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Research Center

Interactive Model-Centric Systems Engineering (IMCSE) Phase Two

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14. ABSTRACT
Model based systems engineering (MBSE) is becoming increasingly more important in the practice of SE. To take advantage of model-based techniques, it is important to improve human and technology integration. The Interactive Model-Centric Systems Engineering (IMCSE) research program develops SE methods, processes and tools (MPT) to improve this interaction. 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. This project explores development between value choice-tradeoff, supportive MPTs, and interactive Epoch-Era Analysis (IEEA), a framework for narrative and computational scenarios. Exploration includes human interface and reasoning considerations for epoch, era characterizations, and multi-epoch/era analyses. Leveraging prior work from DARPA META, the Interactive Schedule Reduction Model (ISRM) was extended promoting sensitivity analyses and benchmarking to be the central use case. The IMCSE research program for Phase 2 extends the original set of objectives. The work accomplished includes: Pathfinder state fo the art-practice research gathered and published, further strategies and implementations for IEEA, and completion of ISRM web-based prototype.

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OVERVIEW

This report is the annual report for Phase 2 of the Interactive Model-Centric Systems Engineering (IMCSE) research project. Portions of the Phase 1 report have been repeated in this report for completeness.

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 2

The IMCSE research program involves three tasks initiated in May 2014, with two additional tasks added for Phase 2 that extended from the original set of three. The work accomplished in this second phase includes:

1. Pathfinder Project. This effort has continued to investigate the current state of the art/practice in IMCSE. The research team conducted knowledge gathering and additional literature review, building on the Phase 1 work. The expanded knowledge gathering was used to inform the design of an invited workshop, focused on identifying research opportunities, gaps and issues along with associated priorities and initial plans. The team designed, planned, and conducted a Pathfinder IMCSE Workshop on 20 January, 2015. The workshop report is included in Appendix A.

2. Interactive Schedule Reduction Model (ISRM). The research team continued development of the ISRM, which was based on 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. Extending the effort in phase 1, the team completed Phase 2 objectives for demonstrating a service-based tool to support rapid sensitivity analysis. A back-end implementation uses a

MongoDB/Express/Node.js stack to provide remote model execution and services to store and query model results. Front-end user interfaces support several activities. An execution module performs full-factorial design of experiments to vary parameters of interest, execute a local or remote model, and store results. A visualization module provides three capabilities based on result query services: 1) time series comparison to visualize simulation results across several scenarios, 2) sensitivity analysis to compare relative magnitude of results to a baseline scenario, and 3) tradespace exploration to visualize all results in a two-dimensional space. These features exceed the existing capabilities of Vensim and have been demonstrated to analyze and visualize results across more than 1000 scenarios. The completed prototype provides a proof-of-concept prototype that has potential to inform future interactive model development.

3. Interactive Epoch-Era Analysis. The research team further developed a strategy for extending a current approach for evaluating systems under uncertainty, Epoch-Era Analysis (EEA), through the development of an interactive capability. Effort has focused on the exploratory development of Interactive Epoch-Era Analysis (IEEA) methods, including human interface and reasoning considerations for epoch and era characterizations, as well as single and multi- epoch and era analyses. The team has explored visualization techniques and methods for mitigating computational resource restrictions that facilitate improved decision-making. A preliminary method has been developed with a demonstration prototypes, and case examples. Various potential visual representations and user interaction flows were proposed during this phase, and some are being implemented for potential user testing. These include epoch characterization and selection, and era construction and analyses. The team has identified key user tasks and objectives to be further evaluated during user tests.

The following two projects were added for the Phase 2 period.

4. Supporting MPTs. During Phase 2, the research team continued to define and prototype implementations of parts of Interactive Epoch-Era Analysis.

5. Trading Models. During this phase, the research team expanded its research on trading models, with further development of an exploratory case on value model trading. The team began developing an alternative performance model for the demonstration case to be added in Phase 3.

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 3 of the project. The following findings have resulted from the Phase 2 effort over the 5 month period of performance:

1. Phase 1 investigation led to the identification of three challenges at the intersection of the four pillars (key topic areas): tradeoff of models, visual analytics of artificial data, and perceptual and cognitive considerations in human-model interaction. In Phase 2 these

have been further explored, and specific research needs were identified. These have been incorporated into the Phase 3 research plan.

2. The Pathfinder IMCSE Workshop was designed, planned and conducted on 20 January 2015. The workshop demonstrated the interest around the IMCSE topic, and validated the need for much more research in this area. Results of the workshop have been published (see Appendix A), and feed forward into Phase 3 to further evolve the research agenda and roadmap, and define priorities.
3. The Interactive Schedule Reduction Model (ISRM) was completed, demonstrating web-based technologies as new methods for human-model interaction enabling rapid sensitivity analysis of various factors. The resulting proof-of-concept prototype with supporting documentation is available as a model for how such technology can be used.
4. A preliminary method for Interactive Epoch-Era Analysis (IEEA) has been developed with demonstration prototypes, and case examples. Various potential visual representations and user interaction flows were proposed for potential use.
5. A demonstration case for value model choice and tradeoffs was refined and applied in a Space Tug system, highlighting methodological considerations.

NEXT STEPS

- The research team will use knowledge from Phase 1 and Phase 2 to focus ongoing efforts in Phase 3 to further explore the identified IMCSE-related considerations within four key areas, and the challenges and opportunities at their intersection.
- The Pathfinder Workshop Report (Appendix A) will be disseminated to elicit comments and recommendations, augmented by discussions with selected subject matter experts. This will feed into creating a collaboratively-derived research agenda. A research roadmap will be derived in collaboration with other SERC researchers and the broader systems community. A leadership summit is targeted to support validation of research priorities, recommend pathways to accelerate research progress, and enable transition to the systems community.
- The research team will mature the approach for evaluating systems under dynamic uncertainty, with further development of the extended framework to for interactive capability and scaling to big data. This work extends the Phase 2 effort on a demonstration prototype, using the MIT IVTea Suite, applying IMCSE principles to enhance the user interface, data handling and analysis widgets. In Phase 3 the research team will enhance the method and degree of interactive capability, focusing specifically on the Epoch-Era Analysis method, a novel method for value-driven tradespace exploration and analysis. The maturing prototype framework with associated supporting tools will be applied to a case analysis including various types of uncertainties. This case application will be used to elicit feedback on relevance, ease of use, feasibility and tractability of data scaling and visualization techniques. The research team will extend the Phase 2 prototype efforts for Interactive Epoch-Era Analysis (IEEA) and test using case applications, along with preliminary supporting

infrastructure. This will inform the transition strategies, additional case application and prototype user testing.

- The research team will build on the Phase 2 work on value model trades to further evolve the framework and process. In Phase 3, the research team will build on prior phase results to further evolve the framework and process for conducting value model choice and tradeoffs and apply this through an expanded case application set, to validate the framework and identify workflow considerations. The model choice and tradeoff framework will be expanded including demonstration cases beyond value models (to include trading of other types of models including performance and cost models). The expanded framework will consider alternative use cases for the impact of model choice and tradeoffs on decision-making. For example, this includes the context of multi-stakeholder negotiations using tradespace exploration, where the data source(s) (i.e. "models") strongly impact the trust and framing of the shared decision problem.
- The research team will continue to investigate the cognitive and perceptual considerations in human-model interaction, a topic for which little research exists, though there is a body of knowledge to draw from. Preliminary heuristics/design principles will be gathered, adapted for human-model applicability, and synthesized as a draft guidance document. The guide will be shared for review and comment by model developers, users and model-based software designers, toward publication of a validated set of guiding principles for effective human-model interaction during Phase 4. A goal is to involve one or more SERC collaborators as transition partners, to pilot use of the guiding principles during Phase 3.
- The research team will use the results of Phase 1 and Phase 2, along with ongoing Phase 3 research interim results, to develop several publishable papers for journal and conference submissions. Evolving prototype MPTs will be shared and demonstrated at one or more SERC-related events during Phase 3, including the CSER 2015. The research team will continue active knowledge exchanges with several other SERC researchers performing related work, where IMCSE outcomes can inform and/or be applied in their work.

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.

The Phase 2 Pathfinder Workshop Report (Appendix A) includes further discussion on these insufficiencies, as identified by participants in the workshop.

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 the previously published SERC IMCSE Phase 1 report.

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

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

new shows. House of Cards, produced by Netflix, 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

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[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, which was conducted during Phase 2. Extending the results of the workshop, a more extensive effort in Phase 3 will build a community of interest. The end result will be a collaboratively-derived research roadmap and set of priorities.

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 continue to inform the research agenda, and 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 includes face-to-face gatherings of stakeholders in the research agenda, as well as specifically focused research meetings. An initial workshop held during Phase 2 has seeded the initial research agenda. 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 has explored various approaches that have been used, and will leverage the ideas from 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.

Pathfinder Project

Preliminary efforts in defining a research vision and results of exploratory knowledge gathering have been used to design and conduct the IMCSE Pathfinder Workshop during Phase 2. The workshop was conducted on 20 January 2015, bringing together interested stakeholders for an initial dialogue on human-model interaction, identifying research needs from both a model-centric perspective and an interactive perspective. A rich set of participant observations, insights, feedback and recommendations was gathered during the event. Stage-setting talks were employed to orient the participants on the four "pillars" and some of the identified challenges at their intersection. Following the workshop, an activity has been initiated to gather input from SERC members and the broader systems community to evolve a research agenda for IMCSE. The ultimate goal is to establish a shared set of IMCSE research priorities and roadmap, excite the research community around the topic, and build partnerships for research collaboration and for transition to practice.

The outcome of the workshop event is a workshop report (Appendix A). The event identified level research needs and questions, along with identifying gaps, issues and opportunities. A vision for the individual's experience in the ideal work was captured during the workshop. The results of the workshop have been made available for review and comment. The goal of the workshop and resulting report was to seed the larger effort to build a community of interest and undertake a more extensive research pathfinder activity. Feedback from the review of the report and follow-on discussions with subject matter experts will be captured and evolved during Phase 3.

The pathfinder activities in Phase 1 and Phase 2 of this research project 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 roadmap.* 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.

BUILDING A COMMUNITY OF INTEREST

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.

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.

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

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 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.

In Phase 2, the research team worked toward a concept for generating a collaboratively-derived research agenda, to build on the outcomes of the initial pathfinder workshop. In Phase 3 this will be developed into a structured approach and implemented using some web-based technology support.

EXPLORING THE IMCSE-RELEVANT STATE OF THE ART AND PRACTICE

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.

