by legacy databases such as the Space Tug[68] database (Figure 12, Figure 13, and Figure 14). It also demonstrates techniques for more easily appending or culling a database from within the interactive interface rather than relying on a 3rd party piece of software.
3. Recent example that extends the above example to use online analytical processing (OLAP) techniques to enable a decision maker to more rapidly filter their data to identify patterns in high-dimensional data.
4. A final example (hexagonal binning) to show that we can extend the above prototype system to easily be capable of handling 1,000,000 alternatives that can be conveyed quickly and effectively to a decision maker in an interactive way (Figure 15).
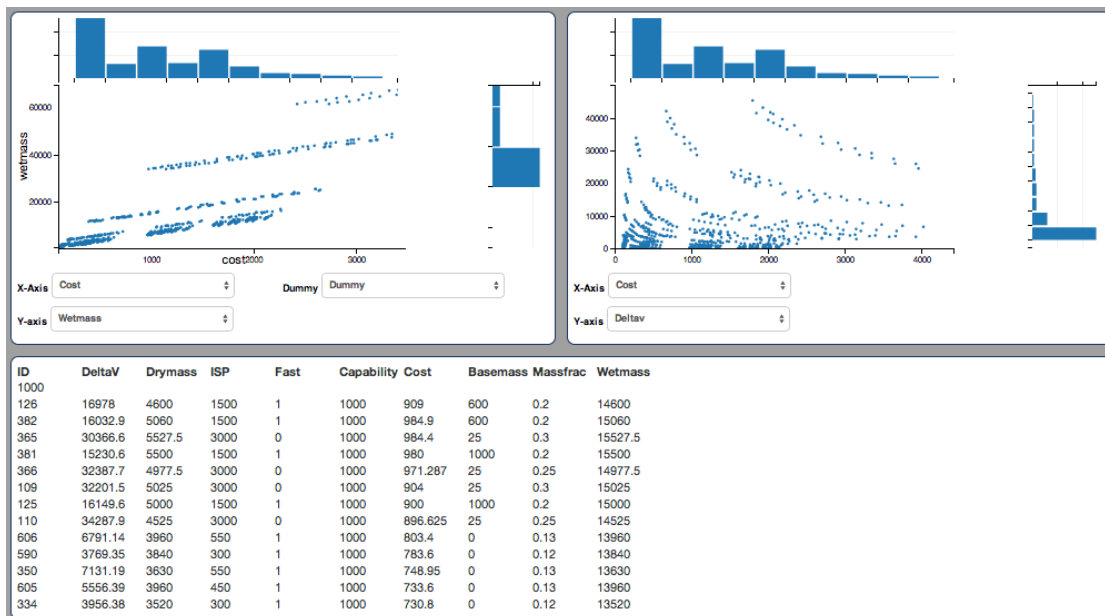
Figure 12. Prototype tool using D3, demonstrating coordinated views.

Figure 12 is a screenshot of a prototype tool implemented in D3 demonstrating coordinated views using online analytical processing to "slice" across dimensions or perform "drill-downs"

---

[67] D3.js is a JavaScript library for enabling interactive web documents based on data (http://www.d3js.org)
[68] McManus, H., and Schuman, T., "Understanding the Orbital Transfer Vehicle Trade Space," AIAA Space 2003, Long Beach, CA, September 2003.

and "roll-ups" of multiple design alternatives. The left plot shows wet mass vs cost and the right plot shows delta-V available vs cost for a theoretical Space Tug. The histograms at the top and bottom of each chart show a binned view of the data projected from the x and y axis.
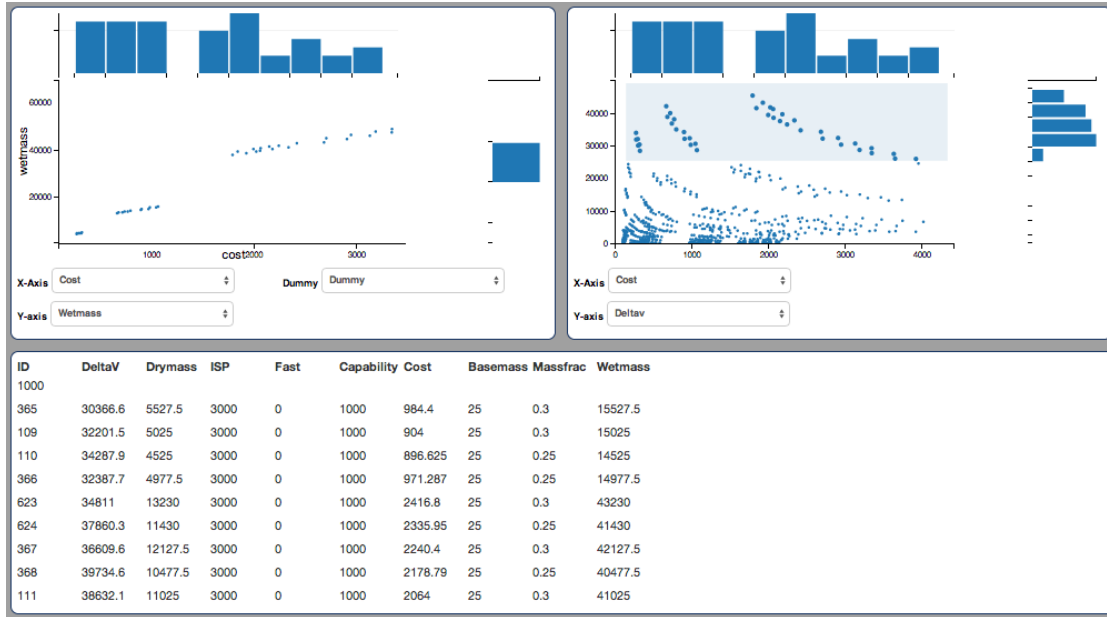
Figure 13. Example of brushing and linking between the coordinated data views.

ID	DeltaV	Drymass	ISP	Fast	Capability	Cost	Basemass	Massfrac	Wetmass
1000									
365	30366.6	5527.5	3000	0	1000	984.4	25	0.3	15527.5
109	32201.5	5025	3000	0	1000	904	25	0.3	15025
110	34287.9	4525	3000	0	1000	896.625	25	0.25	14525
366	32387.7	4977.5	3000	0	1000	971.287	25	0.25	14977.5
623	34811	13230	3000	0	1000	2416.8	25	0.3	43230
624	37860.3	11430	3000	0	1000	2335.95	25	0.25	41430
367	36609.6	12127.5	3000	0	1000	2240.4	25	0.3	42127.5
368	39734.6	10477.5	3000	0	1000	2178.79	25	0.25	40477.5
111	38632.1	11025	3000	0	1000	2064	25	0.3	41025

In Figure 13, a brushing tool has been used to draw a lasso around design points of interest in the right chart and the left chart updates to reflect the new constrained design space. The histograms also update to provide the designer with immediate feedback on the effects of the constraint. This allows the designer to recognize more quickly whether restrictions they place on a certain variable have impacts they might not have intended on other variables. The list at the bottom shows the remaining available designs and their characteristics.
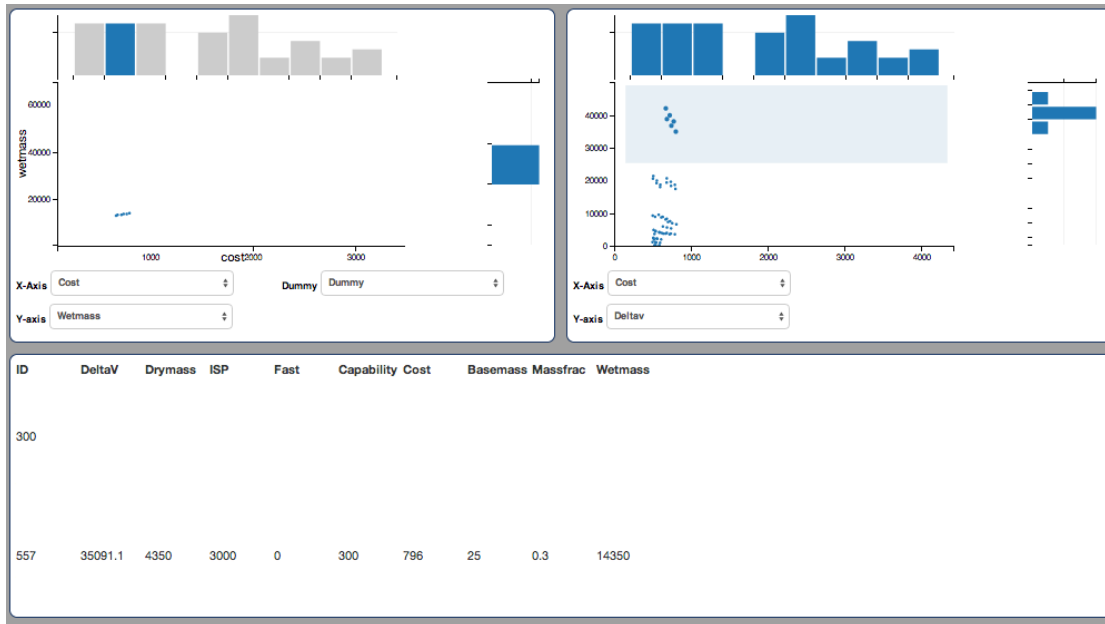
Figure 14. Histogram filtering.

The designer can further restrict the design space by clicking on the bins of histograms (Figure 14). Note that the bin second from the left in the left-top histogram has been clicked to constrain the design space in this example. This coupled with the brushing constraint has restricted the design space to only a few designs.
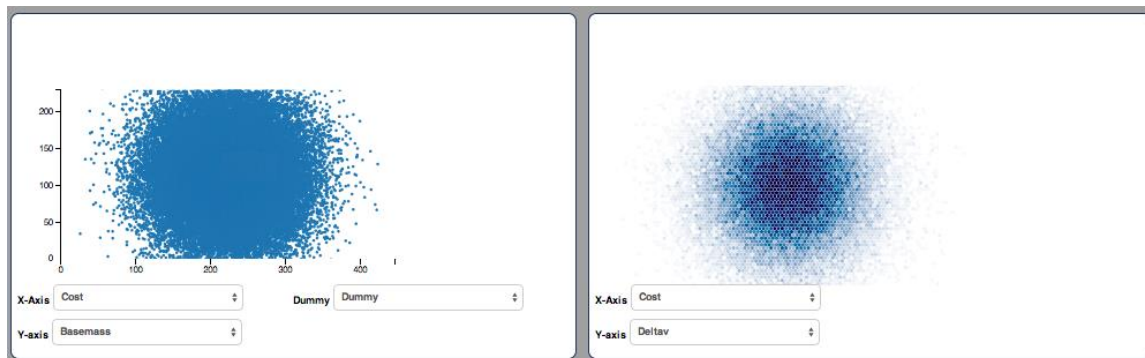
Figure 15. Using hexagonal binning to represent large numbers of designs.

An issue with tools of this type is scalability due to processing and rendering. For iEEA we will want to look at many more design alternatives than were previously possible using traditional EEA applications. Figure 15 demonstrates how a design space of 1,000,000 alternatives could be rendered more effectively through 2-D hexagonal binning. Both charts plot the same randomly generated design data. The left chart shows the traditional scatter chart view of the data which, due to the density of points, leaves many of the points occluded. The chart on the right shows the binned version with the density of points in an area encoded by color. The right-hand chart renders much more quickly due to the reduced number of polygons and allows the designer to filter the design and epoch space much more quickly.

In the next phase of the research, prototyping will continue, leveraging additional techniques from visual analytics and more explicitly addressing hypotheses 1 and 3 in addition to 2. The key benefits are expected to result from having a human in the loop and many more design, context and needs alternatives to consider. As a consequence, our current working hypothesis is that iEEA enables improved decision-making relative to traditional EEA because:

1. It applies advanced techniques from parallel computing, OLAP and new visualization techniques to allow consideration of many more alternatives the previously possible. These techniques also control growth of data size and improved processing of high-dimensional data.
2. Data elicitation on possible epochs and design variable ranges of interest is significantly improved through interactive techniques that allow a human-in-the-loop to identify patterns, areas of interest or errors in the space of alternatives.
3. Improved intuition and buy-in is achieved from the fact that many more alternatives can now be considered and interactive approaches allow decision-makers to more quickly understand impacts of design decisions on performance across epochs. Understanding that certain design choices make a design resilient to some contexts, but much more brittle in others is a key insight.

NEXT STEPS

In Phase 2, work will continue investigating framing and implementation challenges uncovered in Phase 1, with additional prototype software tools to be developed. Depending on progress, some iEEA capability may be incorporated into the IVTea Suite MPT (described in later section of this report). One or more case studies will be started to work through the development of visualizations and supporting infrastructure for iEEA.

VALUE-MODEL TRADEOFF

One of the key challenges identified in preliminary research for IMCSE involves understanding the role that model choice plays in the generation and analysis of data for decision making. IMCSE anticipates making a key contribution in terms of framing this challenge and insights gained when actively trading models as a part of a study.

BACKGROUND

Figure 16 depicts the general relationship between decision problems and decision solutions as they relate to data and models for IMCSE. In this figure, decision problems suggest a space of potential solutions, which span a design space. The design space is then sampled and evaluated through two types of models: cost models and performance models. Cost models seek to predict the resources need to develop and operate each of the evaluated potential systems. Typically these estimates are in terms of dollars, and potentially time (i.e. schedule). Performance models seek to predict the operational behavior in context of the evaluated potential systems. Value models seek to map the resulting resource and performance predictions into decision-friendly perceived benefit and cost metrics. Value models can be simple (e.g. just pass through the cost and performance measures), or complex (e.g. aggregate perceived benefit under uncertainty of a large number of measures). Each of these models, and the artificial data generated by them, can be potentially altered by changes in the epoch space (e.g. exogenous context and needs changes). Updating occurs when users seek to modify the space definitions, or the models, in order for them to better address the problem under consideration (or to improve the trust or truthfulness (i.e. validity) of the models and data).
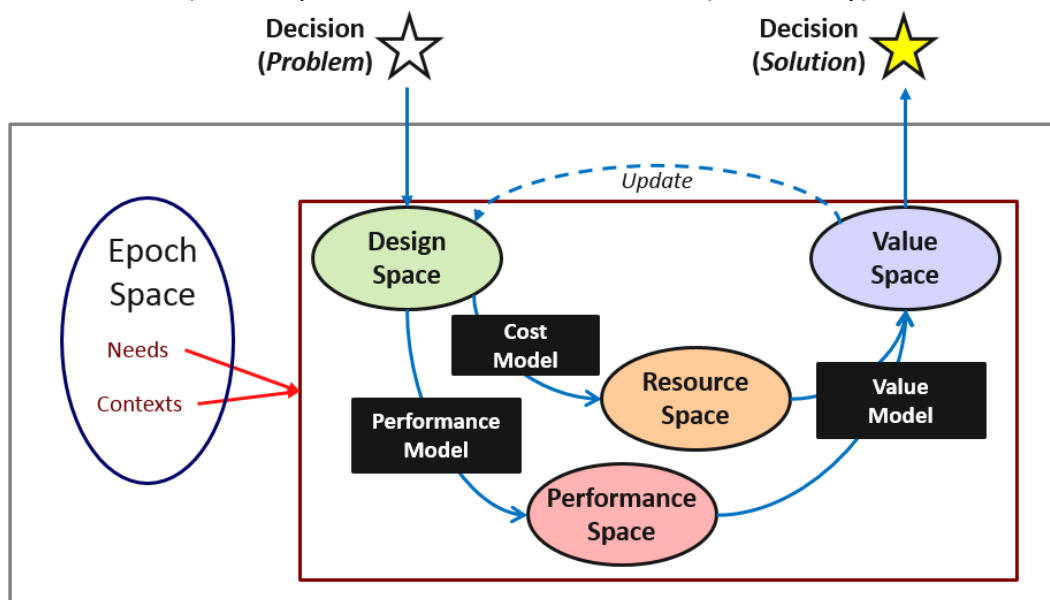
Figure 16. Role of key models for supporting system decision making

During this phase of the research, the team has begun exploratory work defining model types and formulation of how model trading might be implemented. Leveraging insights from Ricci

et al. (2014)[69], which described the role of interactivity in refining a user's captured value model, we generalized the concept of "value model trading" from tuning parameters within a particular value model (i.e. utility function shapes and weights for a Multi-Attribute Utility value model) to also include trading of value model formulations as well. There are many possible value models (e.g. see Ross et al. (2010)[70]). For this demonstration, four alternative value models were used: Multi-Attribute Utility (MAU), Analytic Hierarchy Process (AHP), Cost-Benefit Analysis (CBA), and Measure of Effectiveness (MOE) (see Figure 17 below). Recall a value models attempt to predict how a particular decision maker might perceived net benefits and costs for alternatives under consideration. Different value models treat the mapping of raw data to perceived costs and benefits differently. For illustration purposes, we treated perceived costs as just lifecycle cost (essentially as a single dimensional metric of perceived cost), while we varied the perceived benefit model from MAU to AHP to CBA to MOE. The results of this variation were analyzed in terms of how the set of most perceived benefit versus perceived cost efficiency changed. This was calculated as the Pareto efficient set for given value models. The sets were then compared to see the impact of value model choice on proposed "best" alternative solutions. This demonstration case utilized the IVTea Suite software environment being developed as an IMCSE supporting MPT (described below).
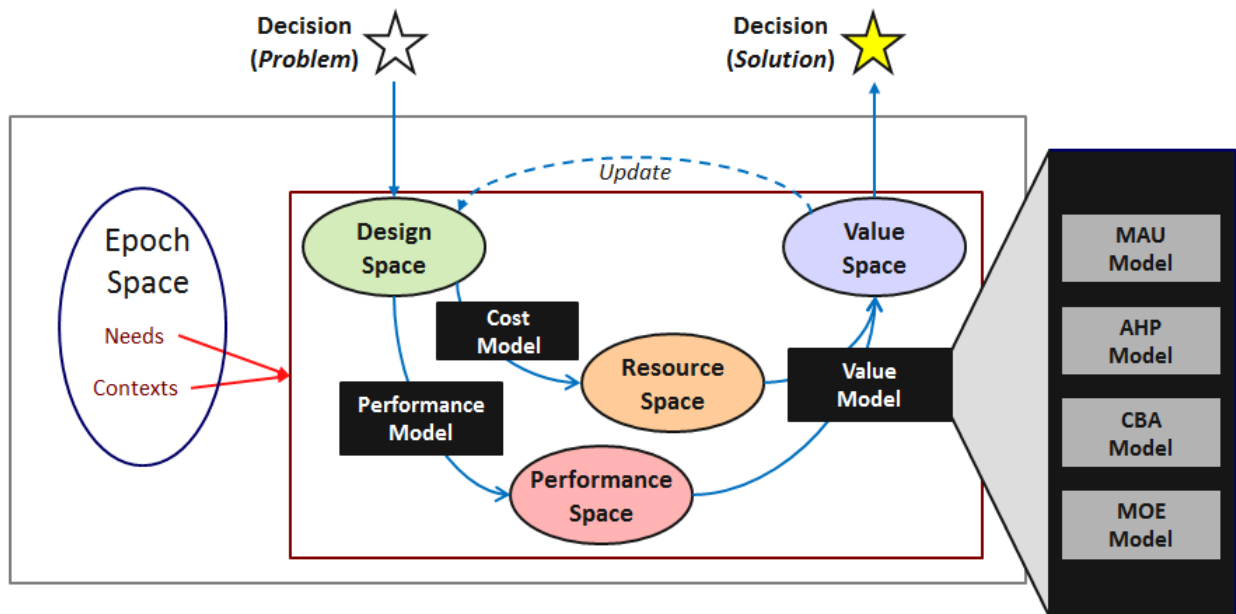
Figure 17. Various value models for demonstration case

DEMONSTRATION OF VALUE MODEL TRADING: SPACE TUG

For this exploratory case, the problem is framed as the following:
A decision maker has a budget for an orbital transfer vehicle (a.k.a. "Space Tug") and thinks he knows what he wants (in terms of attributes of goodness in a system alternative). But he is

[69] Ricci, N., Schaffner, M.A., Ross, A.M., Rhodes, D.H., and Fitzgerald, M.E., "Exploring Stakeholder Value Models Via Interactive Visualization," 12th Conference on Systems Engineering Research, Redondo Beach, CA, March 2014.
[70] Ross, A.M., O'Neill, M.G., Hastings, D.E., and Rhodes, D.H., "Aligning Perspectives and Methods for Value-Driven Design," AIAA Space 2010, Anaheim, CA, September 2010.

aware that he may not have formulated his value model correctly. He wants to explore three types of uncertainties in his value model:

1. What value model best represents his preferences?
2. What parameters for a given value model best represent his preferences?
3. What if he really doesn't know what his true preferences are and wants instead a robust solution?