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[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

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. These informed the pathfinder workshop activity

These challenges were further investigated during Phase 2, and have evolved into specific activities. Research on the tradeoff of models in Phase 2 has been on value models. In Phase 3 this will be extended to cost and performance models. The visual analytics of artificial data has become part of the Interactive Epoch-Era Analysis research, which will continue in Phase 3. Further investigation of the perceptual and cognitive considerations during Phase 2 has elevated the importance of this topic. Phase 2 included literature review, presentation at conferences, and discussions with subject matter experts. Phase 3 will leverage the work toward development of heuristic guidelines for human-model interaction considerations.

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, 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.

[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.

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.

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.

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

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 sources are mapped to visual representations, which finally populate the view used by the analyst.*

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[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

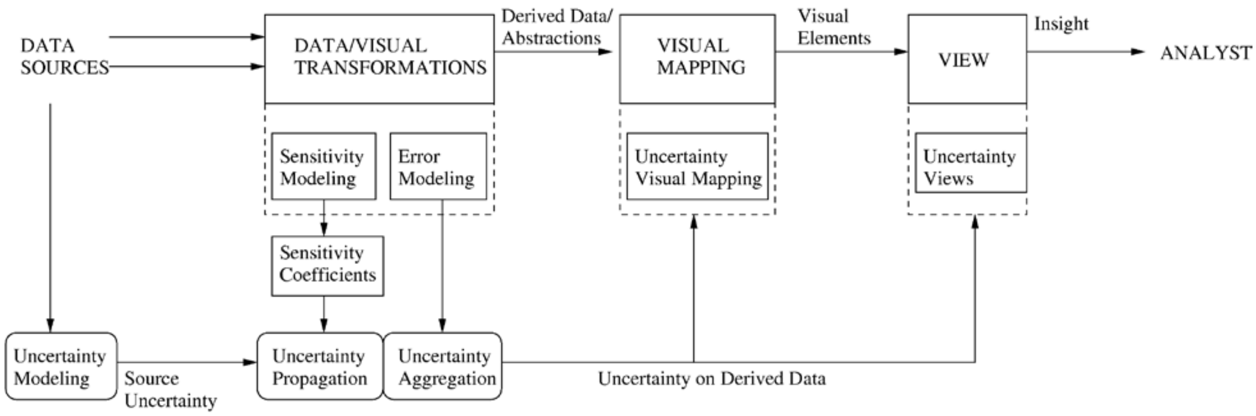

Figure 2. Uncertainty-aware visual analytics process (source: Correa, et al. 2009[14])

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

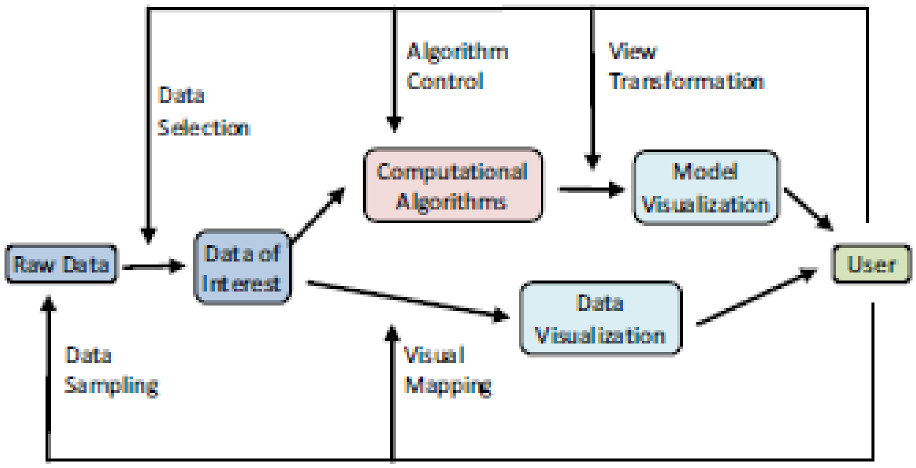

Figure 3. Framework of work-centered visual analytics (source Yan et al.[17])

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 relate to the number of constituent and component interconnections, and to the necessary rapid rate

[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

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.

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[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

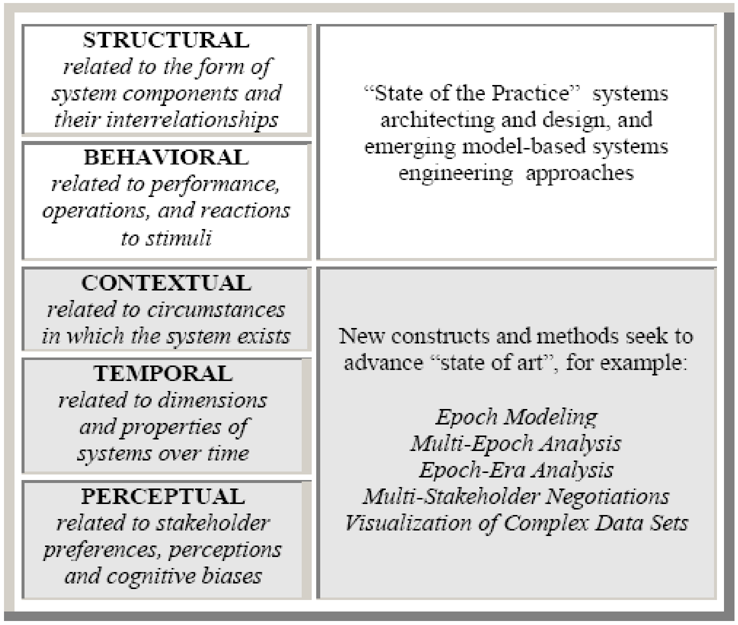

Figure 4. Five Aspects of Complex Systems[24]

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

[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.

complexity are correlated and constitute a tradeoff between design-efficiency and design-robustness (refer to page **Error! Bookmark not defined.** for the detailed discussion).

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]

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[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

“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 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

[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

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.

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]

		Mental Model v. Values	
		Low Δ_1 (truthful)	High Δ_1
Constructed Model v. Mental Model	Low Δ_2 (trust)	**Correct Trust:** Trust present. Correct representation of values.	**Type I error:** Trust present. Incorrect representation of values.
	High Δ_2	**Type II error:** Trust not present. Correct representation of values.	**Justified Mistrust:** Trust not present. Incorrect representation of values.

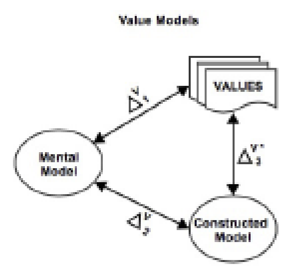

Figure 5. Trust and truthfulness in value models (Ricci et al. 2014)

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.

[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

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 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.

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[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.

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 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

[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.

them.[45] To this end, model-based forecasts 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.

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

FUNDAMENTALS

The Fundamentals thrust presently includes three areas: Interactive Epoch-Era Analysis project, Value-Model Choice and 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 be 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 lifecycles.

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 relevant epochs and eras, conducting analysis across these epochs and eras, and extracting useful and actionable information from the analyses. Schaffner (2014)[48]

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[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.

[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.

showed that the number of potential eras to consider grows very quickly, becoming computationally infeasible.

As an example, a system model represented by 5 epoch variables, each with 3 levels, would result in $3^5 = 243$ possible epochs. If the length of our eras is 10 epochs and each epoch can transition between any other epoch, then the size of the potential era space would be $243^{10} \sim 10^{24}$. 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]. Research in both the areas of big data analysis and visual analytics have led to techniques that could be leveraged to mitigate these challenges. It is hypothesized in this research that augmenting the traditional EEA approach with new analytic and interactive techniques will fundamentally enable new capabilities and insights to be derived from 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 a human-in-the-loop implementation, will help to intelligently limit the potentially unbounded growth in the epoch/era space.
    a. Using visual analytic techniques such as filtering, binning, pattern matching, search algorithms, and human-in-the-loop interaction, 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. By allowing decision makers 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 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.

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[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.

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 large amounts of data to quantify the effectiveness of large numbers of actionable alternatives across large numbers of possible futures in order to support the best possible decision. To assist in solving the stated problem, this research will leverage and expand upon some human-in the-loop techniques that are emerging in studies of visual analytics and big data analysis. 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, and how it has been defined and measured in past studies has varied across problem domains (Goerger et al 2014)[53]. 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 uncertainty" (Madni 2012)[54]. Yet another definition of resilience (called system "survivability" elsewhere, adding to semantic confusion) is "the ability of a system to minimize

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[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.

[53] Goerger S, Madni A, Eslinger O., "Engineered Resilient Systems: A DoD Perspective," 12th Conference on Systems Engineering Research, Redondo Beach, CA, March 2014.

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

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)[55].

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. More recent work has generalized this concept into something called *value sustainment* (Beesemyer 2012[56]). 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.

a. "Long" duration perturbation (unlikely to revert)

b. "Short" duration perturbation (likely to revert)

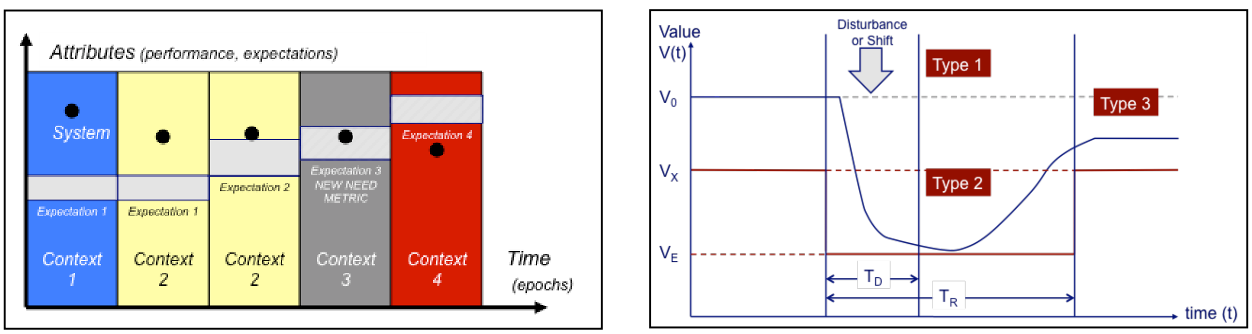

Figure 6. Long (a) and short (b) run impacts of perturbations on value delivery

TRADITIONAL 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 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

[55] 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.

[56] Beesemyer, J.C., Empirically Characterizing Evolvability and Changeability in Engineering Systems, Master of Science Thesis, Aeronautics and Astronautics, MIT, June 2012.

Era Analysis (Ross 2006)[57]. 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[58]; Fitzgerald et al. 2011[59]; Schaffner et al. 2013[60]). 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)[61].

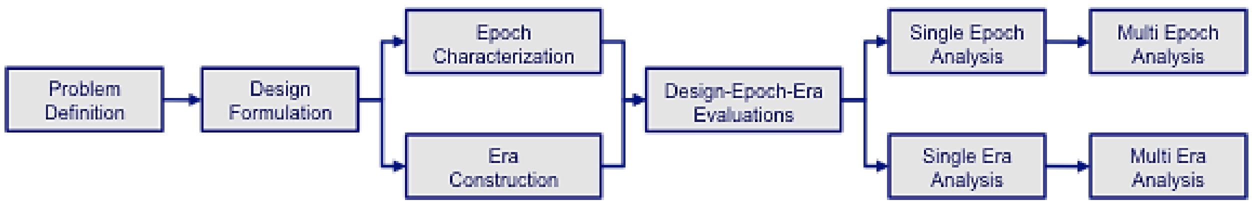

Figure 7. Activities in Epoch-Era Analysis

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.

2. Epoch/Era Generation:

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

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

[58] 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.

[59] 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.

[60] 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.

[61] 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.

4. Single Epoch/Era Analysis:

- **a. Single Epoch Analysis**: 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.
- **b. Single Era Analysis**: 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.

5. Multi Epoch/Era Analysis:

- **a. 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.
- **b. 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.

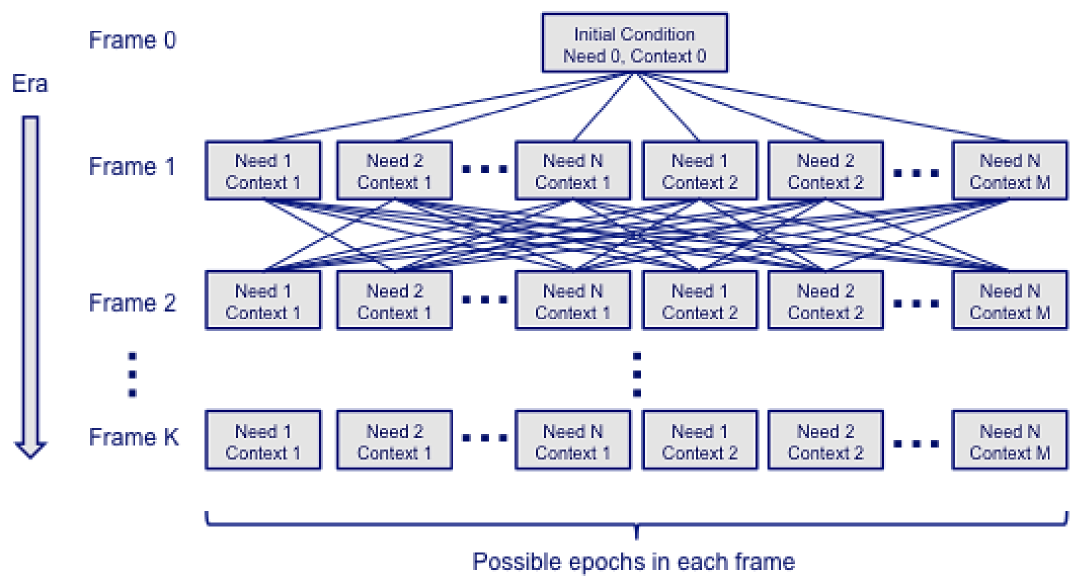

Figure 8. Era-tree showing potential temporal paths through the epoch space (based on Ross et al. 2008[62])

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. A *frame* is a particular slot within an era that consists of an epoch and a duration (Schaffner 2014)[63]. This allows an EEA user to specify eras 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

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[62] 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

[63] Schaffner, MA, Designing Systems For Many Possible Futures: The RSC-Based Method For Affordable Concept Selection (RMACS), With Multi-Era Analysis, SM in Aeronautics and Astronautics, Cambridge, MA: MIT, 2014.

3-frame clips, for example, which might appear in multiple different eras. When looking for patterns, such a unit of analysis may be useful.

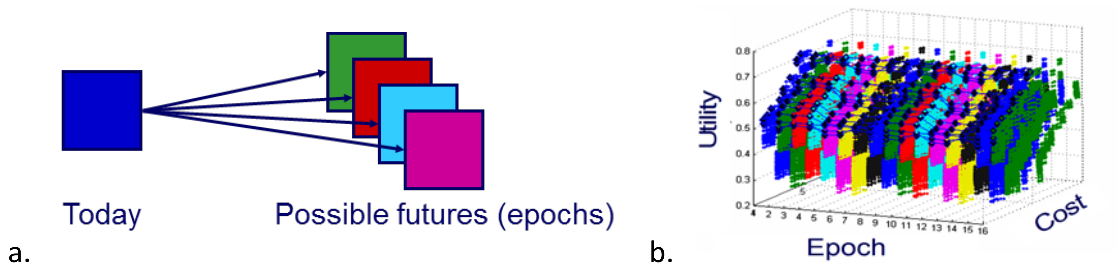

Figure 9. Epochs as Alternative "Point" Futures (a) and Multi-Epoch Analysis (b)

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.

As previously noted, 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. Notably, trends in the area of ERS-related research are moving towards analysis of tradespaces on the order of multiple terabytes of data. Drawing on recent research in the areas of big data analysis and visual analytics, EEA methods can be augmented to allow a decision maker to interactively filter, sort, aggregate, and identify patterns in the data more efficiently than predetermined or automated algorithms, enabling a more effective tradeoff of evaluation "completeness" versus insights gained.

Liu et al. (2013)[64] and Heer and Shneiderman (2012)[65] 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 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 also include custom workflows such as those described in Sitterle et al. (2014)[66]. Methods for sorting and filtering data may include, but are not limited to, interactive brushing and linking of multiple coordinated visual displays.

The problems that may arise when scaling up to larger decision problems with traditional EEA can 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-

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

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

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

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.

Solutions to these and other issues relevant to IEEA will be discussed in the following sections. Demonstration cases that test applicability of various research methods will also be discussed.

ENABLING AREAS OF RESEARCH

Several areas of research that will enable IEEA and address or mitigate the issues previously discussed have been identified. The sections below describe background research on various techniques and ongoing efforts to extend them for IEEA applications.

Data Reduction Methods

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 including (1) filtering; (2) sampling; (3) binned aggregation; and (4) model-fitting (Liu et al. 2013).[67]

Filtering is a commonly applied technique to reduce the problem to a subset of the original data. This is accomplished by placing bounds on the data such that not all of it is displayed at once which could be overwhelming to a decision maker. Likewise, sampling is a technique for reducing the amount of data displayed to the user by randomly drawing a subset of the points to create a reduced set for display. Sampling has the potential downside of unintentionally concealing features of the dataset that may correspond to rare events. These are oftentimes the very data points in which a decision maker is most interested.

Filtering and sampling are often used in practice because they are relatively easy to implement and do not require any changes in the standard visualizations types that would be used for a larger dataset. Both techniques are useful, but we would also like to consider techniques that allow all the data to be visualized. Binned aggregation is powerful in that it allows a decision maker to observe global patterns in the data as well as local features that may be hidden by filtering or sampling (Liu et al. 2013).[68] In TSE and EEA, which often use 2-D scatter plots to display data, one example of binned aggregation is to project the data into a 1-D histogram. Alternatively, the data could also be aggregated into smaller 2-D bins with the density of points

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

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

encoded by color. Examples of these techniques are demonstrated in prototype visualization tools described in the following sections.

Model-fitting is another approach that can be applied to reduce the resources required to visualize a large dataset. Examples of model-fitting include simple regression models or complex surrogate models that reduce the dataset to representative equations. Model-fitting can be a powerful technique, but computing an appropriate model can sometimes be computationally expensive. Models also typically have some amount of error in how well they represent the underlying data and this must be carefully considered when using their outputs for the purpose of decision-making.

Online Analytical Processing

Online Analytical Processing (OLAP) is an approach for creating abstract representations of high-dimensional datasets. OLAP is frequently applied in data mining and other exploratory analysis applications with large amounts of data. These datasets are often stored in relational databases with multiple tables connected by keys, but can also be as simple as a spreadsheet with records stored in each row and with columns representing different attributes or properties of the data. In fact, pivot tables generated in MS Excel are one example of a common application of OLAP for summarizing data. A notable application of OLAP is its successful use in business intelligence applications to parse large amounts of sales, cost and other data to evaluate trends and inform business decisions.

For IEEA, the benefit of OLAP is that it enables a user to view data from multiple points of view and quickly uncover previously undiscovered relationships and patterns within the dataset. A decision-maker looking at a large number of candidate designs across a large possible epoch space can apply OLAP techniques to slice, dice, drill down, roll up or compute pivots of the hyper-dimensional data cube representing design alternatives over epochs and eras. This allows them to easily extract data that is of interest to them which, in turn, enables better intuition on which to base decisions.

Human Interaction Methods

As a component of the IEEA research, several concepts related to how humans interact with their data are being examined. Interaction methods may extend beyond visualization approaches to include touch and auditory interaction as well. For the effort presented here, however, we will primarily focus on research related to visual techniques. In this paper, we use multiple coordinated views and animated transitions as approaches for facilitating deeper understanding of the data. Multiple coordinated views can be used in exploratory visualization to more effectively expose relationships in the underlying data. Coordinated views are separate, independent views of a given set of data that serve as complementary representations, and may aid in identifying patterns as well as errors in the data. The individual views of the data are not intended for use in isolation, but rather to be combined to generate insights. The primary purpose of coordinated visualizations is to allow improved understanding through user interaction with different simultaneous representations of the data (Roberts 2007)[69]. While choosing which combinations of views to use in order to generate insights can be complicated, several guidelines, including compactness and diversity of the visualizations, have been discussed in prior literature (Scherr 2009)[70].

Search Algorithms

As the number of design and epoch variables increase, TSE and EEA techniques quickly become computationally expensive due to the non-linearity between number of variables and number of model evaluations required (Schaffner 2014)[71]. This can be true even if model evaluations can be computed relatively quickly. In his research, Schaffner explores application of both breadth-first and depth-first algorithms to improve the computational efficiency of multi-era analysis. This area, however, remains an important area of further research to enable IEEA.

[69] Roberts J., "State Of The Art: Coordinated & Multiple Views In Exploratory Visualization," 5th Int'l Conf on Coordinated and Multiple Views in Exploratory Vis. Washington, DC, 2007.

[70] Scherr M., "Multiple And Coordinated Views In Information Visualization," Media Informatics Advanced Seminar on Info Vis. 2008/2009

[71] Schaffner MA., Designing Systems For Many Possible Futures: The RSC-Based Method For Affordable Concept Selection (RMACS), With Multi-Era Analysis, SM in Aeronautics and Astronautics, Cambridge, MA: MIT, 2014.