The second question was partly addressed in Ricci et al. (2014)[71], and will be done in this study in Phase 2. The first and third questions are investigated in this exploratory case during Phase 1.

Approach: Use four different value models to evaluate and represent benefit vs. cost tradeoffs; identify the most value efficient alternatives under different value models; compare preferred alternatives across value models.

Models Used in the Study

The design alternatives and performance and cost models for Space Tug are described in McManus and Schuman (2003)[72]. The value models that were used in this study are now described:

Multi-Attribute Utility (MAU)

Multi-Attribute Utility value model generates an aggregate measure across multiple criteria (called attributes). Each of the attributes have single attribute utility functions that map attribute level to perceived benefit under uncertainty of that attribute (typically quantified on a zero to one scale). Each of the single attribute utility functions are then aggregated via a multi-linear function into a multi-attribute utility score.

The equation for multi-attribute utility is as follows:

$$U(\hat{X}) = \frac{\left[\prod_{i=1}^{n}(K \cdot k_i \cdot U_i(X_i)+1)\right]-1}{K}, \text{ where } K = -1 + \prod_{i=1}^{n}(K \cdot k_i + 1)$$

Here K is the normalization constant, $U(\hat{X})$ is the aggregate utility value across the multiple single attributes X_i and their respective single attribute utilities, $U_i(X_i)$; k_i is the swing weighting factor for the attribute X_i; and n is the number of attributes. Figure 18 illustrates the three single attribute utility functions for each of the attributes (capability, delta V, and response time), along with their k_i weights for the multi-attribute utility function. In the special case where the weights add to 1, the function becomes a linear weighted sum, and therefore each attribute contributes independently to the aggregate value.

---

[71] Ricci, N., Schaffner, M.A., Ross, A.M., Rhodes, D.H., and Fitzgerald, M.E., "Exploring Stakeholder Value Models Via Interactive Visualization," 12th Conference on Systems Engineering Research, Redondo Beach, CA, March 2014.
[72] McManus, H., and Schuman, T., "Understanding the Orbital Transfer Vehicle Trade Space," AIAA Space 2003, Long Beach, CA, September 2003.
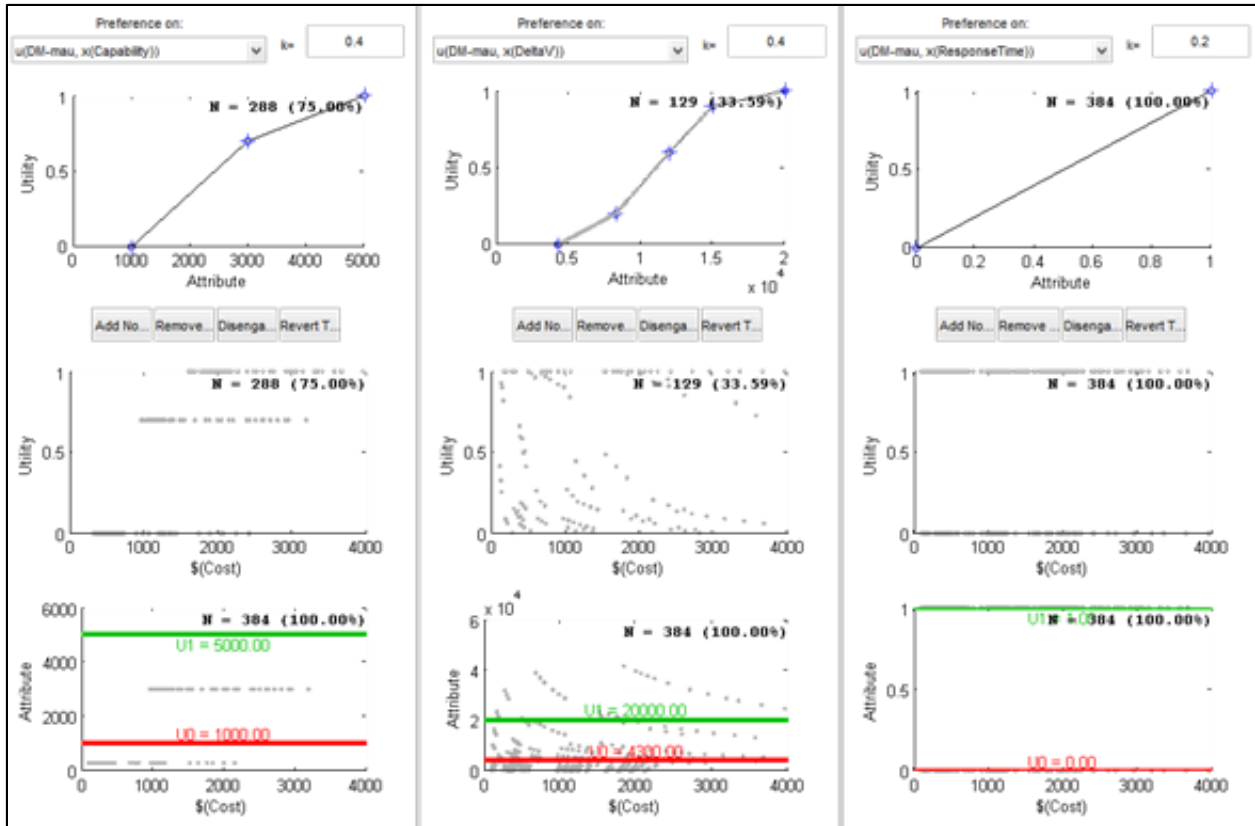
Figure 18. Single attribute utility functions for the MAU value model

Each of the Space Tug design alternatives were then evaluated in terms of the MAU benefit and cost and are plotted in Figure 19. Additionally, the Pareto Efficient set of designs, which are the most benefit-cost efficient solutions, non-dominated in this two objective space, are indicated with blue triangles (flat side on bottom). Due to the nature of multi-attribute utility, design alternatives that do not meet minimum acceptable levels in any particular attribute are deemed unacceptable and are treated as infeasible. This results in a smaller set of designs to consider (here as N=83, out of the total possible of 384). The designs in the Pareto Set did not share many common features, but all had propulsion systems that were electric (type 3) or nuclear (type 4).
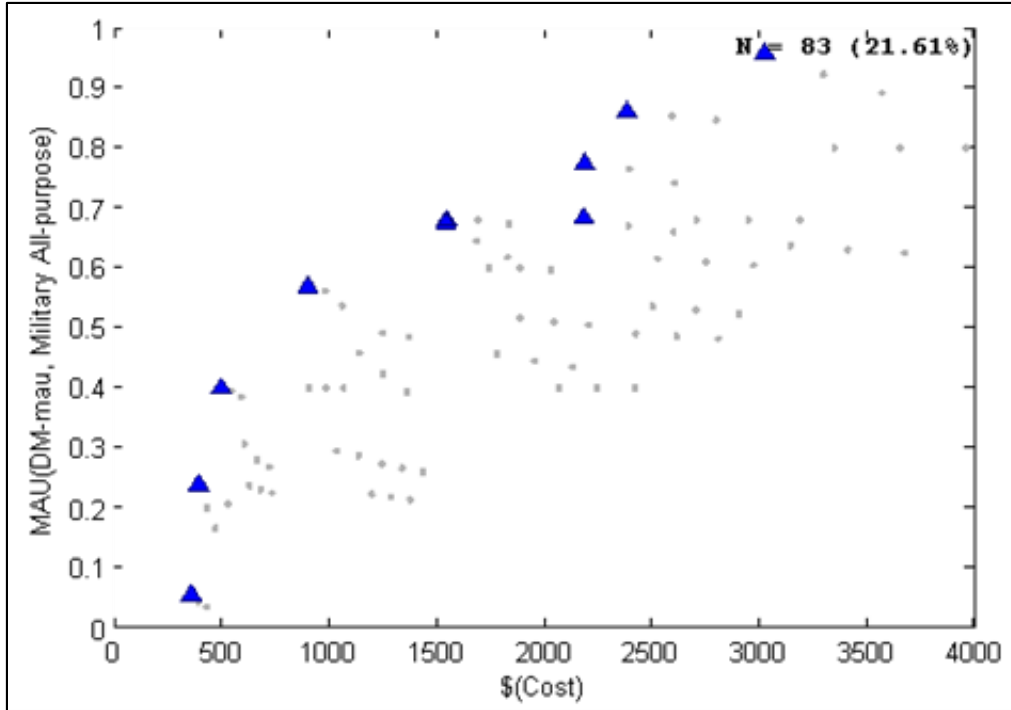
Figure 19. MAU benefit versus Cost tradespace with Pareto Efficient designs indicated

Analytic Hierarchy Process (AHP)

Analytic Hierarchy Process value model generates an aggregate measure across multiple criteria. Each of the criteria are evaluated pair-wise to determine relative value contribution. The aggregate AHP score is determined using a linear-weighted sum, where the weights are derived from the pairwise comparisons.

The equation for AHP value is as follows:

$AHP(\hat{X}) = \sum_{i=1}^{n} k_i \cdot AHP_i(X_i)$, where

$AHP_i(X_i) = \frac{(X_i - X_{i,min})}{X_{i,max} - X_{i,min}}$, if bigger is better for X_i

$AHP_i(X_i) = \frac{(X_{i,max} - X_i)}{X_{i,max} - X_{i,min}}$, if smaller is better for X_i, and the k_i weights are determined from the AHP matrix.

$k_i = \frac{\sum_{q=1}^{n} \frac{a_{i,q}}{\sum_{p=1}^{n} a_{p,q}}}{n}$, where a_{pq} is the element in row p, column q in the AHP matrix, n is the number of criteria (i.e. number of rows and columns in the matrix).

Figure 20 illustrates the pair-wise comparison matrix for the three criteria (capability, delta V, and response time), which resulted in weights of 0.4, 0.4, and 0.2 respectively.

	x(Capability)	x(DeltaV)	x(ResponseTime)
x(Capability)	1	1	2
x(DeltaV)	1	1	2
x(Response Time)	1/2	1/2	1

Higher is Better ⇒

Lower is Better ⇒

Figure 20. Matrix of weights for the AHP value model

Each of the Space Tug design alternatives were then evaluated in terms of the AHP benefit and cost and are plotted in Figure 21. Additionally, the Pareto Efficient set of designs, which are the most benefit-cost efficient solutions, non-dominated in this two objective space, are indicated with green triangles (flat side on right). Due to the nature of AHP value, no design alternatives are rejected, so the full tradespace appears feasible (N=384). The designs in the Pareto Set have no common patterns except they never have electric propulsion (type 3).

Figure 21. AHP benefit versus Cost tradespace with Pareto Efficient designs indicated

Cost-Benefit Analysis (CBA)

Cost-Benefit Analysis value model converts multiple criteria into a common currency (typically dollars) in order to simplify comparisons. In order to construct this model, one must create currency conversion functions for each of the criteria. For this case demonstration, each conversion function has three parameters, which assumes a minimum acceptable level (zero), a marginal dollar per unit of the attribute (the conversion rate), and (optionally) a diminishing returns rate (if the marginal rate decreases with an increase in attribute level). After calculating each individual criterion as a dollar figure, the aggregate is a simple sum of the three.

The equation for CBA value is as follows:

$$CBA(\hat{X}) = \sum_{i=1}^{n} CBA_i(X_i),$$
$CBA_i(X_i) = \frac{m_i}{r_i}(1 - e^{-r_i \cdot X_i})$, when $X_i >= X_{i,min}$ and
$CBA_i(X_i) = 0$, when $X_i < X_{i,min}$

Where m_i is the marginal rate of dollars per unit attribute, r_i is the (optional) diminishing return rate, and X_{min} is the minimum acceptable level (or zero point) for bigger is better functions. When there is no diminishing returns rate, CBA function is simply a linear function of $m_i X_i$. Figure 22 illustrates the three monetization functions for the three criteria (capability, delta V, and response time).
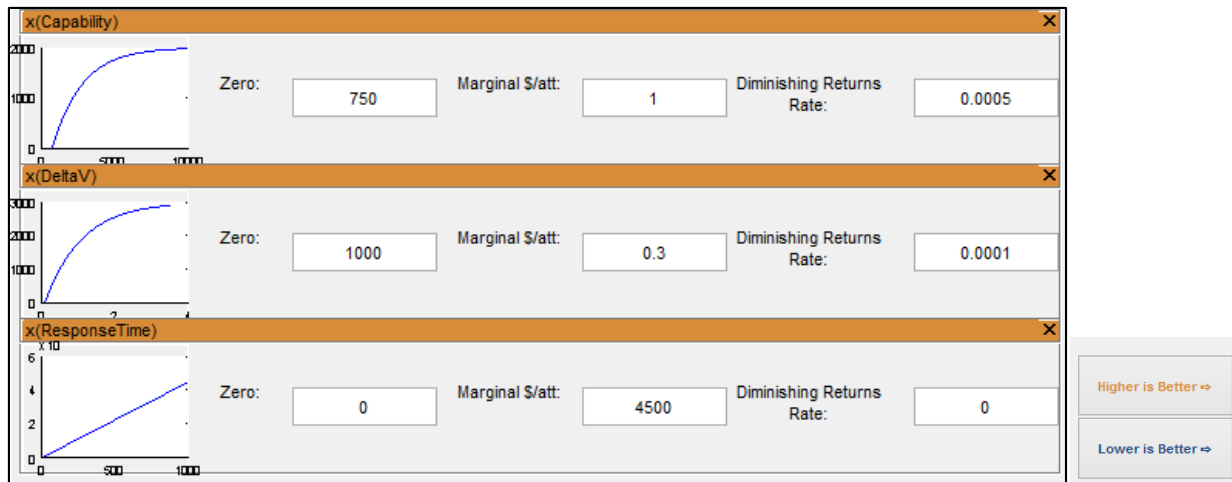
Figure 22. Attribute monetization functions for the CBA value model

Each of the Space Tug design alternatives were then evaluated in terms of the CBA benefit and cost and are plotted in Figure 23. Additionally, the Pareto Efficient set of designs, which are the most benefit-cost efficient solutions, non-dominated in this two objective space, are indicated with red triangles (flat side on left). Due to the nature of CBA value, no design alternatives are rejected, so the full tradespace appears feasible (N=384). The designs in the Pareto Set tend to have small payloads, never have electric propulsion (type 3), and otherwise vary in their design variable levels.
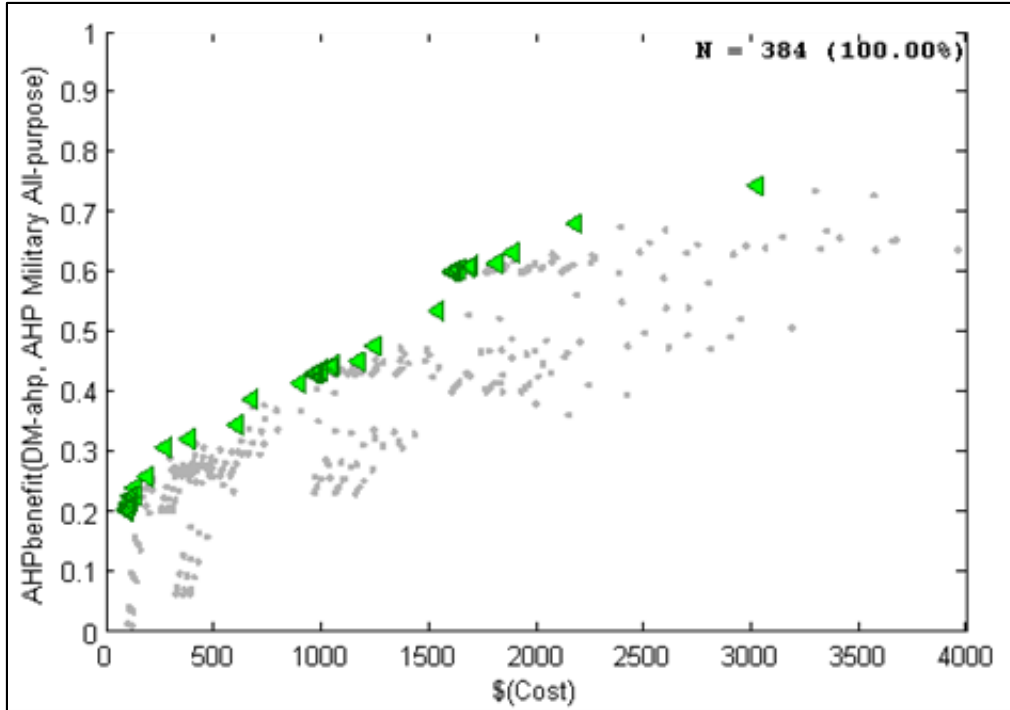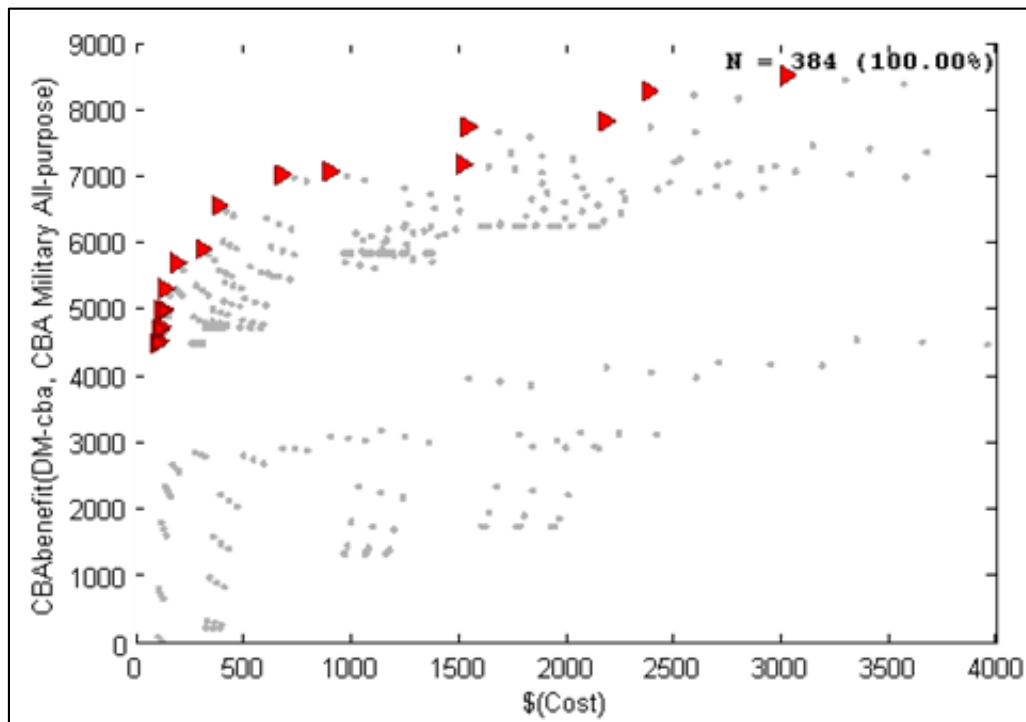

Figure 23. CBA benefit versus Cost tradespace with Pareto Efficient designs indicated

55

Measure of Effectiveness (MOE)

Delta V was used as a single dimension Measure of Effectiveness since it represents the fundamental capability for transferring target vehicles from one orbital slot to another. Each of the Space Tug design alternatives were evaluated in terms of the MOE benefit and cost and are plotted in Figure 24. Additionally, the Pareto Efficient set of designs, which are the most benefit-cost efficient solutions, non-dominated in this two objective space, are indicated with cyan triangles (flat side on top). Due to the nature of MOE value, no design alternatives are rejected, so the full tradespace appears feasible (N=384). The designs in the Pareto Set tend to have electric propulsion since this choice results in the largest delta V for a given mass spacecraft. All of the designs also have the minimum size payload, which again reduces the overall dry mass of the spacecraft, resulting in additional delta V capability for the Space Tug to impart on target spacecraft.
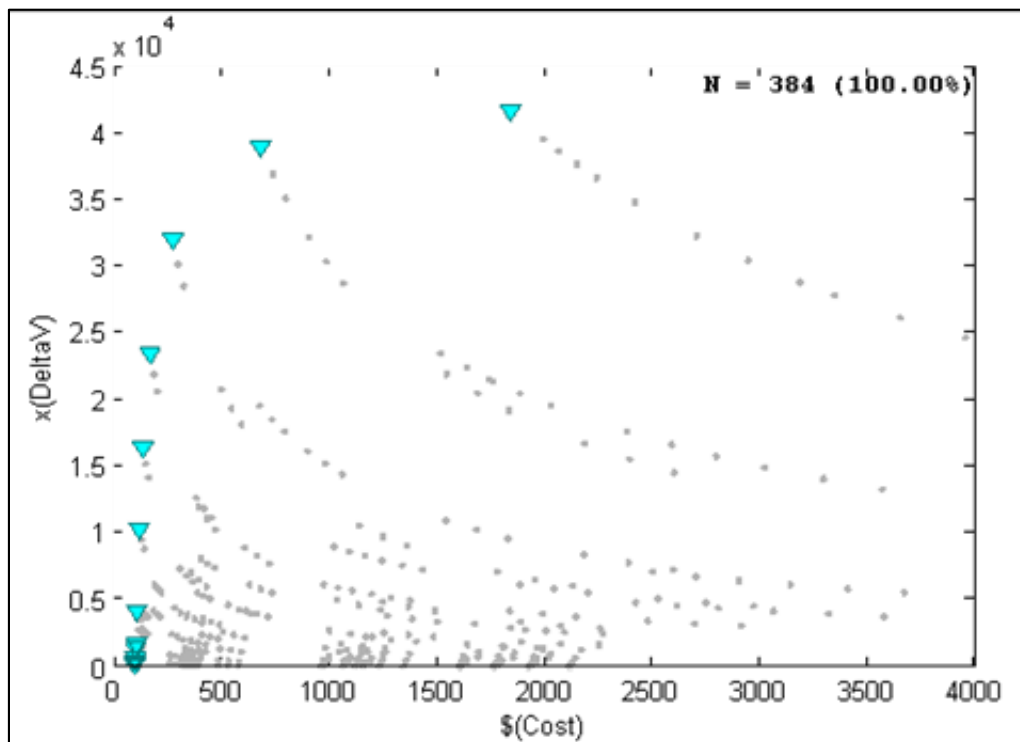
Figure 24. MOE (DeltaV) versus Cost tradespace with Pareto Efficient designs indicated

Results

Now that each of the Space Tug designs have been evaluated with each of the value models and each suggests a particular set of value efficient designs, the next step is to compare Pareto Sets across the four value models.

Comparisons via Pareto Sets

Figure 25 illustrates the symbol key for the key comparison charts to follow.

Figure 25. Key for various value model benefit versus cost Pareto Efficient sets
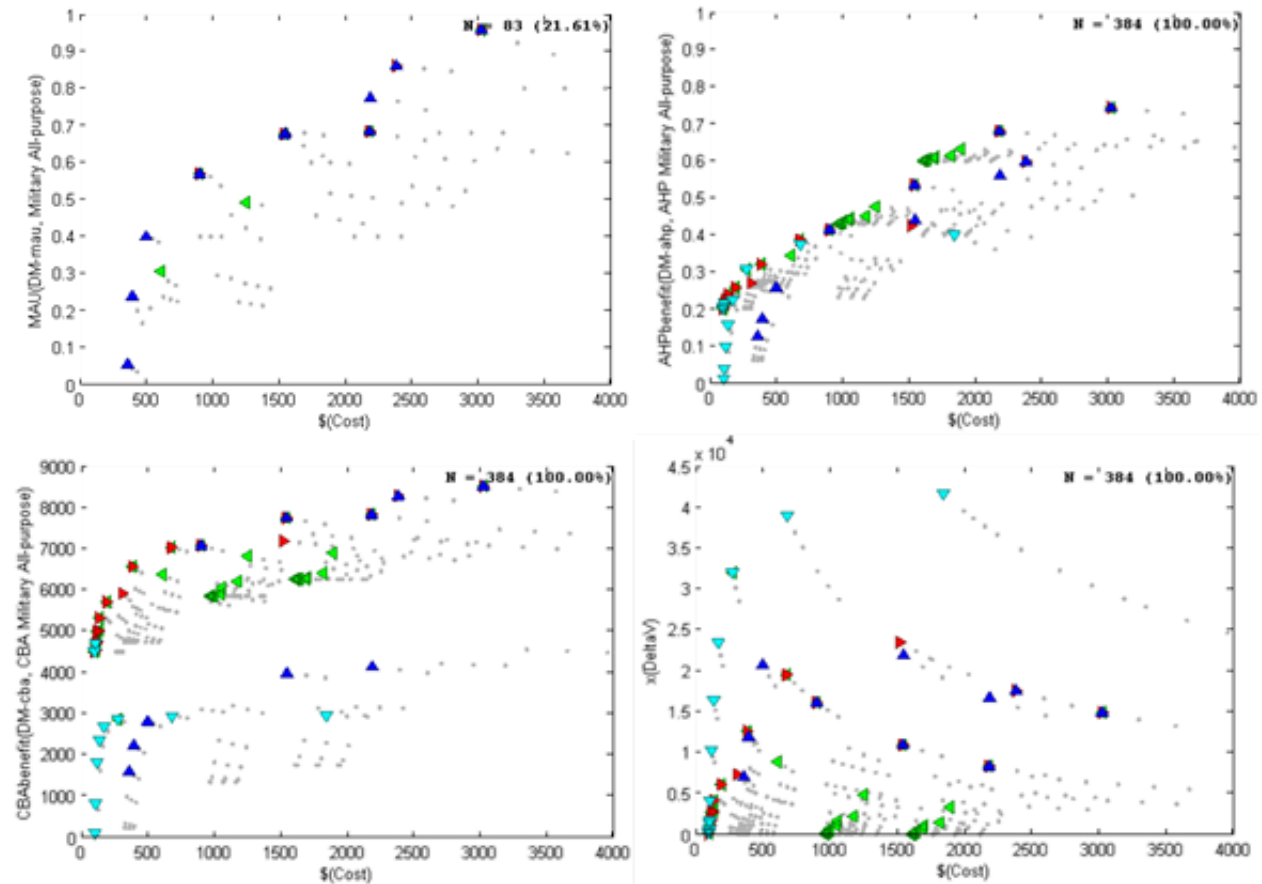
Figure 26. Comparison of four value tradespaces

Figure 26 illustrates the four perceived benefit versus cost tradespaces across the four value models, with all four Pareto sets indicated. Upon inspection, it appears that no single point appears in all four Pareto sets, but there are a few that appear in three out of four. The next step was more formal joint Pareto set analysis to determine the specifics of apparently attractive designs.

Joint Pareto Analysis

The Joint Pareto analysis entailed determining the Pareto Set for each of the four pairs of objectives (i.e. benefit and cost functions for each of the four value models). The number of valid designs, along with each Pareto Set size is indicated in Figure 27. It is important to note that there are zero "joint" designs. Here, "joint" means that the design appears in all individual Pareto Sets. Instead, there are some "compromise" designs, which are determined by

calculating the Pareto Set across the union of all objective functions. These represent efficient solutions that are non-dominated across the full set of objectives.
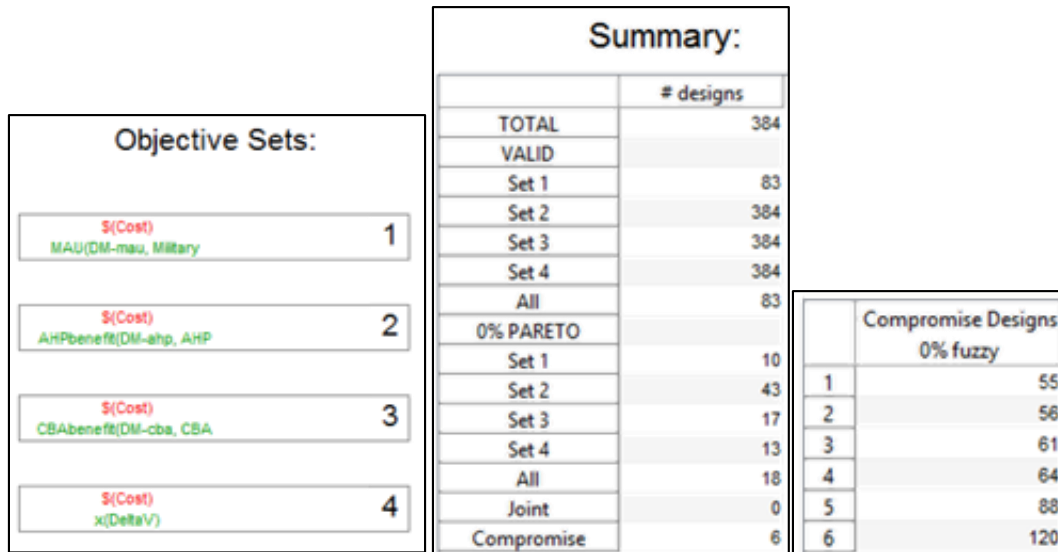
Figure 27. Joint Pareto analysis set up with four objective sets of two objectives each

Upon close inspection, we found that there are six designs that are in three out of four Pareto Sets. These are listed in Figure 28, but two of the six are invalid for the MAU value model (meaning they do not provide minimum acceptable benefit in one or more attributes).

ID Number	Pareto Efficient For	Invalid For
1	2, 3, 4	1
11	2, 3, 4	1
63	1, 2, 3	
95	1, 2, 3	
127	1, 2, 3	
128	1, 2, 3	

Figure 28. Promising designs that are joint Pareto efficient across three out of four value models

The details of the promising designs are described in Figure 29. If we do not consider designs 1 and 11, which are invalid for the MAU value model, we see a few common design choices among the remainder of the designs. They all use propulsion system type 4, and a large amount of fuel.

	1	11	63	95	127	128
$(Cost)	96.876	105.24	900	1540	2180	3020
$(Cost)	96.876	105.24	900	1540	2180	3020
$(Cost)	96.876	105.24	900	1540	2180	3020
$(Cost)	96.876	105.24	900	1540	2180	3020
$(Cost)	96.876	105.24	900	1540	2180	3020
dv(DesignforChange)	0	0	0	0	0	0
dv(DesignID)	1	11	63	95	127	128
dv(PayloadMass)	300	300	1000	3000	5000	5000
dv(PropMass)	30	300	10000	10000	10000	30000
dv(PropType)	1	2	4	4	4	4
x(Capability)	300	300	1000	3000	5000	5000
x(DeltaV)	142.608	1697.46	16149.6	10984.1	8387.01	14948.9
x(ResponseTime)	1	1	1	1	1	1
x(DeltaV)	142.608	1697.46	16149.6	10984.1	8387.01	14948.9
iv(BaseMass)	0	0	1000	1000	1000	1000
iv(DryMass)	603.6	639	5000	9000	13000	17000
iv(SpecificImpulse)	300	450	1500	1500	1500	1500
iv(MassFrac)	0.12	0.13	0.2	0.2	0.2	0.2
iv(WetMass)	633.6	939	15000	19000	23000	47000
MAU(DM-mau, Military All-purpose)	NaN	NaN	0.5692	0.67607	0.68376	0.95796
u(DM-mau, x(Capability))	NaN	NaN	0	0.7	1	1
u(DM-mau, x(DeltaV))	NaN	NaN	0.92299	0.49017	0.20941	0.89489
u(DM-mau, x(ResponseTime))	1	1	1	1	1	1
AHPbenefit(DM-ahp, AHP Military All-purpose)	0.20114	0.2161	0.4147	0.53522	0.68045	0.74358
CBAbenefit(DM-cba, CBA Military All-purpose)	4500	4702.108	7075.5553	7745.3006	7827.9318	8517.5532

Figure 29. Details on the "promising" designs

One other technique we can leverage in trying to find "robust" solutions that are insensitive to value model choice is to calculate fuzzy Pareto Efficient sets. We varied the fuzziness level and found that a single design does appear to be fully joint Pareto efficient at a fuzzy level of 7%. This means this design is within 7% of Pareto Efficiency for all four value models.
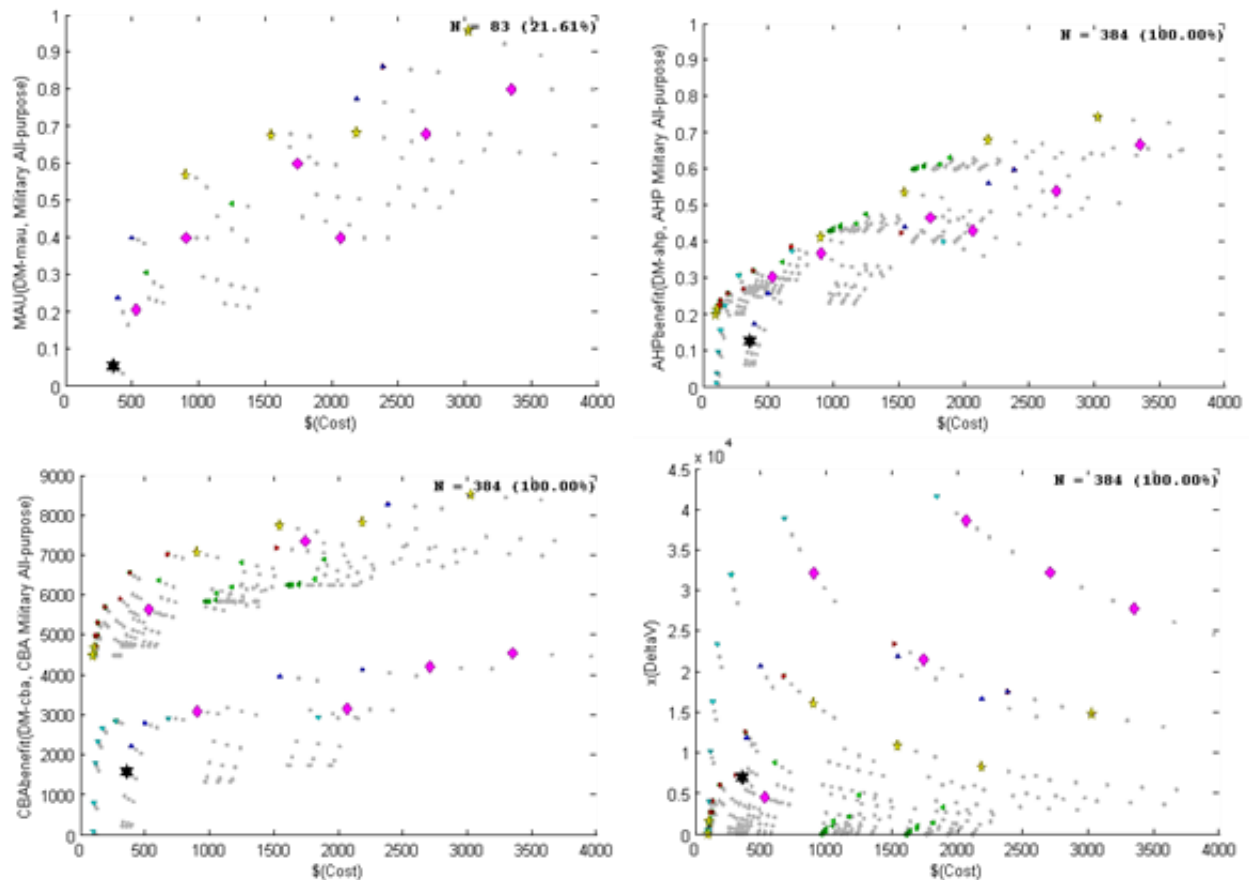
Figure 30. Comparison of benefit versus cost tradespaces with compromise, promising, and fuzzy joint designs indicated

Figure 30 illustrates the four tradespaces again, this time with the compromise (pink diamonds), promising (yellow five-pointed stars), and 7% fuzzy joint (black six-pointed star)

designs. Design 52 is the single 7% fuzzy joint Pareto design and represents the most robust choice if the decision maker is unsure of which of the four value models best captures his preferences. Interestingly this design uses electric propulsion, which was a design choice absent from the Pareto sets of AHP and CBA value models. Appealingly, this design also appears in the low cost region of all of the tradespaces.