A FRAMEWORK FOR INTERACTIVE EPOCH-ERA ANALYSIS

The current vision of Interactive Epoch-Era Analysis (IEEA) leverages humans-in-the-loop interaction, 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 to improve sense making of the results. Figure 10 below illustrates three insertion points for interactivity to directly address the three hypotheses outlined earlier (i.e., improved elicitation, improved analyses, and improved decision-making).

As shown in the figure, many of the techniques discussed above can be applied to augment the existing EEA workflow. OLAP techniques may be applied to advance current data handling, and search algorithms may improve our ability to offer more informed recommendations to decision-makers during the epoch-era elicitation process. Similarly, enhanced human interaction techniques and visualizations may aid in the analyses of the vast amounts of information required to reach an informed decision.

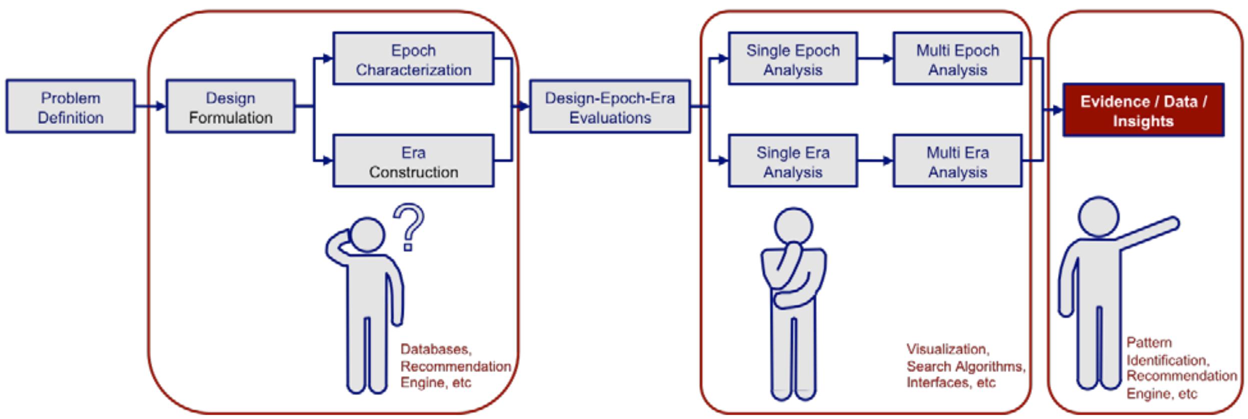

Figure 10. Interactive Epoch-Era Analysis leverages humans-in-the-loop analysis and supporting infrastructure

When considering human-interaction in EEA (in both current and potential implementations), one can see a large number of potential tasks that can be addressed. These include, but are not limited to, the following: elicitation of the objectives to be met (e.g. evaluation criteria) as well as categories of uncertainties (e.g. epoch/era categories), as well as design alternatives to consider; generation of epoch factors within the uncertainty categories, along with the epoch variables used to quantitatively represent the epoch factors, as well as the ranges and allowable enumerations for each epoch variable; sampling of which particular epochs and eras to eventually evaluate; development and execution of evaluations of designs in epochs in eras; analyses of designs within particular epochs and/or eras as well as across many particular epochs and/or eras; and finally decision-making through synthesis of gathered evidence, perhaps through iterative refinement.

A key challenge in EEA is that the number of possible epochs generated by enumerating epoch variables can quickly exceed a feasible number for users to explore, potentially resulting in biased or uninformative analysis. For IEEA to be effective, it must enable effective management of this challenge. The proposed IEEA framework, in which certain EEA activities are performed as a partnership between computer and human feedback, seeks to enable more informative and satisfactory selections and analyses. The above framework has been extended in Figure 11, in order to make explicit particular workflow considerations (i.e., the above tasks) for human-in-the-loop IEEA.

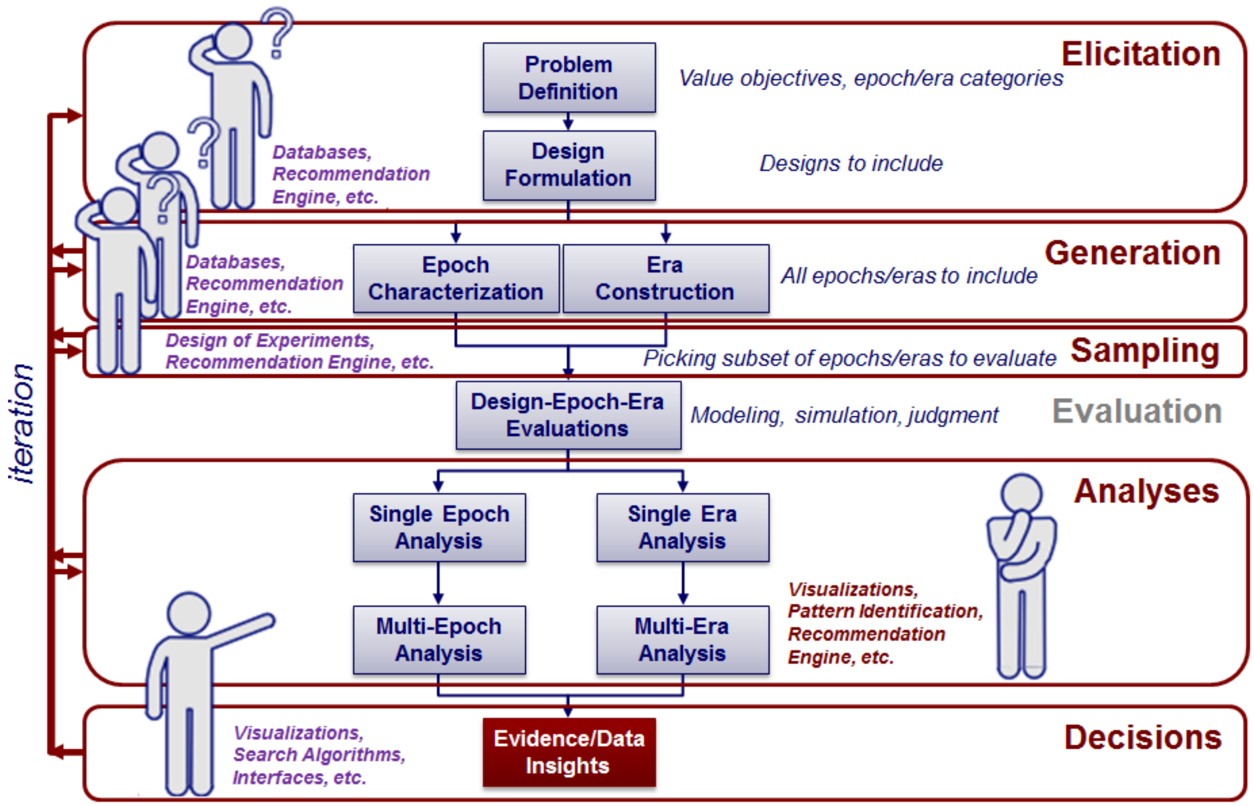

Figure 11. A framework for Interactive Epoch-Era Analysis, showing five "modules" with human interaction

This framework can be abstracted into six main modules:

Elicitation of relevant epoch and design variables (often through interview),
Generation of all epochs and design tradespaces (often including enumeration),
Sampling of epochs and eras in which to evaluate design choices,
Evaluation of designs in sampled subset of epochs and eras
Analyses of design choices in the previously evaluated epochs and eras, and finally
Decisions of final designs based on iterative evidence from previous modules.

While the sequence of these modules flows logically, IEEA is intended to be an iterative process where users can go back and change responses within earlier modules at any point to reflect what they have learned from later ones.

In the past*, elicitation* and *generation* have been primarily a human-centric task, with some structured support via static documentation; *sampling,* however, is the first module in the framework that can clearly benefit from human-computer interaction and feedback. In this module, the human must make sense of, and decide upon, which subset of epochs and eras to spend computational and human attention (i.e., scarce) resources. Visualization and feedback are key tasks for the user in order to interact with the data representing possible epoch and era subset samples from the generated larger epoch and era spaces. For now, we focus on this module as a proof of concept before expanding considerations to other modules. In the following subsections we present and evaluate different visualization options and considerations for use in the epoch/era sampling module, and then propose metrics for usability analysis, with the idea that this kind of analysis can (and should) be conducted on other interactivity modules as well in future implementations of IEEA.

VISUALIZATION CONSIDERATIONS FOR MULTI-DIMENSIONAL DATA

BACKGROUND ON "GOOD" VISUALIZATIONS

Before examining techniques that could be used in epoch sampling visualization, we set a baseline for good overall design principles. There are countless guidelines that have been developed over the years that prescribe measures to be taken when creating data visualizations. These range from very general (e.g. "Tell the truth about the data," "Important data should be easy to find and understand") to very specific (e.g. "Colors should be chosen so that all, including color-blind, users can distinguish them," "Avoid using gray scale to represent more than 2-4 values," "Words should be spelled out and run horizontally, left-to-right"). There should be internal consistency within the visualizations, as well as external consistencies with common conventions the user may be familiar with. Visualizations should attract the viewer to think about the substance rather than the methodology or any other distracting features. They should be clear and reveal the data at several levels of detail, attracting and encouraging the user to explore further. Above all, they should enable the user to be more productive, efficient, and/or gain more insight than they could have without the tool (Ware 2013; Tufte 1983)[72,73].

Especially when dealing with quantitative data, it is important to take into account how different values are encoded to reflect their size or order. According to a 1984 study by Cleveland and McGill, viewers are most accurately able to encode quantitative data in the following ways, in order (Cleveland 1984)[74]:

1) Position along a common scale (e.g. scatter plots)
2) Position along nonaligned scales (e.g. multiple scatter plots)
3) Length, direction, angle/slope (e.g. bar chart, pie chart)
4) Area (e.g. bubbles)
5) Volume, curvature (e.g. spheres)
6) Shading, color saturation (e.g. heatmap)

Thus representations of quantitative (or even some categorical) information should take this list into account.

While the more general guidelines are more obvious and widely accepted, more specific ones should be treated with caution, as not all users share the same visual preferences. Regardless, all of these guidelines strive to optimize the processing power of human cognitive ability to understand whatever is being displayed. Tufte summarizes the concept of *graphical excellence* as "that which gives to the viewer the greatest number of ideas in the shortest time with the

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[72] Ware, Colin. Information Visualization: Perception for Design. Elsevier, 2013.

[73] Tufte, Edward R. The Visual Display of Quantitative Information. Cheshire, Conn.: Graphics, 1983.

[74] Cleveland, W.S. and R. McGill, "Graphical Perception: Theory, Experimentation, and Application to the Development of Graphical Methods," Journal of the American Statistical Association, 79-387, 1984.

least ink in the smallest space." For all of the types of visualizations we are about to introduce, we credit that these baseline design criteria are heeded and satisfied.