Next Steps

This exploratory demonstration case for value modeling trading was intended to help create supporting infrastructure and processes for model trading capabilities more generally. In this sense, the case was quite successful in that it resulted in the ability to use different value model formulations within the IVTea Suite software. In Phase 2, we will continue the analysis of the value model trades in this case, along with developing a more complete framework and process for how to conduct value model trades more generally.

During research activities within IMCSE, a number of opportunities to develop supporting methods, processes, and tools have arisen. In addition to the three specific projects within the three thrusts of the IMCSE program, these MPTs will contribute to the IMCSE body of knowledge and facilitate knowledge transfer to practice. During this phase, a software suite called IVTea Suite was augmented, to facilitate the ongoing IMCSE research.

IVTEA SUITE

IVTea Suite (Interactive Value-Driven and Tradespace Exploration and Analysis Suite) is a software package developed in MATLAB® at the MIT Systems Engineering Advancement Research Initiative (SEAri). It is intended to help engineering analysts, stakeholders, and decision makers uncover insights about their systems and support value robust decision making in the face of large, uncertain problems. The software is a research support tool, and not intended for broad circulation as a final product for users.

Motivation

Development of IVTea began in 2009 under the name VisLab (Visualization Laboratory). The original vision for VisLab was to create a platform leveraging the research library of SEAri and allow for the effective reuse of data and advanced tradespace visualizations without the need to 'reinvent the wheel' for every project. Interactive software providing real-time feedback could reduce the delay between imagining questions and finding answers, thus accelerating the development of insight into the systems of interest. Additionally, the promise of a highly modular code base could enable graduate students to contribute individual 'widgets', thus rapidly and easily expanding the software's capabilities over time as new techniques were created at MIT SEAri.

During the development of VisLab 1.0, the key vision captured by the software was one of supporting epoch-centric analysis: the visualization and analysis of the different tradespaces created by varying the context and preferences under which the system operates. As SEAri research began to expand more heavily into multi-epoch and era analysis (across all uncertainty and across time-dependent sequences of uncertainty, respectively), it became apparent that VisLab would require considerable architecture upgrades in order to handle these advanced analysis types. VisLab 2.0 and subsequently IVTea 1.0 have gradually improved the architecture and user experience of the software, now supporting all of these analyses and providing a comprehensive set of perspectives from which to view the design problem.

Relationship between IVTea and IMCSE

IMCSE is intending to dramatically enhance the knowledge base and capabilities of systems engineers who interact with models. Models are a critical part of systems engineering, usually providing all or nearly-all of the data available to assist early concept design and decision making. The models are necessary because systems engineers typically work on problems for which it is infeasible to construct prototypes and simply test or benchmark data relevant to the

decisions they need to make, and thus must either collect natural data to form empirical models or generate artificial data from a theoretical model. IMCSE acknowledges this core dependence and seeks to empower systems engineers to better understand how they interact with models and leverage their strengths while respecting their weaknesses.

IVTea supports the goals of IMCSE by allowing for direct feedback between engineers and models. IVTea can run on fractional datasets and provide updates on the progress of models running in the background, in order to allow analysis to occur before the completion of all simulations which may sometimes take days, weeks, or more. IVTea also fully supports the real-time creation and modification of value models applied to the system. Multi-Attribute Utility Theory, the Analytic Hierarchy Process, Cost-Benefit Analysis, and simple Measure of Effectiveness models are all present in the IVTea architecture and can be compared side-by-side, modified, or swapped on the fly in order to understand the impact that different models of value (and their associated parameters) have on the tradespace. IVTea also features partial support, to be developed further in the future, for the tradeoffs between performance models and simulations, enabling the visualization of tradespaces at varying levels of fidelity or with different assumptions.

Capabilities of IVTea

IVTea provides visualization and analysis capabilities for the interrogation of performance and value models. The requirements to use IVTea for a case study are (1) a performance model or models (either natural or artificial) that can evaluate potential design alternatives and (2) a properly structured MySQL database populated by the input/output data of that model. The IVTea database structure has only seven mandatory tables and is easily formatted.

IVTea reads data from a specified database and displays it through the use of a variety of 'widgets'. Widgets are tools or visualizations specifically designed to perform one task, with the full set of widgets providing the complete functionality of IVTea when used together. Widgets are linked not only by the underlying database data but by locally-stored session data as well. This allows information such as favorite designs or contexts of interests to be propagated between analysis tools quickly and effectively. Session data can also be saved in a file and loaded at a later time to resume an in-progress case study without losing valuable information.

The main window of IVTea is called the Dashboard. The Dashboard is the interface for opening new widgets and managing session-level commands such as saving data or loading a new project. Figure 31 shows the Dashboard in its standard view. Each square button opens a corresponding widget, and the list on the right shows all currently open widgets, allowing for easy managements of active windows. The widget panel is tabbed, separating widgets into categories based on the type of analysis they most often support: design-centric, epoch-centric, or era-centric, in addition to data management widgets and prototype widgets. Also note the top bar which has a few key feature consistent across all widgets. Options contains a 'screenshot window' function, View allows for customization of widgets based on user type, and Help opens an interactive HTML help directory for IVTea, including screenshots and usage instructions for all of the widgets.
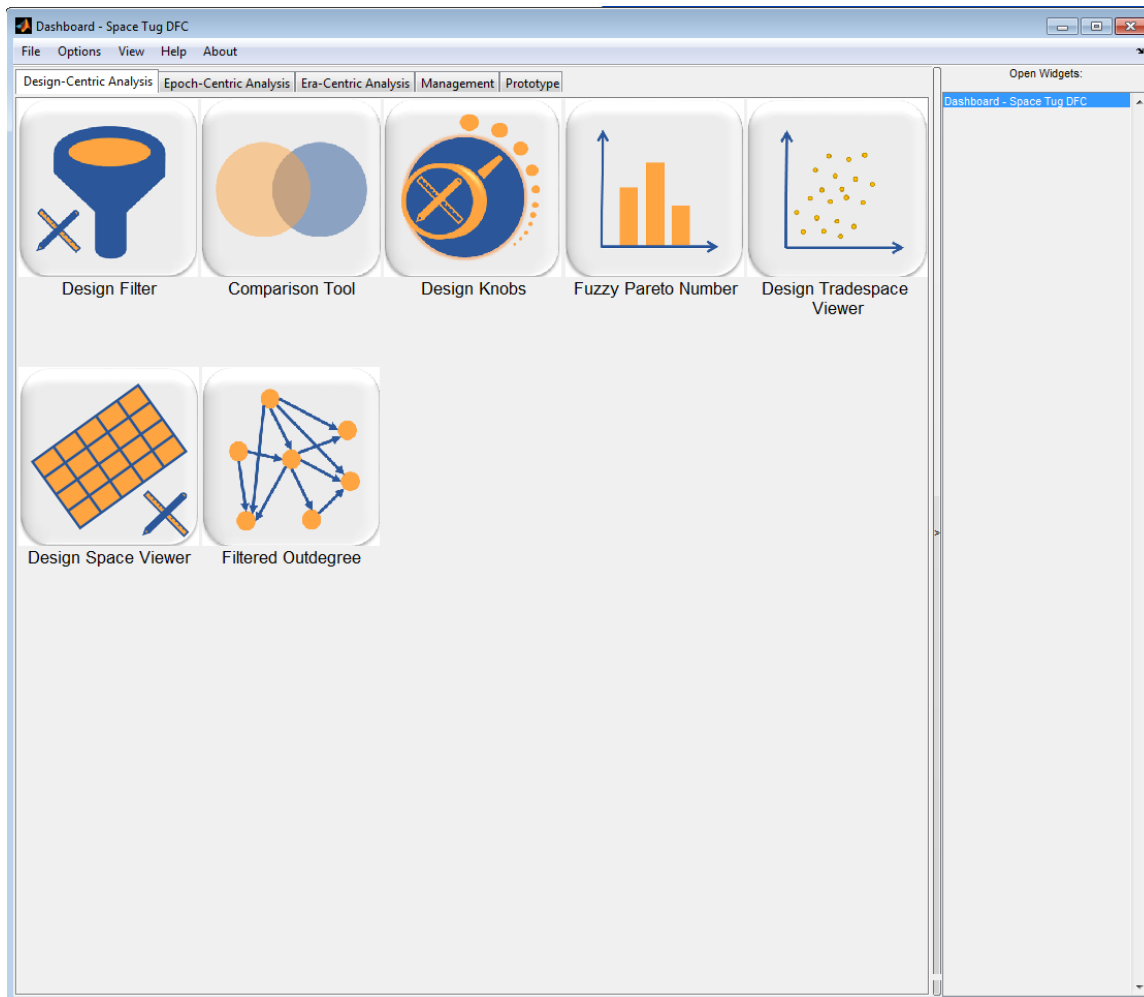
Figure 31. The IVTea Dashboard

The following is a list of the current widgets in IVTea with a brief description of their capabilities:

Epoch-Centric Analysis

Epoch-centric analysis focuses on one (or a few) epoch(s) at a time, for example looking at all designs' performances within a given epoch. The widgets in this category tend to focus on picking one or a few epochs, and then representing and helping users to analyze within that set.

- *Epoch Filter* – Find the set of epochs that obey a user-specified group of logical statements about their context.
- *Epoch Knobs* – See the defining context and preference variables of an epoch, and easily modify them to find similar epochs.
- *Tradespace Viewer* – The standard tradespace view shows all valid design alternatives for a specified epoch as points on a graph. The x, y, z, color, and size axes are all customizable to display different variables in the database. Hotkeys are available to

snap axes to the benefit/cost view of different stakeholders. The scatterplot has pan, zoom, rotate, and group brush tools, as well as the ability to right-click design points to bring up a context menu with information about that design and/or save it as a favorite. Figure 32 gives an example of this widget.
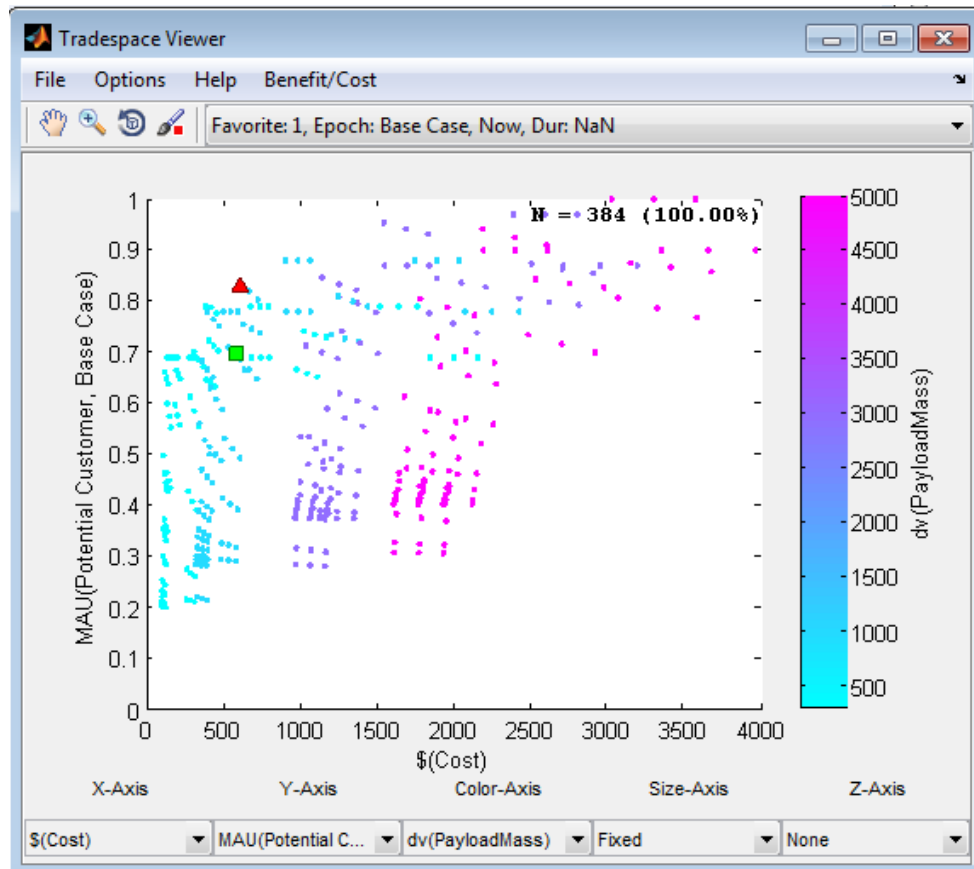
Figure 32. A tradespace with benefit/cost axes, colored by design variable, with two highlighted favorite designs

- *Context Space Viewer* – Create a grid of scatterplots and histograms showing the enumeration scheme and completeness of the context space.
- *Carpet Plot* – Create a grid of scatterplots showing the effect of each design variable (on the x-axis) against each performance attribute (on the y-axis). This view is useful for verifying intended variable interactions in the models or uncovering unexpected interaction.
- *Preference Explorer* – View the specified preferences of each active decision maker in a specified epoch. This includes capability for all of the different value models included in IVTea (MAU, AHP, CBA, and MOE), each with an accompanying interface. The preferences can be modified and stored locally, shared among the other widgets. Figure 33 gives an example of this widget.
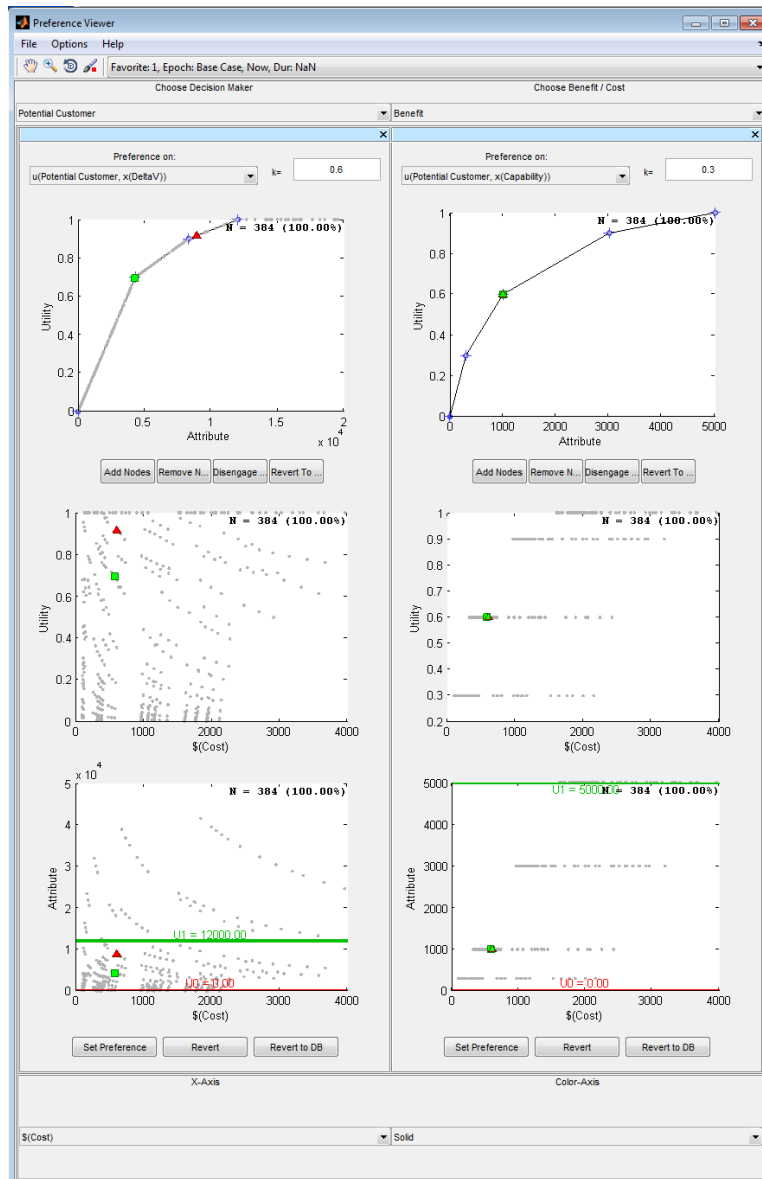
Figure 33. The preference explorer viewing two attributes of a Multi-Attribute Utility function

- *Pareto* – Specify objective sets and find the designs which are Pareto efficient across them for a given epoch. Objective sets can include any number of objectives greater than one. Pareto sets can be modified with allowances for fuzziness, can be compared to find joint- and compromise-efficient designs, and can be easily saved as favorites.
- *DV Streaks* – Shows a standard tradespace view but adds the ability to draw 'streaks' between designs that are the same except for a single, specified design variable. Streaks can be applied to manually or to favorites, and are customizable. This view shows the sensitivity of designs to perturbations in their variables.

Design-Centric Analysis

Design-centric analysis focuses on one (or a few) design(s) at a time for analysis, for example looking at how a design performs across all epochs. The widgets in this category tend to focus on picking one or a few designs, and then representing and helping users to analyze that set.

- *Design Filter* – Find the set of designs that obey a user-specified group of logical statements about their design variables. Figure 34 gives an example of this widget.
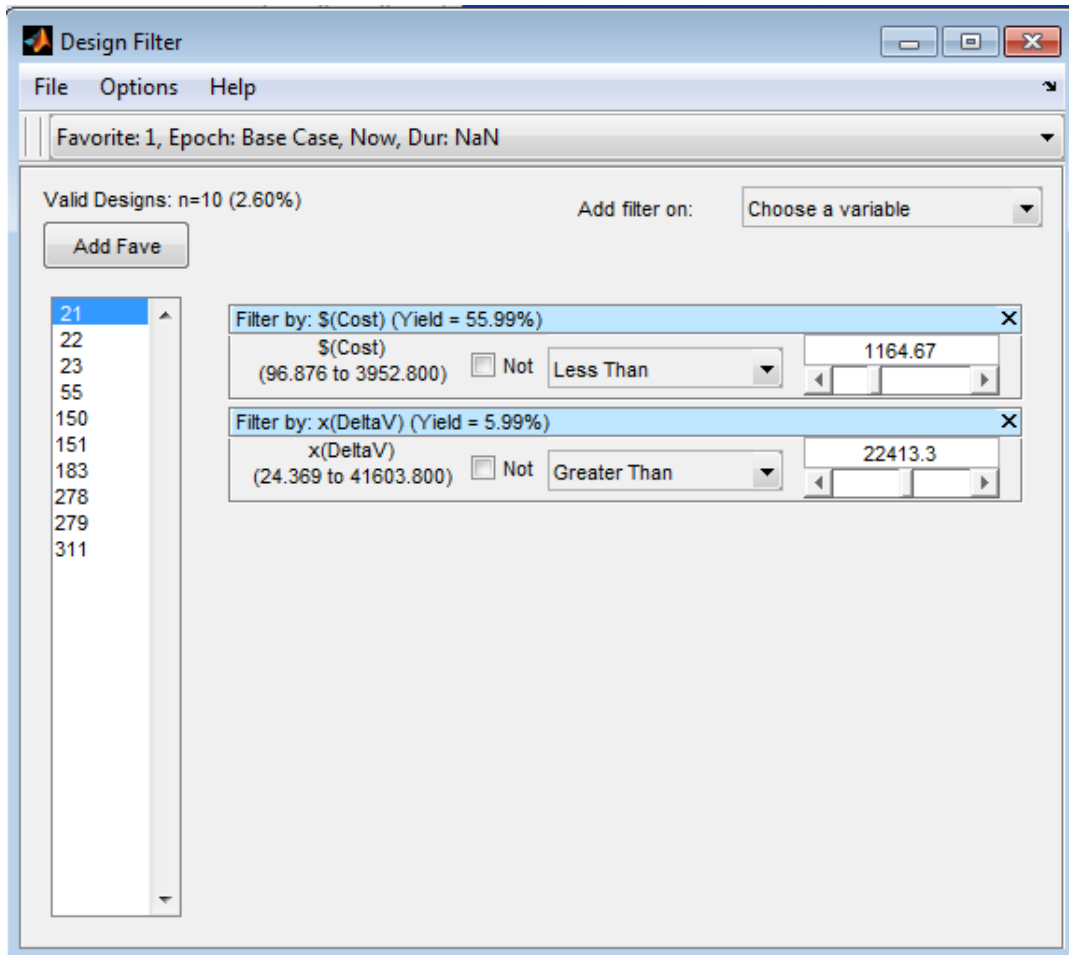
Figure 34. Two filters find ten matching designs in the Design Filter tool

- *Design Knobs* – See the defining variables of a design, and easily modify them to find similar designs.
- *Design Tradespace Viewer* – A variation on the standard tradespace that shows each epoch as a point on the graph for a single design (rather than each design as a point for a single epoch). Has the same features as the Tradespace Viewer, but is used to identify the effects of changing context on the performance of one design.
- *Design Space Viewer* – Create a grid of scatterplots and histograms showing the enumeration scheme and completeness of the design space.

- *Comparison Tool* – Place designs of interest into a table allowing side-by-side comparison of their variables and performance attributes. A baseline design can be set, coloring the other table entries based on their higher/lower relationship to the baseline. Figure 35 gives an example of this widget.

Figure 35. A comparison table comparing a design to a baseline

- *Fuzzy Pareto Number* – Show a histogram of the specified design's Fuzzy Pareto Number (a measure of cost-benefit efficiency) across all epochs. This view gives an overview of the design's performance across the complete uncertainty space.
- *Filtered Outdegree* – Plot a tradespace and color it with live calculation of Filtered Outdegree for specified designs. This illustrates differences in available change options for each design.

Era-Centric Analysis

Era-centric analysis focuses on one (or a few) era(s) at a time analysis, for example looking at all designs' performances across a given era. The widgets in this category tend to focus on picking one or a few eras, and then representing and helping users to analyze across set of eras.

- *Era Constructor* – Build an era (or eras) as a sequence of epochs for use in other widgets.

67

- *Era Viewer* – Plot the tradespaces of each epoch in an era side-by-side on consistent axes.
- *Morph* – Animate the trajectories of each design across the epochs in an era. Allows playback, looping, and frame-by-frame stepping in addition to the standard tradespace visualization options. The animation is particularly effective for helping users track both individual designs and overarching trends.

Management

Management widgets focus on organizing data across the different categories of analyses.

- *Favorites Manager* – This widget keeps track of all designs and epochs locally saved as favorites, and allows for manual entry of new favorites. Favorites can also be saved as batches. Favorites have plotting options that enable other widgets to display them with a consistent, customizable marker (size, shape, and color).
- *Notes* – A text entry field for keeping track of notes during the session. Notes are saved for the current session even if the widget is closed, and can be permanently saved as a text file.
- *Summary Dash* – Presents an overview of the status of the currently connected database. Includes totals for evaluated designs, epochs, preference sets, and others, and can be clicked to display more detail about individual database tables. A diagram view also offers a visual representation of the relationships between the tables.
- *Responsive System Comparison* – A workflow outline of SEAri's RSC method, which can provide guidance for new users on the use of tradespace exploration and the relevant widgets for each step. Figure 36 gives an example of this widget.
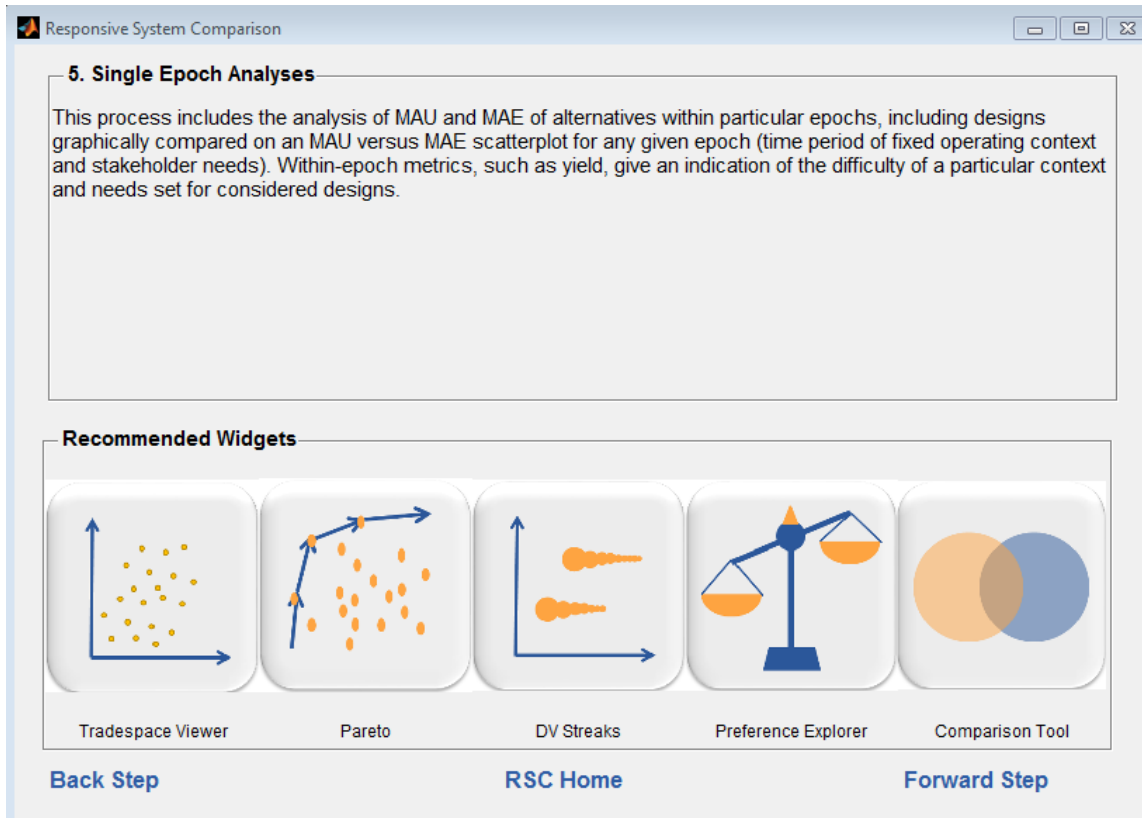
Figure 36. An example guide slide to step 5 of RSC

- *DM Creator* – Allows the insertion of new decision makers to the active database (if appropriate permission is available). New DMs are assigned to new epochs that replicate existing epochs, but with new preferences.
- *Preference Creator* – Allows the insertion of new preference sets to the active database (if appropriate permission is available). This supports all four value models and allows full customization of their parameters.

NEXT STEPS

Going forward, IVTea Suite will continue to undergo refinement of user interface, data handling, as well as development of additional widgets that support ongoing research.

APPLICATIONS

The applications thrust in this phase includes the Interactive Schedule Reduction Model project.

INTERACTIVE SCHEDULE REDUCTION MODEL

Leveraging prior work from DARPA META, the Schedule Reduction Model will be extended with interactivity as a central aspect, promoting sensitivity analyses and benchmarking to be the central use case.

INTRODUCTION

Model-based systems engineering planning environments with interactive capability hold promise for accelerating the planning process, and doing better planning. Sharon, de Weck and Dori (2009)[73] describes a model-based approach and the benefits to be gained through "what-if" interactive planning models.   A systems dynamics model prototype, developed by de Weck (Murray, et al., 2011)[74] in prior DARPA work explored the potential for an interactive project planning environment. An open area of research is to build on the prototype with exploratory extensions for planning.

Large engineering projects face continued risk of significant cost and schedule overruns despite advances in technology and management processes. Industries involving aerospace and defense systems are particularly afflicted. A recent GAO report highlights 74 instances of cost breaches in 47 of 134 major defense acquisition programs since 1997.[75] The largest factors responsible for unit cost growth include engineering and design issues, schedule issues, and quantity changes. Nearly 40 percent of cost breaches occurred after finalizing production decisions, further constraining options for project restructuring. Among other recommendations, a GAO testimony calls for early and continued systems engineering analysis to identify and intervene before significant overruns occur.[76] Increased effort to consider design alternatives and evaluate achievability of objectives during early design reviews would ensure the project meets requirements with available resources.

Proposed methods to reduce the risk of cost and schedule overruns may alter established systems engineering and project management processes. The META II Complex Systems Design and Analysis (CODA) project investigated new design techniques such as deliberate use of layers of abstraction, development and use of a component model library (C2M2L), and virtual

---

[73] Sharon, A., de Weck, O., Dori, D., "Is There a Complete Project Plan? A Model-based Planning Approach", International Council on Systems Engineering (INCOSE) Symposium, 2009.

[74] Murray, B., A. Pinto, R. Skelding, O. de Weck, H. Zhu, S. Nair, N. Shougarian, K. Sinha, S. Bopardikar, and L. Zeidner, "META II Complex Systems Design and Analysis (CODA) Final Report," AFRL-RZ-WP-TR-2011-2102, Air Force Research Laboratory, Wright-Patterson Air Force Base OH, August 2011.

[75] U.S. Government Accountability Office (GAO), "Trends in Nunn-McCurdy Breaches for Major Defense Acquisition Programs," GAO-11-295R, March 2011.

[76] U.S. Government Accountability Office (GAO), "DOD Cost Overruns: Trends in Nunn-McCurdy Breaches and Tools to Manage Weapon Systems Acquisition Costs," GAO-11-499T, March 2011.

verification and validation processes.[74] Due to the long durations and high cost of target projects, it is impossible to empirically evaluate the effectiveness of proposed changes. Instead, models of the project development cycle assess alternative management schemes. Previous work developed the Design Flow Model to illustrate potential benefits of a META-enabled design process.

This project develops the Interactive Schedule Reduction Model (ISRM) to advance knowledge and experience by exploring alternative development processes and resource allocations. Additions to the existing Design Flow Model include rapid sensitivity analysis of factors to determine potential impact on program schedule and development of a customizable and extensible browser-based interactive user interface. This report discusses initial progress towards developing the ISRM, and reviews background literature and theoretical motivation. We introduce the approach for developing the ISRM as a browser-based application, and describe initial progress to develop a JavaScript port of an existing Design Flow model. We outline the future work to complete project objectives.

BACKGROUND AND MOTIVATION

Project Complexity

Aerospace and defense engineering projects are particularly afflicted by cost and schedule overruns. This pattern has been popularized by Augustine's Law 16 which observes that aircraft unit costs increase exponentially while budgets increase linearly, leading to the seemingly-absurd case where the entire defense budget would afford just one aircraft by 2054.[77] A study of fixed-wing aircraft estimates economy-driven factors contribute only about a third of cost growth.[78] The remaining two-thirds are attributed to customer-driven factors with major contributions from complexity of performance characteristics and airframe material.

There are many descriptions and definitions of complexity in literature; however, a unifying perspective for system design relates it to uncertainty in meeting functional requirements within cost and schedule constraints due to increases in required information.[79] Sources of complexity include structural (components and interrelationships), behavioral (functional response to inputs), contextual (outside circumstances), temporal (time dynamics), and perceptual (stakeholder preferences) aspects.[80] Most efforts to quantify complexity focus on structural aspects. For example, entropy-based methods define a metric as a function of system components, their interconnections, and overall architecture.[81] In particular applications,

---

[77] Augustine, N. R., *Augustine's Laws*, Sixth Edition, 1997.

[78] Arena, M. V., O. Younossi, K. Brancato, I. Blickstein, C. A. Grammich, "Why Has the Cost of Fixed-Wing Aircraft Risen?" The RAND Corporation, 2010.

[79] Suh, N. P., "A Theory of Complexity, Periodicity and the Design Axioms," *Research in Engineering Design*, Vol. 11, No. 2, pp. 116-131, 1999.

[80] Rhodes, D. H. and A. M. Ross "Five Aspects of Engineering Complex Systems: Emerging Constructs and Methods," *4th Annual IEEE Systems Conference*, San Diego, California, April 2008.

[81] Sinha, K. and O. L. de Weck, "Structural Complexity Metric for Engineering Complex Systems and its Application," *14th International DSM Conference*, 2012.

systems with higher complexity measures can be shown to provide higher levels of performance than simpler systems if they are optimally managed.[82,83]

The downsides of complexity arise from limitations in individual and social cognition. To emphasize this distinction, consider complexity to have descriptive and perceived factors.[84] Descriptive complexity is the objective system property related to required information described above. Perceived complexity is the subjective property related to uncertainty in meeting requirements within constraints due to incomplete knowledge of required information by an observer. This work hypothesizes that perceived and descriptive complexity are correlated and constitute a tradeoff between design-efficiency and design-robustness also observed in broader systems architecting.[85] Here, design-efficiency describes the performance level of functional requirements (which may increase with descriptive complexity) and design-robustness describes the certainty in achieving those functional requirements within cost and schedule constraints (which decreases with perceived complexity).

Design studies consistently show a super-linear relationship between descriptive complexity measures and time to complete a design with fixed requirements.[86,87,88,89] Although perceived complexity cannot be observed as a hidden intermediate variable, this work hypothesizes it to be the underlying mechanism for cost and schedule overruns. Consider the illustrative example in Figure 37. The first plot shows a new project with an increase in descriptive complexity to meet higher performance requirements compared to past projects. The second plot assumes perceived complexity to be related to descriptive complexity by a monotonically-increasing function dependent on the particular system and its observers. Differences in function slope and shape, for example, distinguish between VLSI and mechanical design.[90] Finally, the third plot shows project cost and schedule to be a super-linear function of perceived complexity similar to findings of design studies.

[82] Deshmukh, A. V., J. J. Talavage, and M. M. Barash, "Complexity in Manufacturing Systems Part 1: Analysis of Static Complexity," *IIE Transactions* Vol. 30 No.7, pp. 645–655, 1998.

[83] Frizelle, G. and E. Woodcock, "Measuring complexity as an aid to developing operational Strategy," *International Journal of Operations & Production Management*, Vol. 15 No.5, pp. 26–39, 1995.

[84] Schlindwein, S. L., and R. Ison, "Human knowing and perceived complexity: Implications for systems practice," *Emergence: Complexity and Organization*, Vol. 6, No. 3, pp. 27-32, 2004.