CONSIDERATIONS FOR SAMPLING MODULE IN IEEA

We now turn to the sampling module of IEEA to examine the effectiveness of different visualization types. Sampling epochs, as mentioned in the previous section, is made difficult by the rate at which the number of possible epochs grows. While computers are good at handling vast amounts of data, it takes human judgment to decide which epochs are most likely, important, or urgent to analyze further. Thus, human-in-the-loop interaction is necessary to achieve effective epoch sampling results. We recall the main goals for this module, adapted from Curry et al.'s hypotheses regarding IEEA (Curry 2015)[75]:

1) The user should **understand** how each of the **epochs are defined** in the dataset (e.g. epoch variables and values; what is a context and what is a need, etc).
2) Based on this, the user should be able to **find and select** important **epochs** on which to conduct further analysis.
3) Finally, the user should **understand** a) **the size of the epoch space**, b) what **fraction** is **available to explore** (for which epochs data has already been generated), c) what **fraction** of this has **already been explored** or selected to explore, helping to "intelligently limit the potentially unbounded growth in the epoch/era space."

In summary, these are the goals (and implied evaluation criteria) for potential visualizations:

Goal #1: help user understand specific epoch definitions
Goal #2: help user find and select epoch(s)
Goal #3: help user understand a) epoch space size, b) fraction available to explore, c) fraction already explored

In the next section we will describe an existing implementation and evaluate it on these three goals. In following sections we will introduce five selected visualization techniques, describing and evaluating the strengths and weaknesses of each, both for IEEA based on the three goals above, and for general use.

EXISTING IMPLEMENTATION IN IVTEA SUITE

A sampling module is currently implemented as the first step in the Interactive Value-Driven Tradespace Exploration and Analysis Suite (IVTea). IVTea Suite begins with the user loading a dataset, which contains a pre-elicited and generated dataset. Users are then required to specify an epoch subset, or construct an era, using a simple drop-down menu that contains a name or ID number of all of the possible epochs in the dataset (see Figure 12). Other "widgets" within IVTea suite do allow users to gain more information about the definition of the epochs (via ID numbers,

[75] Curry, M.D. and A.M. Ross, "Considerations for an Extended Framework for Interactive Epoch-Era Analysis," CSER 2015.

and context variables and preference sets), however these are not readily apparent to a novice user. The interface does work (albeit a little inefficiently) for experienced users, who understand the epochspace, labels, and where to find important/useful epochs, but it provides minimal guidance to a new user in completing the main goals.

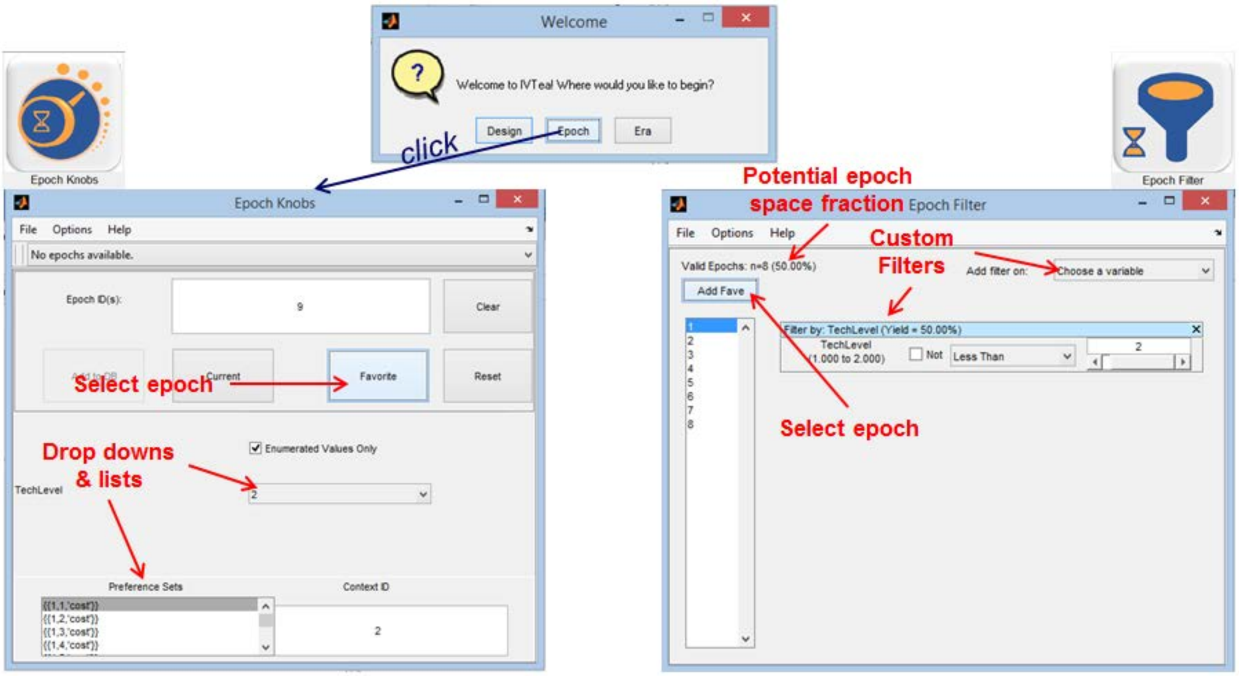

Figure 12. IVTea Suite example interfaces for finding and selection task

Keeping in mind a user may not be the same one that generated the information in the first place, the interface should make the tasks of understanding and finding/selection readily apparent. Less experienced users, or those unfamiliar with the particular dataset, will not know how to interpret poorly labeled epochs (most likely failing Goal #1), much less which are important for analysis, and will most likely choose epochs near the top of the drop-down, biasing their eventual analysis results (most likely failing Goal #2). The initial interface ("Epoch Knobs") does not allow for examining the properties of an epoch beyond what is shown in the drop-down, and the only epochs displayed are the ones the user is able to explore, leaving no sense of the total epoch space or the fraction already explored (failing Goal #3). Users must use a combination of "Epoch Knobs" and "Epoch Filter" for the task of epoch finding and selection (Goal #2) (via specification of an epoch as a "favorite"). For the task of epoch understanding (Goals #1 and #3), the user must use a combination of "Summary Dash" to drill down to "Epoch Summary" and "Context Summary" and "Preference Summary" (see Figure 13). We hypothesize adding more effective targeted visualization, along with appropriate interactivity would improve the learning process for new users.

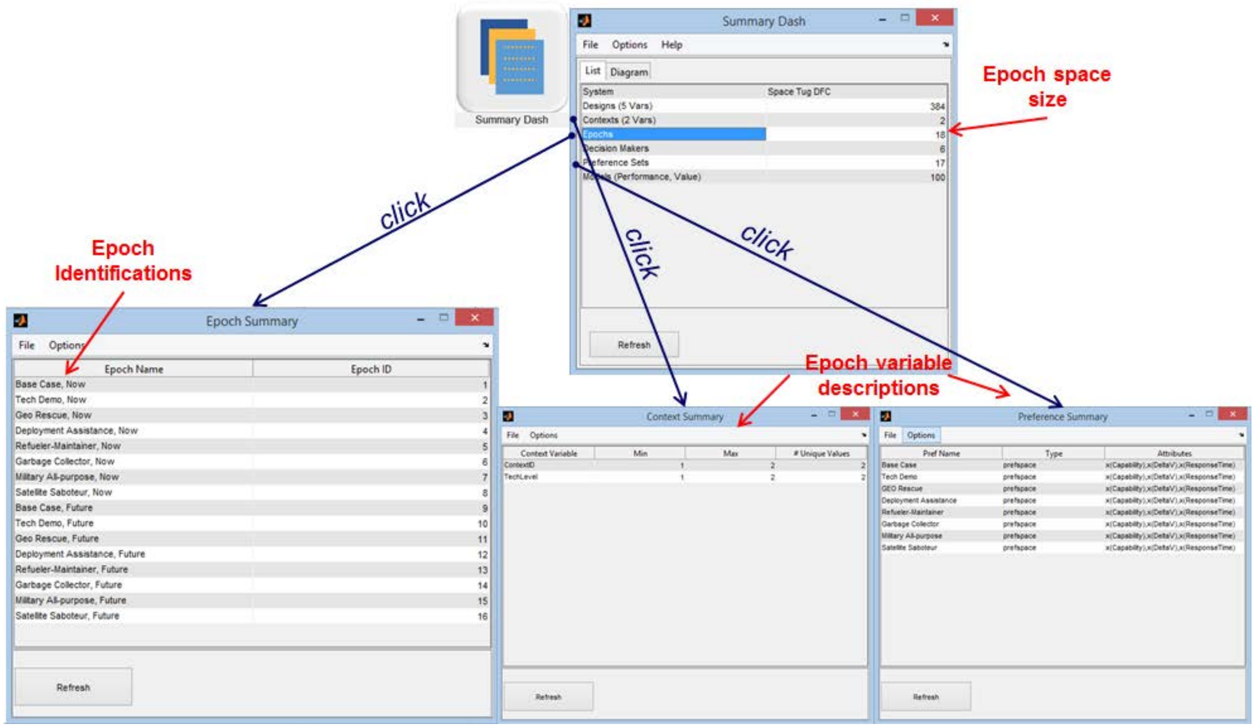

Figure 13. IVTea Suite interface examples for the understanding epochs and epoch spaces tasks

Next we examine a selection of possible visualization techniques made capable by D3.js, a JavaScript library for enabling interactive data-driven web documents[76].

Possible Visualization Implementations

This section will consider a number of alternative visualization techniques with a description, example implementation, and evaluation in terms of supporting the three goals outlined above.

Scatter Plots and Bubble Charts

Description

As shown from Cleveland and McGill's aforementioned study, people are most accurately able to decode information when it is represented by position along a common scale, making a scatter plot a good place to start. A scatter plot allows one variable to be plotted on each axis, so each point's location easily encodes its characteristics to new users. A bubble chart is a scatter plot with two additional values encoded using color and size. Figure 14 shows an example of a scatter plot, while Figure 15 shows an example of a bubble chart.