[85] Doyle, J. C., and M. Csete, "Architecture, constraints, and behavior", Proceedings of the National Academy of Sciences of the United States of America, Vol. 108, No. Supplement 3, pp. 15624-15630, 2011.

[86] Hirschi, N. W. and D. D. Frey, "Cognition and complexity: An experiment on the effect of coupling in parameter design," *Research in Engineering Design* Vol. 13, pp. 123-131, 2002.

[87] Sinha, K. *Structural Complexity and its Implications for Design of Cyber-Physical Systems*. PhD thesis. Cambridge, Massachusetts: Massachusetts Institute of Technology, 2014.

[88] Flager, F., D. J. Gerver, and B. Kallman. "Measuring the impact of scale and coupling on solution quality for building design problems," *Design Studies* Vol. 35 No. 2, pp. 180-199, 2014.

[89] Grogan, P.T. *Interoperable Simulation Gaming for Strategic Infrastructure Systems Design*, PhD thesis. Cambridge, Massachusetts: Massachusetts Institute of Technology, 2014.

[90] Whitney, D. E., "Why Mechanical Design Cannot be like VLSI Design", *Research in Engineering Design*, Vol. 8, No. 3, pp. 125-138, 1996.
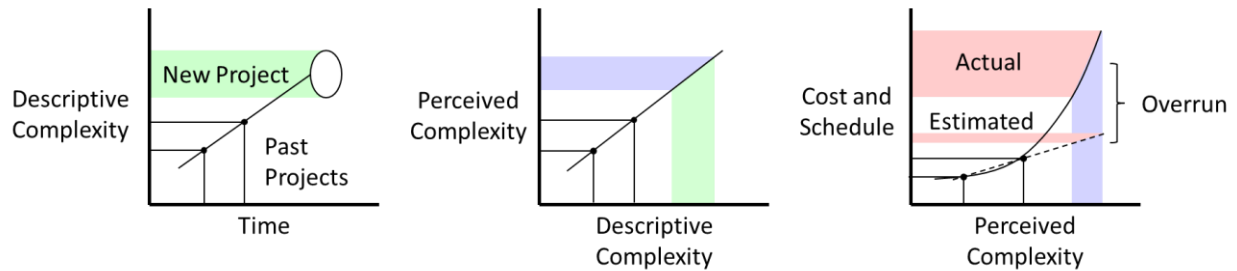
Figure 37. New projects with high descriptive and perceived complexity can lead to large overruns on cost and schedule.

There are three potential sources of cost or schedule estimation errors in this model: errors in level of descriptive complexity, errors in relating perceived and descriptive complexity, and errors in relating perceived complexity and cost and schedule. However, the third factor is the most likely to occur and has the largest impact on large engineering projects for two reasons. First, humans have difficulty in estimating geometric or exponential growth, instead using linear extrapolations in intuitive assessment which lead to gross under-estimations as shown by the overly-optimistic estimate in Figure 37.[91] Second, the super-linear growth of cost and schedule magnifies estimation errors for projects most susceptible to cost and schedule overruns.

Design Methods and Tools

There are two general approaches to address cost growth in engineering projects: decrease descriptive complexity at the cost of lower performance, or improve the ability to perceive it. This work takes the second approach by leveraging the subjective nature of perceived complexity. We hypothesize new methods and tools may reduce perceived complexity and help designers acquire the required knowledge for descriptively-complex systems. Figure 38 shows this effect by reducing perceived complexity for a given descriptive complexity. Due to the super-linear effect on cost and schedule, innovations of new design tools can produce significant cost and schedule savings.
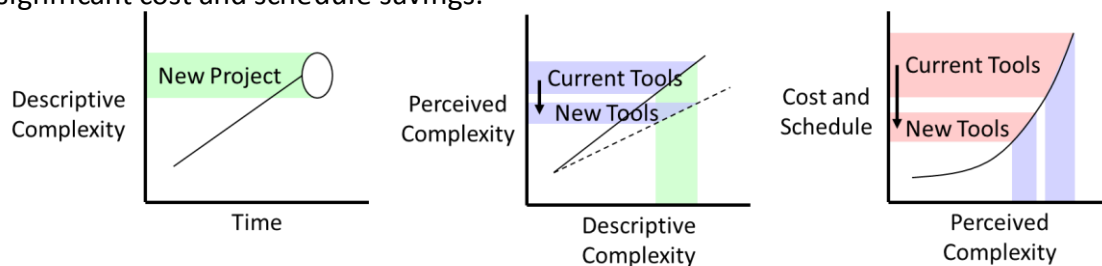
Figure 38. New design methods and tools may reduce project cost and schedule by lowering perceived complexity.

Model-based systems engineering (MBSE) applies methods and tools throughout the entire product lifecycle to replace labor-intensive, error-prone, and cumbersome document-based processes with model-based methods more suitable to support human cognition and

---

[91] Stango, V. and J. Zinman. "Exponential Growth Bias and Household Finance," *The Journal of Finance*, Vol. 64, No. 6, 2009.

collaboration. In addition to basic efficiency gains, MBSE may reduce perceived complexity of descriptively-complex systems and achieve greater cost and schedule reduction on complex engineering projects.

Design Flow Model

The DARPA META II program developed a method for complex systems design and analysis (CODA) to implement several design innovations related to MBSE.[92] First, multiple layers of abstraction allow a project to be quickly developed at a coarse level and refined during detailed design. Second, designers develop and maintain a trusted component model library to limit costly model-building and validation exercises. Finally, re-design cycles take place in virtual environments, allowing designers to rapidly evaluate concepts.

Past work developed the Design Flow Model to evaluate the feasibility of a five-fold speedup in system development under the META approach.[93] It uses the System Dynamics (SD) formalism to functionally specify stocks (accumulations) and flows (rates of change) associated with a product development cycle. Important stocks include requirements elicited, architectures explored and retained, specifications generated, tests performed, changes pending, requirements validated, and cost incurred. SD uses numerical techniques to integrate stocks as a system of differential equations in a time-stepped simulation.

Results of simulated projects show an idealistic project requires 42.25 months and $27.9M of non-recurring engineering (NRE) cost to complete. When considering rework due to change generation, however, a realistic project requires 70 months and $51.9M in NRE costs. A demonstrative META-enabled project with partial model library completion requires only 15.75 months and $31.5M in NRE costs – a speedup factor of 4.4. Most performance gains are due to early design work at higher levels of abstraction which catches problems earlier in the development cycle.

While initial results are promising, further work must determine the model's applicability to other engineering projects and evaluate the sensitivity of results to input parameters. Furthermore, as Sterman writes, "effective learning from models occurs best, and perhaps only, when decision-makers participate actively in the development of the model."[94] Interactive "what-if" planning models have been shown to provide benefits in similar project management

---

[92] Murray, B., A. Pinto, R. Skelding, O. de Weck, H. Zhu, S. Nair, N. Shougarian, K. Sinha, S. Bopardikar, and L. Zeidner, "META II Complex Systems Design and Analysis (CODA) Final Report," AFRL-RZ-WP-TR-2011-2102, Air Force Research Laboratory, Wright-Patterson Air Force Base OH, August 2011.

[93] de Weck, O. L., "Feasibility of a 5X Speedup in System Development Due to META Design," in *International Design Engineering Technical Conferences & Computers and Information in Engineering Conference*, DETC2012-70791, Chicago, IL, August 2012.

[94] Sterman, J. D., "Learning in and about complex systems," *System Dynamics Review*, Vol. 10, No. 2-3, pp. 291-330, 1994.

contexts and may be effective to allow practitioners to understand and evaluate benefits of applied MBSE efforts such as META.[95]

The Interactive Schedule Reduction Model (ISRM) extends the Design Flow Model with two new objectives. First, ISRM develops new methods to rapidly generate, access, and interpret large quantities of data generated from model executions, such as those required in sensitivity analyses. Second, the existing SD model will be transformed into a browser-based tool to facilitate interaction and extension. While its current implementation in Vensim is an industry-standard SD modeling tool, it lacks key features for application customization and methods to generate and visualize large data sets across many model executions. Furthermore, as a commercially-licensed product, the current model itself cannot easily be modified or broadly distributed. Browser-based technologies now represent some of the most innovative interactive tools and extensible models using a commonly-available platform.

APPROACH

This project develops ISRM as an interactive browser-based modeling and model exploration tool in six key steps completed under Phases 1 and 2:

Phase 1			Phase 2		
1. Develop a model API	2. Port existing model to JavaScript	3. Develop a model UI	4. Develop a multi-model API	5. Develop the multi-model backend	6. Develop a multi-model UI

Phase 1 Approach

Phase 1 develops a browser-based ISRM tool to replicate previous results of the Design Flow Model implemented in Vensim. The resulting application allows users to redefine input parameters, run a simulation execution, and view or export numerical results.

Step 1 develops an application programming interface (API) for JavaScript-based simulation models. Unlike other programming languages such as Java, Python, and MATLAB, JavaScript is not frequently used for mathematical computing and may lack core functionality. Developing a simple API sets the groundwork for future model development. The API shall use existing libraries when possible and may identify new components specific to modeling and simulation to be developed.

Step 2 ports the existing Design Flow Model from Vensim to JavaScript using the API developed in step 1. The revised model shall provide easy modification of input parameters, customization, and integration with user interfaces in step 3. Once complete, outputs from the

---

[95] Sharon, A., O. L. de Weck, and D. Dori, "Is There a Complete Project Plan? A Model-based Project Planning Approach," in *Nineteenth Annual International Symposium of the International Council on Systems Engineering (INCOSE)*, Singapore, 2009.

ported model shall be cross-validated against existing model outputs under a variety of inputs to verify correctness.

Step 3 develops a user interface (UI) to allow interactive model exploration in a browser environment. This step gives a user control over model execution and provides graphical interfaces for visualizing model structure and data outputs. In addition to visual displays, it shall provide data export for further post-processing.

Phase 2 Approach

Phase 2 investigates rapid sensitivity analysis of various factors to determine their potential impact on project schedule. This phase develops an application which allows users to specify ranges of input parameters to be considered. The application processes necessary model executions to generate and store required outputs. Once complete, the user visualizes and exports results of the requested analysis. Phase 2 requires a different architecture from Phase 1 to avoid long delays between requests and results which may include hundreds or thousands of model executions.

Step 4 develops a multi-model API to aggregate and interpret results across many model executions. It defines how to configure, execute, store, and access results from model executions. It may rely on service-oriented architectures to make high-performance model execution or access to a large database of past execution results accessible to clients.

Step 5 develops the backend components to interact with the API in step 4. It may include a server-side model for rapid execution and databases for storing and caching results. For sensitive projects, server functionality can be included on a protected local network or as a separate service on a client machine. New metrics may be developed to aggregate time-stepped result outputs to key figures of interest.

Finally, step 6 develops a new UI to allow uses to interact with multi-model data in a client-side browser. New visualization and data visualization techniques shall be created to show and interpret large quantities of information and support model execution under conditions of interest.

INITIAL PROGRESS

This section documents Phase 1 progress towards the ISRM completing steps 1-3 above.

JavaScript Model API

There are a few existing modeling tools available to web platforms such as JavaScript. Forio Simulate is a commercial web-based service addressing many of the same goals of this project; however it is closed-source and proprietary.[96] Insight Maker is a similar open web-based modeling tool.[97] Rather than providing a general-purpose library, however, Insight Maker is an

---

[96] Forio Simulate, http://forio.com/simulate, accessed 22-Sept 2014.
[97] Insight Maker, http://insightmaker.com, accessed 22-Sept 2014.

integrated graphical tool which limits model extension and use for other purposes. SIM.JS is a JavaScript discrete event simulation library with support for important features such as random number generation but does not support the SD formalism.[98] Other mathematical computing libraries such as Numeric Javascript and Sylvester implement features such as vectors and matrixes, but do not explicitly provide numerical integrators required for the SD formalism.[99,100]

Based on limitations of existing JavaScript implementation, the model API develops a new JavaScript library (tentatively JSIM) for SD models. It uses the Backbone.js library for object-oriented class structuring and improved collection support.[101] Figure 39 shows an object class diagram for the API to port models in the SD formalism. All simulation components descend from a common `Entity` class which establishes required attributes (`id` and `name`) and methods to initialize (`init`), and advance time (`tick`/`tock`). The `tick` method pre-computes state changes to avoid order dependence which are committed in the `tock` method.
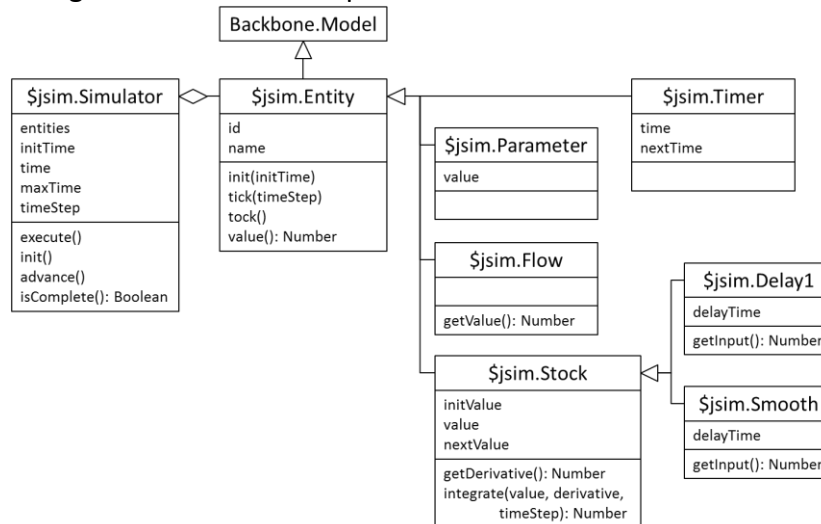
Figure 39. Object class diagram for JSIM library API supporting the System Dynamics formalism.

Several `Entity` subclasses define components within the SD formalism. The `Timer` class maintains the current simulation time. The `Parameter` class defines components with a constant value. The `Flow` class defines components with value dependent on other components, functionally defined by overriding the `getValue` method. Finally, the `Stock` class defines components with a state variable numerically integrated during a simulation with derivative specified by overriding the `getDerivative` method. The default integration technique is explicit Euler; however the `integrate` method can be overridden to implement alternative algorithms. Two additional `Stock` subclasses define specialized functions used within SD. The `Delay1` class defines a first-order exponential delay of an input signal specified

---

[98] SIM.JS, http://simjs.com, accessed 22-Sept 2014.
[99] Numeric Javascript, version 1.2.6, http://www.numericjs.com, accessed 22-Sept 2014.
[100] Sylvester: Vector and Matrix math for JavaScript, version 0.1.3, http://sylvester.jcoglan.com, accessed 22-Sept. 2014.
[101] Backbone.js, version 1.1.2, http://backbonejs.org, accessed 20-Sept 2014.

by overriding the `getInput` method. Similarly, the `Smooth` class defines an exponential smoothing of an input signal.

The `Simulator` aggregates `Entity` objects for a time-managed simulation. The `execute` method initializes (`init`) and advances (`advance`) until the `isComplete` method returns true. The `init` method initializes all entities at the specified `initTime` value and triggers an "init" event. The advance method tick/tocks all entities with the specified `timeStep` value, advances simulation time, triggers an "advance" event, and triggers a "complete" event if complete. The default `isComplete` method checks the current simulation time against the specified `maxTime` value.

Ported Design Flow Model

The Design Flow model is ported to JavaScript by defining an `Application` class which composes a `Model` and `Simulator` object as illustrated in the object class diagram in Figure 40. The `Model` class includes all required SD components to replicate the Design Flow Model including timers, flows, parameters, stocks, and exponential delay and smoothing functions.
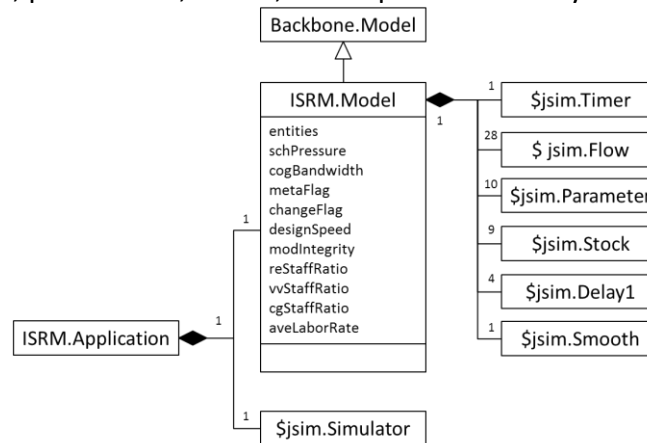
Figure 40. The ISRM Model class composes many Entity objects.

Additionally, the `Model` class includes attributes to set initial parameter values. This allows simple model parameter changes by altering the constructor. For example, two models may be defined by:

```
var metaOff = new ISRM.Model({metaFlag: 0}); // model instantiation without META

var metaOn = new ISRM.Model({metaFlag: 1}); // model instantiation with META
```

Results from the original Vensim Design Flow Model and the new JavaScript ported model are cross-validated by comparing outputs at each time step under several inputs. Numerical outputs are identical between the two models for the no-META condition. Under the META condition differences are observed in intermediate time periods for some variables, possibly due to undocumented implementation details for nested functions in Vensim. Despite transient differences, the overall impact on final simulation values is negligible (< 0.03% difference for all variables). Additional validation should identify the exact implementation of nested functions in Vensim to resolve discrepancies.

78

JavaScript Model UI

The model user interface (UI) uses a combination of HTML and CSS to structure and style a web page and JavaScript for behaviors such as plotting, click-and-dragging, and data toggling in a standard browser environment. Figure 41 shows a screen capture of the UI. The top section controls simulations, the middle section plots data, and the bottom section visualizes the stock-and-flow model.
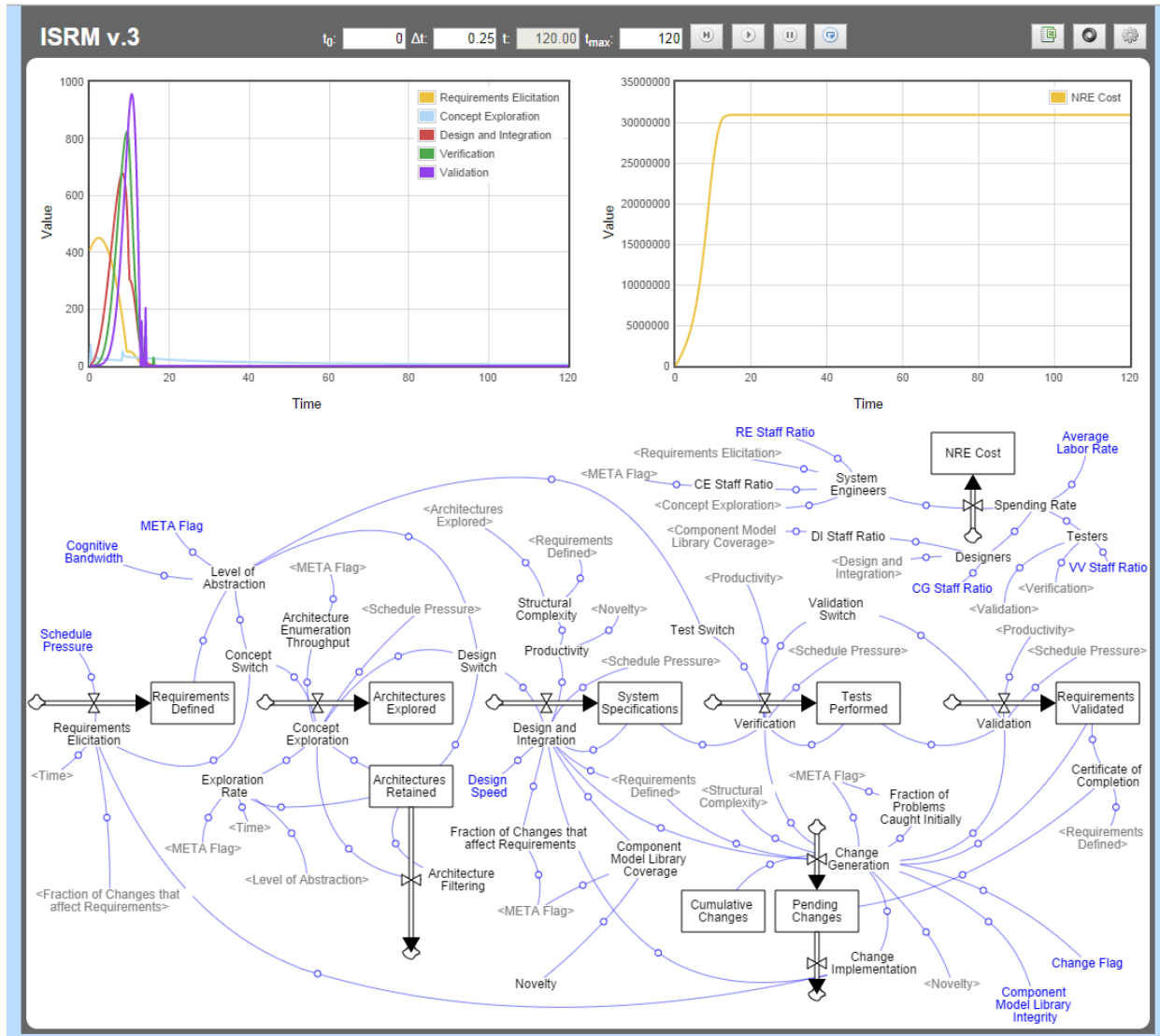
Figure 41. Screen capture of the ISRM user interface.

Several JavaScript libraries contribute to the overall UI. First, jQuery simplifies interaction with the HTML document object model (DOM) for animations, form inputs, and event handling.[102] For example, the text inputs and buttons at the top of the screen allow the user to set initial and final simulation times, time step duration, and execute, start, stop, and reset a simulation execution. Additional buttons allow data export to CSV and JSON file formats. jQuery UI

---

[102] jQuery, version 2.0.3, http://jquery.com, accessed 22-Sept 2014.

provides user interface widgets.[103] Dialog boxes edit simulation settings and provide view or edit access to individual model components including parameters, stocks, and flows.

Flot provides graphical plotting capabilities.[104] Customizable plots display or more data series during a simulation execution. The plots can be updated in simulation time; however, the animation process is resource-intensive and requires about 18 seconds per 120-month execution with 0.25-month time steps on a desktop computer with the Google Chrome browser. Alternatively, plots can be configured to update only at the end of the simulation to achieve a 10-fold simulation speedup (about 1.5 seconds per execution).

Finally, kinetic.js provides an improved object-oriented canvas environment.[105] The canvas element replicates the stock-and-flow diagram from the original Design Flow Model. Users click and drag stocks (rectangles), flows (black labels), parameters (blue labels), and shadow variables (gray labels) to move on the interface. Double-clicking any field opens a dialog to edit parameter values, view flow values, view/edit stock values, and toggle plotting.

Limitations

The current ISRM application is limited by only allowing users to change input parameters for a fixed model structure. Input parameters are most effective to toggle flags such as META features or change generation. They can also customize certain factors such as productivity, model library coverage and integrity, and staff efficiency. However, input parameters cannot make more sophisticated changes to the model behavior to alter original assumptions.

There are a number of assumptions of the original Design Flow Model which may limit its applicability to broader engineering projects. For example, it does not enforce staffing level constraints for design processes. It also assumes a ramp-up profile for initial requirements elicitation, implications of complexity for design productivity, and mechanics of change generation. Changing these assumptions requires a new model-building activity rather than the current model-using activity.

While the JavaScript API is particularly amenable to overriding existing definitions, it requires a certain level of familiarity with programming and the JavaScript language. Furthermore, the existing UI only displays a fixed model structure and cannot automatically generate new diagrams. Adding model-building activities to the ISRM would require a significant software development effort equivalent to creating a tool such as Vensim or Insight Maker and is considered out-of-scope at this time.

NEXT STEPS

Next steps include improvements to the Phase 1 ISRM application and completion of the Phase 2 application for rapid sensitivity analysis of model results.

---

[103] jQuery UI, version 1.10.3, http://jqueryui.com, accessed 22-Sept 2014.
[104] Flot, version 0.8.1, http://flotcharts.org, accessed 22-Sept 2014.
[105] Kinetic.js, version 5.1.0, http://www.kineticjs.com, accessed 22-Sept 2014.

Initial use of the ISRM Phase 1 application identified several potential improvements. A new alternative model view will add UI widgets to edit key parameters of interest. For example, switch widgets toggle META or change generation flags and slider widgets modify other numeric parameters such as schedule pressure, component model library integrity, and novelty. Improved UI dialogs will add more descriptive information including model assumptions and documentation of underlying equations. Finally, new parameters will be introduced to more easily adapt the model to new contexts without editing model behaviors specified in flow variables.

Future work will also evaluate model performance to meet needs. Current model execution takes about 1.5 seconds on desktop computers. If this performance is insufficient for Phase 2 applications, linear algebra or vector math libraries (such as Sylvester or Numeric.js discussed previously) may help parallelize numeric integration and achieve performance improvements. Phase 2 will also consider server-side JavaScript execution to supplement client-side execution to parallelize model simulation.

Phase 2 development activities described in Section 3 will explore and evaluate technologies to generate and interpret large datasets generated from multiple model executions. A data storage mechanism will be crucial to avoid rerunning time-consuming model executions. Non-relational databases will be evaluated to avoid predefined schemas. Communication between a client and server will use an asynchronous JavaScript and XML (AJAX) method with the representational state transfer (REST) architectural style for web services.

Finally, analysis conducted under Phase 2 will use the new application to understand the sensitivity of ISRM results to various input parameters. Initial studies will focus on existing application cases developed for the initial Design Flow Model. Past sensitivity analysis was limited to three input parameters levels due to time constraints, however improvements will evaluate greater numbers of levels for each parameter of interest and consider interaction effects between parameters. Results will demonstrate the capabilities of the ISRM including innovative visualization techniques to interpret large datasets generated across many model executions.

- The research team will be using knowledge and information gained in Phase 1 to focus ongoing efforts in Phase 2 to further explore the identified IMCSE-related considerations within four key areas, and the challenges and opportunities at their intersection.
- The pathfinder workshop plan will be finalized and the workshop will be scheduled. The workshop will be held and a workshop report will be published and released to elicit comments and recommendations. Approaches to creating a broader collaboratively-derived research agenda have been identified, and will be used to design the next steps in building a community for IMCSE research.
- A first prototype for interactive Epoch-Era Analysis will be completed and tested with a case application, along with preliminary supporting infrastructure, which will then be used to inform the design of a next version prototype. Specific next steps are described on page 47.
- The team will continue analysis of the value model trades in the demonstration case, along with developing a more complete framework and process for how to conduct value model trades more generally. Specific next steps are described on page 60.
- The IVTea Suite will continue to undergo refinement of user interface, data handling, as well as development of additional widgets that support ongoing research. Specific next steps are described on page 69.
- The extended interactive schedule reduction model prototype will be completed and made available for user testing. Specific next steps are described on page 80.
- The research team will use the results of Phase 1 to develop several publishable papers for the CSER 2015.

TRANSITION OBJECTIVES

An imperative for SERC research teams is the effective transition of research to practice, including transfer of new knowledge, research findings, and new MPTs to members of the community of interest. In Phase 1, we have developed our initial plan toward this objective. The plan includes identifying and working with transfer partners and research collaboration partners. Included in our evolving plan are the following objectives:

- IMCSE research on current state of the art and practice will be shared among participants in a planned workshop to be held in Phase 2, and in subsequent exchanges extending from this workshop via teleconferences and meetings. Workshop attendees will be asked to identify ways in which the community of interest can be extended.
- The Pathfinder Project Report will synthesize the findings on current art and practice, and define a way forward to build a community of researchers. This report will be issued at the end of Phase 2, and a review/comment period will follow release of the report.
- During Phase 2, the research team will develop the expanded list of individuals and organizations to be contacted for inputs for the activity of developing a collaboratively-derived research agenda. A working paper will be developed during Phase 2 to capture the approach and lessons learned in creating this agenda, as well as the results of this activity. A journal submission will subsequently be prepared from the working paper.
- Results of the Interactive Schedule Reduction Model (project 2) and Interactive Epoch-Era Analysis (project 3) will be shared with the broader SERC community, in selected meetings and workshops, such as INCOSE IW15 and CSER 2015. A paper on each of these projects will be submitted to CSER 2015.
- At the end of Phase 2, an initial demonstration prototype of the interactive Epoch-Era Analysis will be made available to elicit feedback. A plan will be developed to further define transition of the prototype for user testing. At the end of Phase 2, a version of the interactive schedule reduction model prototype will be made available for user testing. During Phase 2, a webpage will be created to provide easy access to prototypes, guidance documentation and other related documents.
- Throughout the effort, synergies with other SERC tasks will be identified and leveraged to transition/implement resulting capabilities of this project, as well as to provide relevant information to impact the work of other researchers.

CONCLUSIONS

The research team has now completed the Phase 1 effort, taking place over a four month period. The activities within the three thrusts – foundations, fundamentals, and applications – are on-track for the overall goals of this year's research, and readiness to move into Phase 2 has been achieved. The research team has discovered project-specific challenges and opportunities in the broader literature and community of interest. Some continued divergent investigation is still necessary, and by the end of Phase 2 the team expects to have converged on research themes and questions. The pathfinder workshop will play an important role in this convergence, and will result in a workshop report aimed to inform and to elicit additional inputs. The research team expects to continue its efforts in Phase 2 to complete the development of a user-testing prototype for the Interactive Schedule Reduction Model. The Interactive Epoch-Era Analysis activity is progressing according to plan, and the team expects to complete a demonstration prototype at the end of Phase 2, which will enable the team to gain specific feedback for the Phase 3 effort to result in a pilot-test version of the prototype.

REFERENCES

Arena, M. V., O. Younossi, K. Brancato, I. Blickstein, C. A. Grammich, "Why Has the Cost of Fixed-Wing Aircraft Risen?" The RAND Corporation, 2010.

Augustine, N. R., *Augustine's Laws*, Sixth Edition, 1997.

Bankes, S., "Exploratory Modeling for Policy Analysis," *Operations Research*, 4, pp: 435-449, 1993.

Beesemyer, J.C., *Empirically Characterizing Evolvability and Changeability in Engineering Systems*, Master of Science Thesis, Aeronautics and Astronautics, Massachusetts Institute of Technology, June 2012.

Brand, M., Labudda, K., Markowitsch, H. J., "Neuropsychological correlates of decisionmaking in ambiguous and risky situations," *Neural Networks*, 19(8), pp: 1266-1276, 2006.

Correa, C., Chan, Y.H., Ma, K.L., "A Framework for Uncertainty-Aware Visual Analytics," IEEE Symposium on Visual Analytics Science and Technology, pp: 51-58, 2009.

Curry, M., "Presentation: Application of Epoch Era Analysis to the Design of Engineered Resilient System," 17th NDIA Systems Engineering Conference, Springfield, VA, October, 2014.

de Weck, O. L., "Feasibility of a 5X Speedup in System Development Due to META Design," in *International Design Engineering Technical Conferences & Computers and Information in Engineering Conference*, DETC2012-70791, Chicago, IL, August 2012.

Department of Defense Architecture Framework, Systems Engineering Research Center, Final Technical Report, April 9, 2012.

Deshmukh, A. V., Talavage, J.J., Barash, M.M., "Complexity in Manufacturing Systems, Part 1: Analysis of Static Complexity," IIE Transactions, 30(7), pp: 645–655, 1998.

Doyle, J. C., Csete, M. "Architecture, constraints, and behavior," Proceedings of the National Academy of Sciences of the United States of America, Vol. 108, No. Supplement 3, pp: 15624-15630, 2011.

Feuchter, C.A., "Air Force Analyst's Handbook: On Understanding the Nature of Analysis," Office of Aerospace Studies, Air Force Materiel Command (AFMC) OAS/DR, Kirtland AFB, NM, January 2000.

Fitzgerald, M.E., Ross, A.M., and Rhodes, D.H., "A Method Using Epoch-Era Analysis to Identify Valuable Changeability in System Design," 9th Conference on Systems Engineering Research, Los Angeles, CA, April 2011.

Flager, F., D. J. Gerver, and B. Kallman. "Measuring the impact of scale and coupling on solution quality for building design problems," *Design Studies*, 35(2), pp: 180-199, 2014.

Fox, C., Tversky, A., "Ambiguity aversion and comparative ignorance." *The quarterly Journal of Economics*, 110(3), 585-603, 1995.

Frizelle, G., Woodcock, E. "Measuring complexity as an aid to developing operational Strategy," *International Journal of Operations & Production Management*, 15(5), pp: 26–39, 1995.

Gaspar, H., Rhodes, D.H., Ross, A.M., Erikstad, E.O., "Addressing Complexity Aspects in Conceptual Ship Design: A Systems Engineering Approach," *Journal of Ship Production and Design*, 28(4), pp: 145-159. November 2012.

Grogan, P.T., *Interoperable Simulation Gaming for Strategic Infrastructure Systems Design*, Doctor of Philosophy Dissertation, Massachusetts Institute of Technology, 2014.

Heer, J., Shneiderman, B., "Interactive Dynamics for Visual Analysis," ACM Queue, 2012.

Hirschi, N. W., Frey, D.D. "Cognition and complexity: An experiment on the effect of coupling in parameter design," *Research in Engineering Design,* Vol. 13, pp: 123-131, 2002.

Hooton, Christopher. "Scottish Independence Referendum Leads to Surge in Sales of Braveheart." *The Independent* [London] 25 Sept. 2014.

Huettel, S. A., Stowe, C. J., Gordon, E. M., Warner, B. T., Platt, M. L., "Neural Signatures of Economic Preferences for Risk and Ambiguity," *Neuron,* 49(5), pp: 765-775, 2006.

International Council on Systems Engineering (INCOSE), "Systems Engineering Vision 2020," (INCOSE-TP-2004-004-02), Sep 2007.

Ingram, J., "Priority research questions for the UK food system", Food Sec., 5, pp: 617-636, 2013.

Thomas, J., "*Visual Analytics: An Agenda in Response to DHS Mission Needs*," USDHS National Visualization and Analytics Center, 2007.

Keim, D., "Designing pixel-oriented visualization techniques: Theory and applications," IEEE TVCG 6, 1, pp: 59–78, 2000.

Klein, G.A., "A Recognition-Primed Decision (RPD) Model of Rapid Decision Making," *Decision making in action: Models and methods*, 5(4), pp: 138-147, December 1993.

Kolmogorov, A.N., "Combinatorial foundations of information theory and the calculus of probabilities," Russian Mathematical Surveys, 38(4), pp: 27–36, 1983.

Kwakkel, J.H.,Pruyt, E., "Exploratory Modelling and Analysis, an approach for model-based foresight under deep uncertainty," *Technological Forecasting and Social Change*, 80(3), pp: 419-431, 2012.

Lazer, D., Kenney, R., King, G., Vespignani, A. "The parable of Google Flu: traps in Big Data analysis," *Science*, 343(6176), pp: 1203-1205, 2014.

Liu, Z. Jiang, B., Heer, J., "imMens: Real-time Visual Querying of Big Data," Eurographics Conference on Visualization (EuroVis), 2013.

Madni, A., "Affordable, Adaptable and Effective: The Case for Engineered Resilient Systems," Engineering Resilient Systems Workshop, Pasadena, CA, August 2012.

Madni, A., "Integrating Humans with software and Systems, Technical Challenges and a Research Agenda," *Systems Engineering*, 13 (3), pp: 232-245, 2010.

McManus, H., Schuman, T., "Understanding the Orbital Transfer Vehicle Trade Space," AIAA Space 2003, Long Beach, CA, September 2003.

Murray, B., A. Pinto, R. Skelding, O. de Weck, H. Zhu, S. Nair, N. Shougarian, K. Sinha, S. Bopardikar, L. Zeidner, "META II Complex Systems Design and Analysis (CODA) Final Report," AFRL-RZ-WP-TR-2011-2102, Air Force Research Laboratory, Wright-Patterson Air Force Base OH, August 2011.

National Research Council, *Human-Systems Integration in the System Development Process: A New Look*, Committee on Human-System Design Support for Changing Technology, R.W. Pew and A.S. Mavor, Eds., Committee on Human Factors, Division of Behavioral and Social Sciences and Education, Washington, DC: The National Academies Press, 2007.