[76] Data-Driven Documents (www.d3js.org)

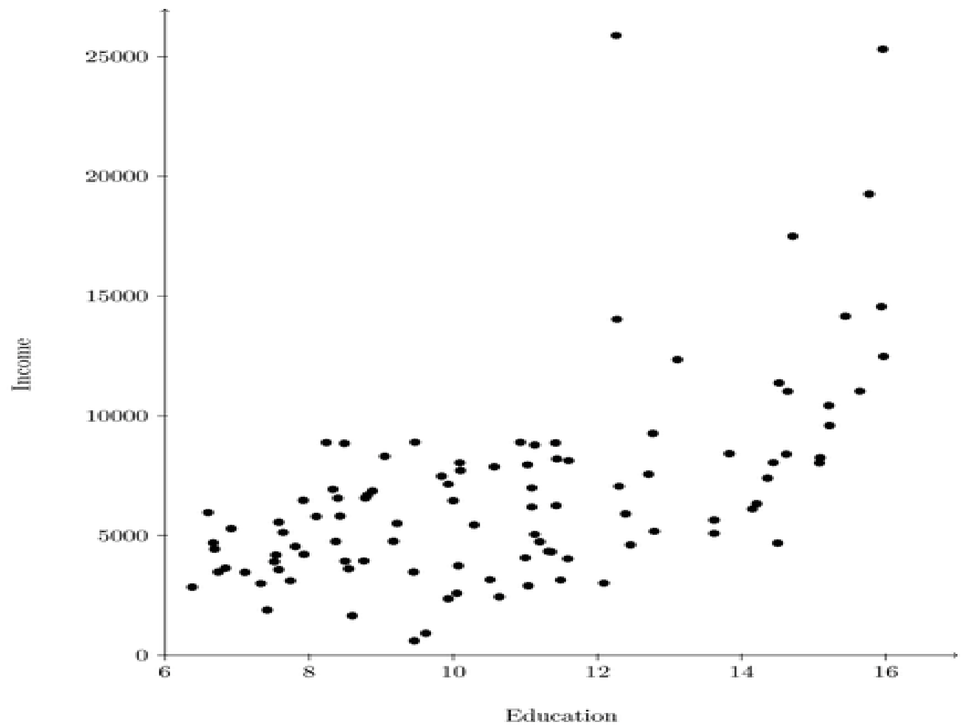

Figure 14. Example of scatter plot from [77]. X-variable is Education, Y-variable is Income

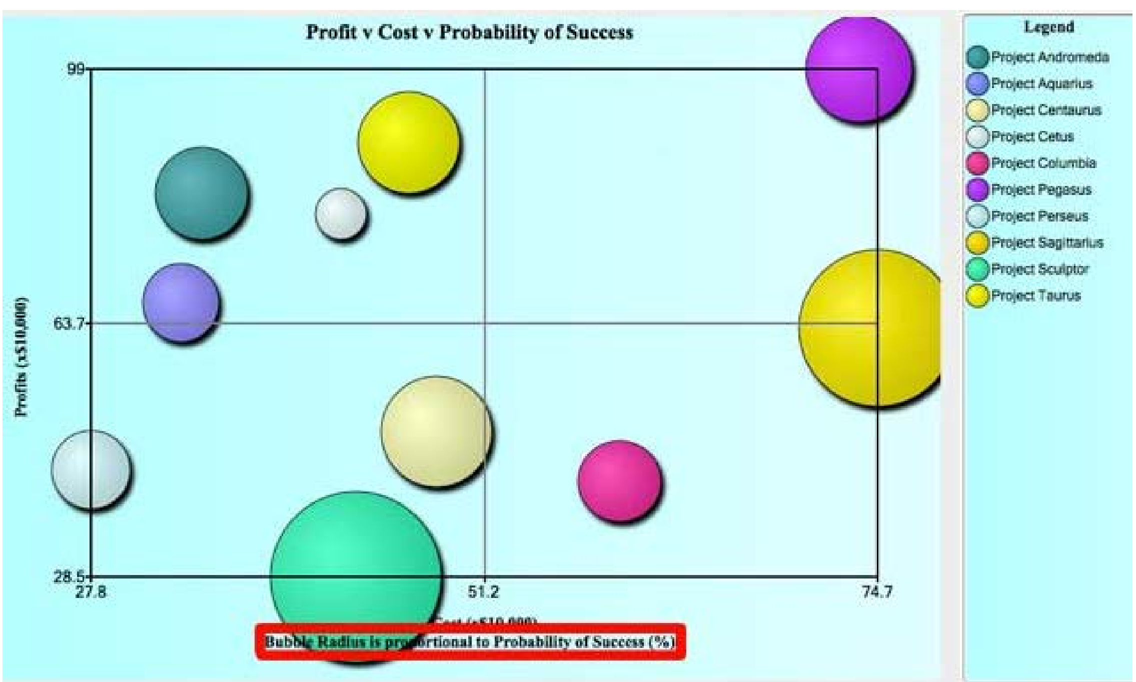

Figure 15. Example of bubble chart from [78]. X-variable is Cost, Y-variable is Profits, Color variable is Project name, and Size variable is Probability of Success

[77] http://www.texample.net/media/tikz/examples/PNG/scatterplot.png
[78] http://www.bubblechartpro.com/content/images/Bubble_Chart_Example_3.jpg

Example implementation and evaluation of goals

Scatter plots are virtually the best way to represent two-dimensional data, so if there are only two epoch variables, a scatter plot may be the best way to visually represent the entire epoch space. A rudimentary implementation of an interface using a scatter plot using 16 epochs is shown in Figure 16.

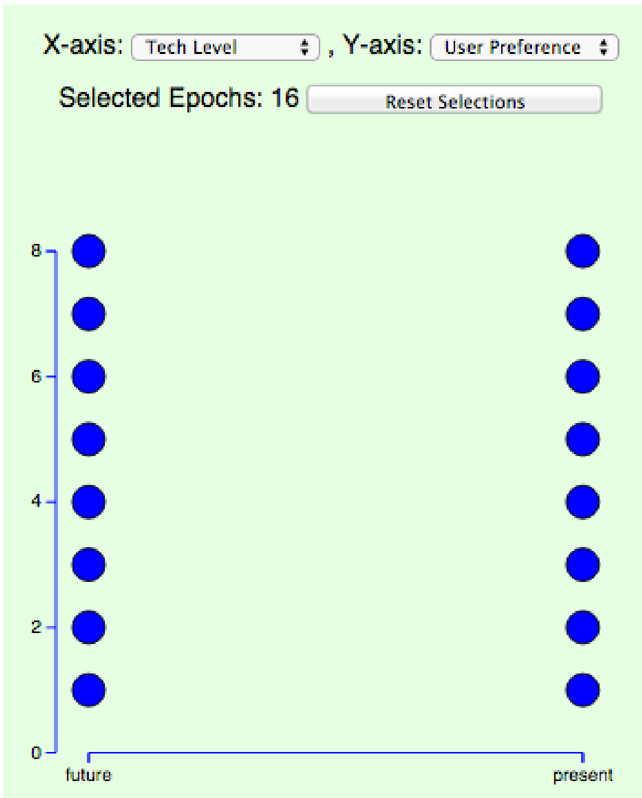

Figure 16. Example of IEEA Epoch Sampling implemented as a scatter plot. The epoch variables were "Tech Level," with values "future" or "present," and "User Preference," with values 1-8.

Given only two epoch variables, scatter plots clearly show the combination of the epoch variables defining each epoch (Goal #1), and based on this, a user can easily locate and select epochs of interest (Goal #2). All possible epoch alternatives can be displayed, with different hues/saturation/shading representing the respective points that can and have been explored, so the user can get a sense of the whole epoch space (Goal #3). Enabling dragging over several epochs to select them all would increase selection efficiency as well.

Other comments

If there are more than two epoch variables to display, each epoch will not necessarily have unique locations on a scatter plot (i.e., multiple different epochs will overlap and be indistinguishable). Even if more dimensions are encoded by size (area placing fourth on Cleveland and McGill's list), color (placing sixth), and shape, as in a bubble chart, points representing epochs will still be on top of each other in x-y space, so users will not have a clear way of separating them spatially to find and select, or to know how deep the epoch space actually goes, impeding Goal #1 and failing Goals #2 and #3.

PARALLEL COORDINATE PLOTS

Description

Parallel coordinate plots, as shown in Figure 17, display high-dimensional data by representing each variable on a vertical axis (in Figure 17, these variables are "Sepal Width," "Sepal Length," "Petal Width," and "Petal Length") that are not necessarily scaled the same. An individual ("horizontal") line spanning the axes represents the point that takes the values of each variable it intersects. For example, following the red line at the top of the "Sepal Width" axis, the corresponding entry seems to have the following approximate values: Sepal Width – 4.4, Sepal Length – 5.8, Petal Width – 0.4, Petal Length – 1.5. Additional characteristics can be encoded in color, as in Figure 17, but are not necessary.

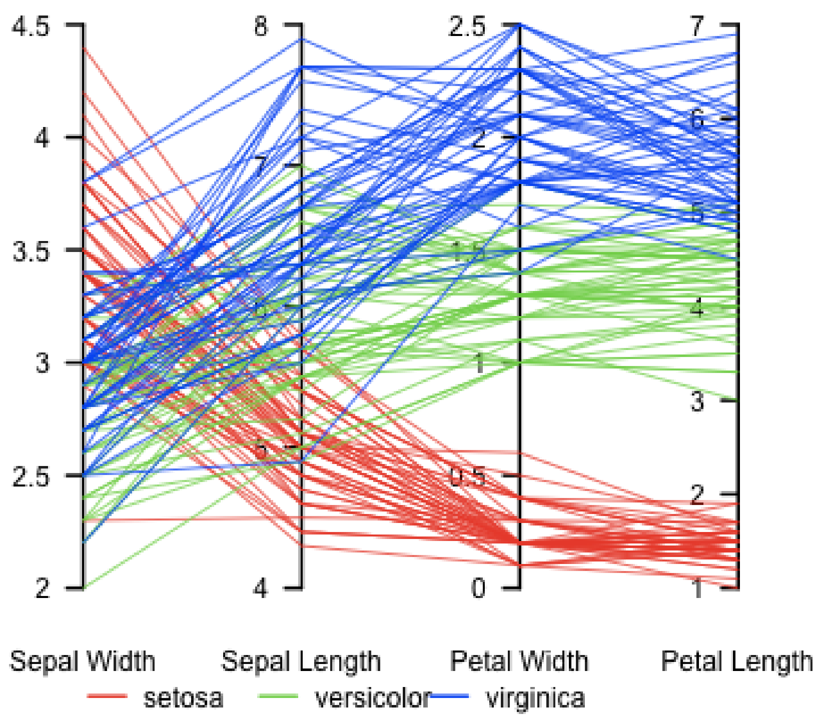

Figure 17. Example of Parallel Coordinate Plot, from [79]

Example implementation and evaluation of goals

Parallel coordinate plots are quite effective at representing and revealing patterns in high-dimensional data when each data point has slightly different values. However, since epochs can be generated as a full factorial of epoch variable combinations, many share more than one variable value, causing this representation to suffer from the same spatial ambiguity problem as

[79] en.wikipedia.org/wiki/Parallel_coordinates

greater-than-two-dimensional scatter plots. In other words, the enumeration of epoch variables causes each segment between adjacent axes to be shared among many epochs, again hiding epochs that share the same segment, or location, from the viewer.

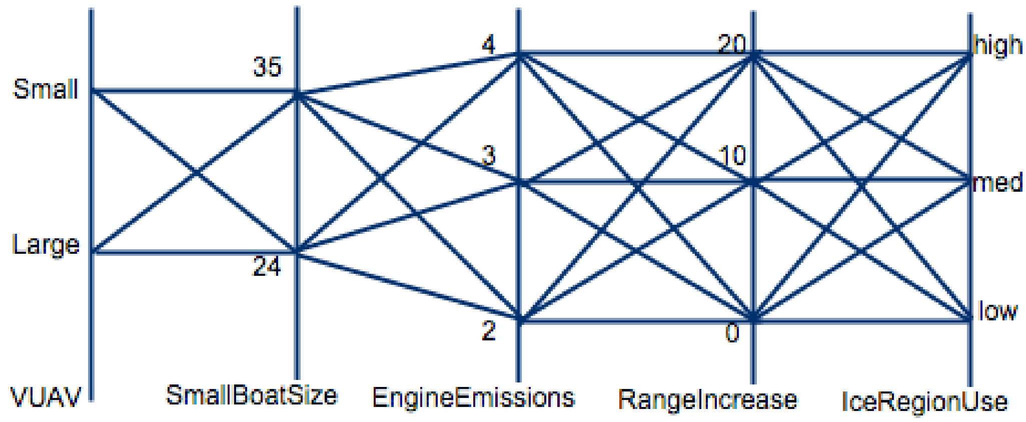

Figure 18. Example of IEEA Epoch Sampling sketched as a Parallel Coordinate Plot

An example sketch of this is shown in Figure 18, using the five epoch variables from the Next Generation Combat Ship (NGCS) dataset developed by Schofield. These epoch variables are VUAV, SmallBoatSize, EngineEmissions, RangeIncrease, and IceRegionUse (Schofield 2010; Schaffner 2014)[80,81]. As an example, two epochs that share the same values for VUAV and SmallBoatSize will share their first segment, but viewers would not be able to tell that the segment encoded more than one entry, skewing interpretation of the epochspace. For this reason, parallel coordinate plots, as with higher-dimension scatter plots, impede Goal #1 and fail Goals #2 and #3.

__Other comments__

It is worth noting that while parallel coordinate plots do not work well as a visualization technique for epoch sampling, they could be quite useful in depicting design alternatives for multi-epoch or -era analyses when the number and variability of designs is so high that patterns may emerge in the groups of design lines. Additionally, modifications to the standard parallel coordinate plots have been done in order to overcome some of the aforementioned shortcomings. As an example, line segment width can be used as an indication of number of overlapping segments (e.g., a thicker line segment indicates more overlapping). Further modifications, leveraging user interactivity, will be discussed in a later section below.

[80] Schofield, D.M. "A framework and methodology for enhancing operational requirements development: Unites States Coast Guard cutter project case study." Massachusetts Institute of Technology, 2010.

[81] 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

Description

The next three visualization techniques require epoch variable data to be stored in a tree structure to pass into built-in D3.js layouts. Trees make it fairly straightforward to visualize all of the options at each variable, making this visualization technique very useful for hierarchical data. To find the characteristics of a certain leaf node (at the bottom of a tree), one traverses up the path to the root from the leaf. Similarly, to find a node with specified values for each variable, traverse down the corresponding paths from the root to reach that node. An example diagram of an unlabeled tree visualization is shown in Figure 19. Each branching point represents alternative enumeration values for the variable at a given level of the tree.

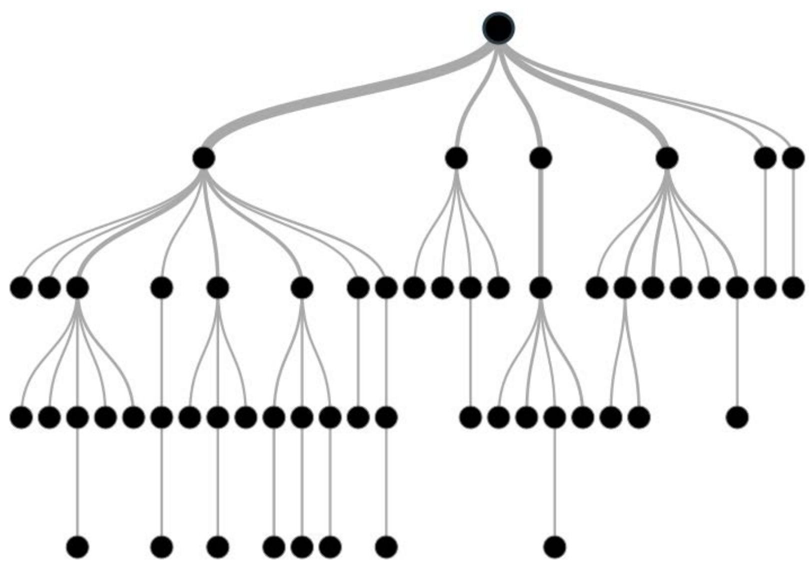

Figure 19. Example unlabeled tree visualization, from [82]

Example implementation and evaluation of goals

In our implementation, we organize the data so that each epoch variable is a fixed depth into the tree, and the epochs are the leaves. One such implementation, using the five epoch variables from the NGCS database is shown in Figure 20. In this implementation, clicking nodes toggles the visibility of their children/descendants. Filled in blue circles signify that the node contains hidden children, and white circles signify that the node has been expanded. At each node, the variable name and value is displayed. To select epochs, the user must click into 'SELECT mode,' in which clicking nodes adds all descendant epochs to the list of selected epochs (e.g. Clicking Epoch #8's parent node 'IceRegionUse: high' would only select Epoch #8, whereas clicking the root node 'All Epochs' would select all 108 enumerated epochs). The variables' levels in the tree

[82] https://littleml.files.wordpress.com/2012/01/screen-shot-2012-01-23-at-10-00-17-am1.png

can be reordered for easier mass selection (e.g., if I only want to select epochs with IceRegionUse: high, I can reorder IceRegionUse to be at the top of the tree, and only expand out that node).

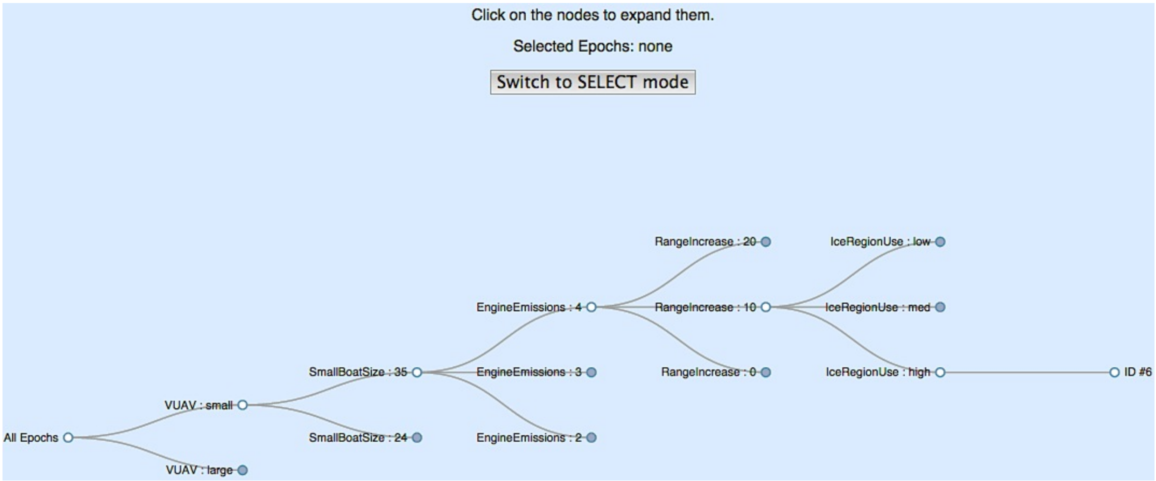

Figure 20. Example of IEEA Epoch Selection on NGSC data implemented as a Tree

Evaluating this interface with regard our epoch sampling goals, it does present a clearly defined pathway to every epoch, so users should easily be able to tell how epochs are defined and how to find and select epochs based on epoch variable levels (meeting Goals #1 and #2). If all of the nodes were expanded, the user would be able to see the size of the full epoch space, and further hue/saturation/shading could indicate the epochs the user is able to and already has explored (meeting Goal #3).

TREEMAPS

Description

Treemaps are another built-in D3.js layout in which tree nodes are represented by rectangles, and "parent" rectangles are recursively partitioned into smaller "children" rectangles. Again, this is very effective for hierarchical data, as well as representing all of a tree's leaf nodes compactly (Wang 2006)[83]. There is the option of encoding additional values in shapes' color and size to reveal more attributes of leaf nodes, but this capability is not necessary for simply viewing the whole epoch space. Treemaps are generally good for representing trees when the distribution of children is non-uniform, so that they can display the variety at a glance. An example of such a treemap is shown in Figure 21, displaying the populations of all the countries in the world. The tree structure in this example stores the six continents as the children of the root, and each continent's children are all the countries that belong to that continent. The divisions between continents in the figure are denoted with bold black lines, whereas those between countries are

[83] Wang, Y., Teoh, S.T., Ma, K. "Evaluating the Effectiveness of Tree Visualization Systems for Knowledge Discovery." Eurographics/IEEE-VGTC Symposium on Visualization, 2006.

simply gray. In this example, the country's population is encoded in area and its Gross National Income (GNI) is encoded in color.