NDIA Systems Engineering Division, Modeling and Simulation Committee, "Final Report of the Model Based Engineering (MBE) Subcommittee," Feb 10, 2011.

Office of Aerospace Studies (OAS), "Analysis of Alternatives (AoA) Handbook: A Practical Guide to Analyses of Alternatives," Air Force Materiel Command (AFMC) OAS/A9, Kirtland AFB, NM, July 2008.

Oliver, D., Kelliher, T., Keegan, J., Engineering Complex Systems with Models and Objects, NY: McGraw-Hill, 1997.

Orellana, D. and Madni, A., "Human System Integration Ontology: Enhancing Model Based Systems Engineering to Evaluate Human-System Performance," Conference on Systems Engineering Research, Procedia Computer Science, 28, pp: 19-25, 2014.

Pike, W. A., Stasko, J., Chang, R., O'Connell, T.,A., "The science of interaction," Information Visualization, 8(4), 263-274, 2009.

Rhodes, D.H., Ross, A.M., "Anticipatory Capacity: Leveraging Model-Based Approaches to Design Systems for Dynamic Futures," 2nd Annual Conference on Model-based Systems, Haifa, Israel, March 2009.

Rhodes, D.H., Ross, A.M., "Five Aspects of Engineering Complex Systems: Emerging Constructs and Methods," 4th Annual IEEE Systems Conference, San Diego, CA, April 2010.

Ricci, N., Schaffner, M.A., Ross, A.M., Rhodes, D.H., Fitzgerald, M.E., "Exploring Stakeholder Value Models Via Interactive Visualization," 12th Conference on Systems Engineering Research, Redondo Beach, CA, March 2014.

Richards, M.G., Hastings, D.E., Rhodes, D.H., Weigel, A.L., "Defining Survivability for Engineering Systems," 5th Conference on Systems Engineering Research, Hoboken, NJ, March 2007.

Roberts, C.J., Richards, M.G., Ross, A.M., Rhodes, D.H., Hastings, D.E., "Scenario Planning in Dynamic Multi-Attribute Tradespace Exploration," 3rd Annual IEEE Systems Conference, Vancouver, Canada, March 2009.

Ross, A.M., *Managing Unarticulated Value: Changeability in Multi-Attribute Tradespace Exploration*, Doctor of Philosophy Dissertation, Engineering Systems Division, Massachusetts Institute of Technology, June 2006.

Ross, A.M., D.H. Rhodes, "Using Natural Value-Centric Time Scales for Conceptualizing System Timelines through Epoch-Era Analysis," INCOSE Symposium, 2008.

Ross, A.M., McManus, H.L., Long, A., Richards, M.G., Rhodes, D.H., Hastings, D.E., "Responsive Systems Comparison Method: Case Study in Assessing Future Designs in the Presence of Change," AIAA Space 2008, San Diego, CA, September 2008.

Ross, A.M., McManus, H.L., Rhodes, D.H., Hastings, D.E., Long, A.M., "Responsive Systems Comparison Method: Dynamic Insights into Designing a Satellite Radar System," AIAA Space 2009, Pasadena, CA, September 2009.

Ross, A.M., McManus, H.L., Rhodes, D.H., Hastings, D.E., "A Role for Interactive Tradespace Exploration in Multi-Stakeholder Negotiations," AIAA Space 2010, Anaheim, CA, September 2010.

Ross, A.M., O'Neill, M.G., Hastings, D.E., Rhodes, D.H., "Aligning Perspectives and Methods for Value-Driven Design," AIAA Space 2010, Anaheim, CA, September 2010.

Ross, A.M., "Interactive Model-Centric Systems Engineering," Presentation to the 5th Annual SERC Sponsor Research Review, Georgetown University, Washington, DC, February 2014.

Schaffner, M.A., *Designing Systems for Many Possible Futures: The RSC-based Method for Affordable Concept Selection (RMACS), with Multi-Era Analysis*, Master of Science Thesis, Aeronautics and Astronautics, Massachusetts Institute of Technology, June 2014.

Schaffner, M.A., Wu, M.S., Ross, A.M., Rhodes, D.H., "Enabling Design for Affordability: An Epoch-Era Analysis Approach," Proceedings of the 10th Annual Acquisition Research Symposium-Acquisition Management, April 2013.

Schlindwein, S. L., R. Ison, "Human knowing and perceived complexity: Implications for systems practice," *Emergence: Complexity and Organization*, 6(3), pp: 27-32, 2004.

SERC-2009-TR-003, Cloutier, R. and Mostashari, A., Investigation of a Graphical CONOPS Development Environment for Agile Systems Engineering, Systems Engineering Research Center, Final Technical Report, October 30, 2009

SERC-2010-TR-009-1, Boehm, B., System 2020 – Strategic Initiative, Systems Engineering Research Center, Final Technical Report, August 26, 2010.

SERC-2012-TR-024, zur Muehlen,M., Integration of M&S (Modeling and Simulation, Software Design and DoDAF, RT 24, Systems Engineering Research Center (SERC), April 9, 2012

SERC-2012-TR-031, Cloutier, R., Graphical CONOPS prototype to demonstrate emerging methods, processes and tools at ARDEC, Systems Engineering Research Center, Final Technical Report, March 23, 2012

SERC-2013-TR-031-2, Cloutier, R., Graphical CONOPS prototype to demonstrate emerging methods, processes and tools at ARDEC, Systems Engineering Research Center, Final Technical Report, July 17, 2013

SERC-2013-TR-039-1, Boehm, B., Tradespace and Affordability, Systems Engineering Research Center

SERC-2013-TR-039-2 Boehm, B. Tradespace and Affordability, Systems Engineering Research Center

SERC-2014-TR-044, Blackburn, M., Transforming Systems Engineering through Model Based Systems Engineering, Technical Report, Systems Engineering Research Center (SERC), March 31, 2014

Sharon, A., O. L. de Weck, D. Dori, "Is There a Complete Project Plan? A Model-based Project Planning Approach," Nineteenth Annual International Symposium, International Council on Systems Engineering (INCOSE), Singapore, 2009.

Simon, H., "The architecture of complexity," *Proceedings of the American Philosophical Society*, 106(6), pp: 467– 482, 1962.

Sinha, K. and O. L. de Weck, "Structural Complexity Metric for Engineering Complex Systems and its Application," *14th International DSM Conference*, 2012.

Sinha, K., *Structural Complexity and its Implications for Design of Cyber-Physical Systems*, Doctor of Philosophy Dissertation, Massachusetts Institute of Technology, 2014.

Sitterle, V., Curry, M., Ender, T., Freeman, D., "Integrated Toolset and Workflow for Tradespace Analytics in Systems," INCOSE International Symposium, Las Vegas, NV, 2014.

Stango, V., J. Zinman, "Exponential Growth Bias and Household Finance," *The Journal of Finance*, 64(6), 2009.

Sterman, J. D., "Learning in and about complex systems," *System Dynamics Review*, 10(2-3), pp: 291-330, 1994.

Suh, N. P., "A Theory of Complexity, Periodicity and the Design Axioms," *Research in Engineering Design*, 11(2), pp: 116-131, 1999.

Suh, N. P., *Complexity—Theory and Applications*, Oxford University Press, Oxford, UK, 2005.

Sutherland, W. J., Fleishman, E., Mascia, M. B., Pretty, J. Rudd, M. A., "Methods for collaboratively identifying research priorities and emerging issues in science and policy," *Methods in Ecology and Evolution*, 2, pp: 238–247, 2011.

Sutherland, W., et al., "A Collaboratively-Derived Science-Policy research agenda," *PLoS ONE*, 7(3), March 2012.

Tversky, A., Kahneman, D., "Judgement under uncertainty: Heuristics and biases," *Sciences,* 185(4157), pp: 1124–1131, 1974.

U.S. Government Accountability Office (GAO), "DOD Cost Overruns: Trends in Nunn-McCurdy Breaches and Tools to Manage Weapon Systems Acquisition Costs," GAO-11-499T, March 2011.

U.S. Government Accountability Office (GAO), "Trends in Nunn-McCurdy Breaches for Major Defense Acquisition Programs," GAO-11-295R, March 2011.

Vitiello, P., Kalawsky, R.S., "Visual analytics: A sensemaking framework for systems thinking in systems engineering," IEEE International Systems Conference (SysCon), 2012.

Whitney, D. E., "Why Mechanical Design Cannot be like VLSI Design", *Research in Engineering Design*, 8(3), pp: 125-138, 1996.

Wilson, T.D., Gilbert, D.T., "Affective Forecasting". *Advances in Experimental Social Psychology*, 35, pp: 345–411, 2003.

Yan, X., Qiao, M., Li, J., Simpson, T.W., Stump, G.M., Zhang, X., "A Work-Centered Visual Analytics Model to Support Engineering Design with Interactive Visualization and Data-Mining," Hawaii International Conference on Systems Science (HICSS), pp: 1845-1854, January 2012.

Zimmerman, P., "A Review of Model-Based Systems Engineering Practices and Recommendations for Future Directions in the Department of Defense," 2nd Systems Engineering in the Washington Metropolitan Area (SEDC 2014) Conference, Chantilly, VA, April 3, 2014.

APPENDIX A

This appendix includes a short summary of selected relevant prior SERC projects we have identified that inform this work. The research team is in the process of identifying points of connection with other SERC projects.

Graphical Concepts. In related prior SERC research the vision, feasibility assessment and initial process for a Graphical CONOPS development environment for agile systems engineering was developed (SERC-2009-TR-003[106]). This research investigated current approaches to Concept of Operations (CONOPS) development in use in various DoD and commercial organizations with the goal of understanding why CONOPS creation is such a lengthy process, and how the process can be made more agile. Based on findings, an agile CONOPS process that emphasizes stakeholder involvement and expedites shared mental models development is put forth by the team. An initial prototype was developed toward a concept engineering software demonstrator that enabled soldiers to develop a limited set of scenarios centered on squad operations (SERC-2012-TR-030[107]). The prototype was then extended as 3D virtual guide intended to assist one assigned to CONOPS development, through the setup of a combat scenario and the use of the Integrated CONOPS Environment Framework (ICEF). This research (SERC-2013-TR-031-2[108]) demonstrated that it is possible to utilize the strength of a 3D game development environment to create a graphical CONOPS creation tool that is easy for a soldier to use.

Defense Architecture Framework. Different Department of Defense communities prepare models for architecture compliance (e.g., to maintain JCIDS requirements), for simulation purposes (e.g., for performance estimates) and software engineering (e.g, for model-based code generation). Little, if any, information transfer and model reuse takes place across these communities of interest, which leads to redundant efforts, models that are out of sync, and lost domain knowledge. Differences in methods, tools, and data formats are a major reason for this disconnect. The charter of RT-24 was to investigate mechanisms that could help bridge the divide between the modeling & simulation, software engineering, and enterprise architecture modeling communities[109].

System 2020 Strategic Initiative. Systems 2020 is the research effort to answer a ajor portion of the challenge embodied in the DoD's science and technology priority for Engineered Resilient Systems (ERS). As a follow-on to the SERC's work in defining technical approaches for Systems 2020, DASD(SE) requested the SERC to work on two tasks. Task 1 involved working with Government research and engineering centers, and laboratories to characterize the design and systems engineering (SE) tools available to DoD projects, along with their potential for using these tools in integrated demonstrations of their capability to support representative future DoD systems acquisitions with respect to purpose, affordability, and interoperability. Task 2 involved identifying several design challenge problems to

---

[106] SERC-2009-TR-003, Cloutier, R. and Mostashari, A., Investigation of a Graphical CONOPS Development Environment for Agile Systems Engineering, Systems Engineering Research Center, Final Technical Report, October 30, 2009

[107] SERC-2012-TR-031, Cloutier, R., Graphical CONOPS prototype to demonstrate emerging methods, processes and tools at ARDEC, Systems Engineering Research Center, Final Technical Report, March 23, 2012

[108] SERC-2013-TR-031-2, Cloutier, R., Graphical CONOPS prototype to demonstrate emerging methods, processes and tools at ARDEC, Systems Engineering Research Center, Final Technical Report, July 17, 2013

[109] SERC-2012-TR-024, zur Muelhen, M. , Integration of M&S (Modeling and Simulation), Software Design and DoDAF (Department of Defense Architecture Framework, Systems Engineering Research Center, Final Technical Report, April 9, 2012

characterize the integrated environment capabilities being identified in Task 1. Based on discussion of the Task 1 analysis results with the sponsors, the original Task 2 statement was reinterpreted to involve the SERC Research Council in defining one or more representative future design challenge problems, and in determining key research ideas and directions that would enable DoD to cope with the challenges. This report includes the resulting two Grand Challenge scenarios of particularly difficult threat complexes beyond the reach of current tool support capabilities, with indications of the type of next-generation tools that would enable successful DoD responses. It also presents four high-leverage research areas that would be key to realizing the rapid and effective results described in the scenarios, using the Heilmeier criteria for evaluating proposed research initiatives: (1) Affordability, Agility, and Resilience; (2) Enterprise Systems Engineering and Model Integration; (3) Trusted Systems and Cyber Security; and (4) Human-Determined Systems[110].

Introducing Model Based Systems Engineering Transforming System Engineering through Model-Based Systems Engineering. [111] This research topic (RT-48) focuses on a Vision held by NAVAIR's leadership to assess the technical feasibility of creating/leveraging a more holistic Model-Based Systems Engineering (MBSE) approach. The expected capability of such an approach would enable mission-based analysis and engineering that reduces the typical time by at least 25 percent from what is achieved today for large-scale air vehicle systems. The research need includes the evaluation of emerging system design through computer (i.e., digital) models. The first phase of the effort began investigating the technical feasibility of moving to a "complete" model-driven lifecycle and includes four key tasks that can be summarized as follows: Surveying Industry, Government and Academia to understand the state-of the-art of a holistic approach to MBSE; Develop a common lexicon for MBSE, including model types, levels, uses, representation, visualizations, etc.: Model the "Vision," but also relate it to the "As Is" process; Integrate a Risk Management framework with the Vision This report provides details about each task, the focus of the research questions, accomplishments, and the plans for the Phase II efforts, which are to continue under another RT.

Transforming Systems Engineering through Model Based Systems Engineering[112]. The objective of the RT-46 research effort is to assess whether it is technically feasible to transform systems engineering using a fully formalized Model-Based Systems Engineering (MBSE) approach (i.e. model-centric engineering) with integrated and interoperable models to associated simulations, surrogates, digital assets, and supporting environment. Application is to be tested in NAVAIR. According to the report, "the on-going research will be informed by the application of the results and then the research will be tailored to newly discovered needs going forward. This should enable NAVAIR to create a plan informed by the research results for implementation relatively early in the results cycle".

Integration of M&S (Modeling and Simulation), Software Design and DoDAF (Department of Defense Architecture Framework (RT 24). [113] Different Department of Defense communities prepare models for architecture compliance (e.g., to maintain JCIDS requirements), for simulation purposes (e.g. for

---

[110] SERC-2010-TR-009-1, Boehm, B., System 2020 – Strategic Initiative, Systems Engineering Research Center, Final Technical Report, August 26, 2010.

[111] SERC-2014-TR044-1 http://www.sercuarc.org/research/research-program-and-projects/transforming-systems-engineering-through-model-based-systems-engineering-tasks-48-118/

[112] SERC-2014-TR-044-2, Blackburn, M., Transforming Systems Engineering through Model Based Systems Engineering, Technical Report, March 31, 2014

[113] SERC-2012-TR-024 http://www.sercuarc.org/publications-papers/integration-of-ms-modeling-and-simulation-software-design-and-dodaf-department-of-defense-architecture-framework/

performance estimates) and software engineering (e.g, for model-based code generation). Little, if any, information transfer and model reuse takes place across these communities of interest, which leads to redundant efforts, models that are out of sync, and lost domain knowledge. Differences in methods, tools and data formats are a major reason for this disconnect. The charter of RT 24 was to investigate mechanisms that could help bridge the divide between the modeling & simulation, software engineering, and enterprise architecture modeling communities.

Tradespace and Affordability (Task 46, 113)[114]. The focus of the second phase (RT 46) and third phase (RT 113) is to apply the methods and tools developed in the first phase on problems relevant to DoD, ideally using the information available from development of a large weapon system, or a large automated information system.   Ideally, the SERC will work with the system developer to gain a deep understanding of the strengths and limitations of the tradespace tools methods developed under Phase 1. Phase 2 and 3 activities will expand the set of ilities represented in the tradespace. The information learned from Phases 2 and 3 will be used to improve the frameworks and tools developed in the Phase 1 activities.

Engineered Resilient Systems: Tradespace Tools (Task 120)[115]. This research proposes the development of an analytical construct to forecast resilient options and a tradespace toolset framework architecture in support of Engineered Resilient Systems (ERS). This includes conducting research and development of methodologies to include Needs Context based Utility Functions, and risk mitigation of uncertain future events through option buy-ins. Next, this effort investigates various toolset usability upgrades, building on Georgia Tech's experience in building web-based, collaborative systems engineering frameworks, in light of related stakeholder requirements and use cases. Finally, this work will explore a series of ERS Architecture tradespace toolset concepts which would be co-developed between Georgia Institute of Technology, the US Army Engineer Research and Development Center (ERDC), and related stakeholders.

Development and Application of FACT to Support USMC Ground Vehicle Design Analysis (Task 117)[116]. USMC has been developing the Framework for Assessing Cost and Technology (FACT) since 2011. In that time, FACT has been applied to multiple ground vehicle platforms, each time improving the Framework based on the use required by the design analysis team. In this task researchers will improve upon FACT to prepare for the next USMC large ground vehicle acquisition program, to include integration of new modeling tools and simulation environments, toolset improvements such as a task queue and modular architecture to ease collaborative development, and improved interactive data visualizations.

---

[114]   SERC-2013-TR-039-1, SERC-2013-TR-039-2, http://www.sercuarc.org/research/research-program-and-projects/tradespace-and-affordability-task-46-113/

[115] http://www.sercuarc.org/research/research-program-and-projects/engineered-resilient-systems-tradespace-tools-task-120/

[116] http://www.sercuarc.org/research/research-program-and-projects/development-and-application-of-fact-to-support-usmc-ground-vehicle-design-analysis-task-117/