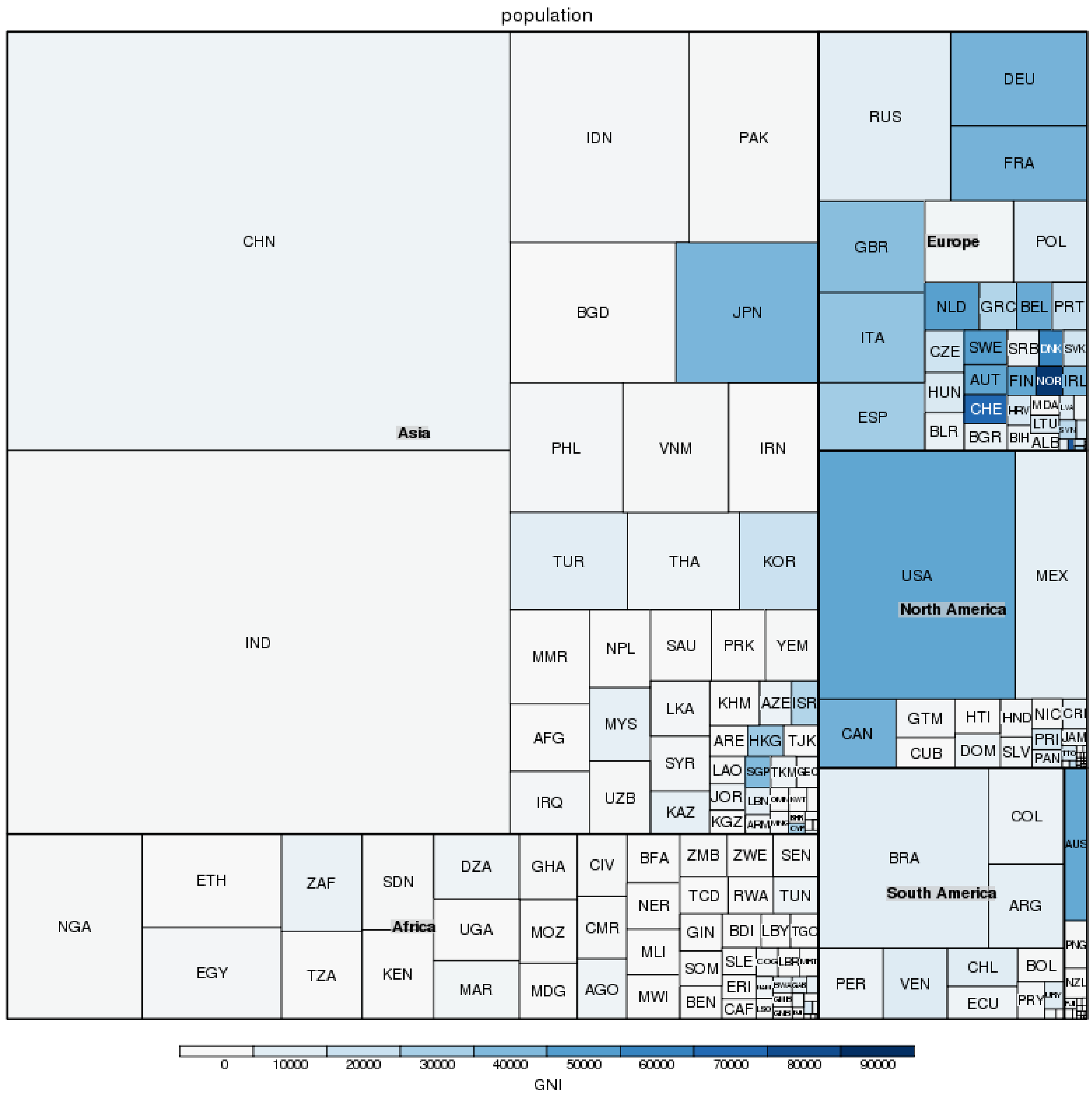

Figure 21. Example treemap of country population by continent, from [84]

Example implementation and evaluation of goals

In the case of epoch sampling, since all sibling nodes contain a copy of the exact same descendants, the treemap can be very repetitive and boring, as seen in Figure 22, which again uses the aforementioned NGCS epochs. It is difficult to distinguish differences because of the nodes' shared boundaries, but the root node (the outermost rectangle) has first been divided into two parts (as the first epoch variable in the tree, VUAV, has two values), then each of those

84 http://www.eecs.tufts.edu/~rveroy/stuff/GNI2010-treemap.png

has been divided into two parts (the second variable also has two values), and so on, down to the leaves of the tree, the epochs.

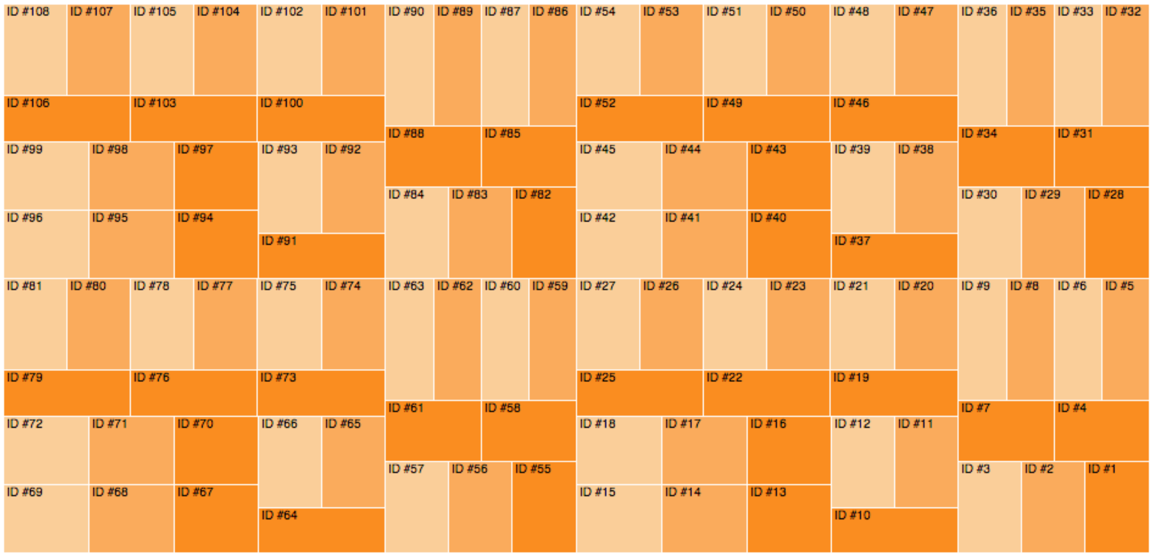

Figure 22. Treemap visualization of NGCS epochs

In terms of evaluating this visualization, all of the epochs (the smallest division of rectangles) are easily seen at a glance, but their hierarchy, and characteristics, are difficult to distinguish. Thus, while our third goal can be easily accomplished by different hue/saturation/shading to compactly display the fraction of all possible epochs selected, static treemaps do not provide help to accomplish Goals #1 and #2 at all.

Circle Packing

Description

Circle packing is yet another built-in D3.js layout in which tree nodes are represented by shapes. In this visualization, children nodes are recursively packed into parent circles to fill the area as compactly as possible, again proving very effective for hierarchical data. Again, there is the option of encoding additional values in shapes' color and size, but this capability is not necessary for simply viewing the whole epoch space. Figure 23 shows an example of a circle packing layout (the original circle packing tutorial on the D3 page, in fact), showing the Flare[85] class hierarchy. The largest (outermost) circle represents the root node. Bigger circles encompass all their children, which in turn encompass all their children until the tree's leaves are reached (the smallest circles). In this example, the leaves have been colored orange while all intermediate nodes are shades of blue.

[85] Flare Data Visualization library, http://flare.prefuse.org/

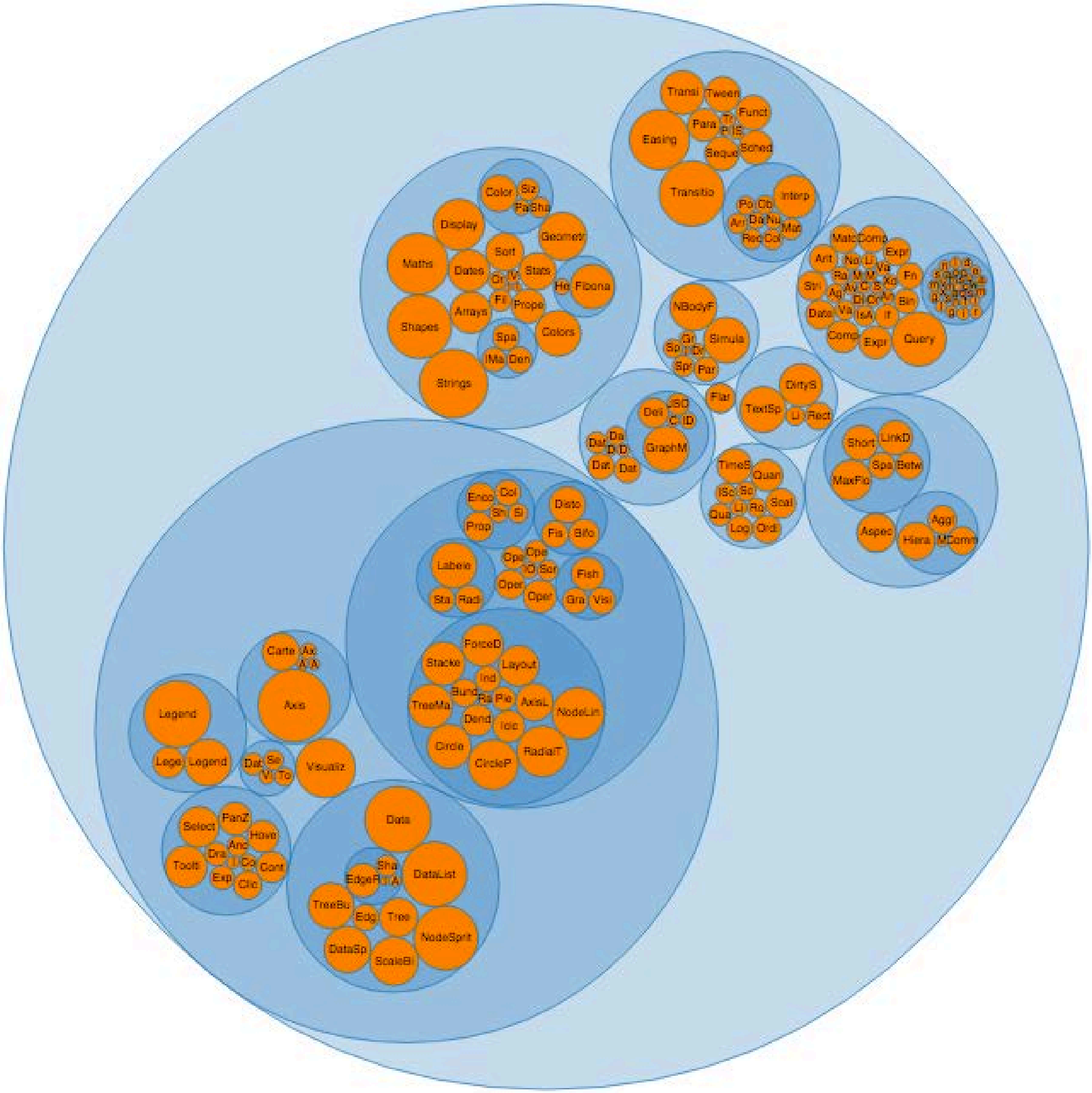

Figure 23. Example circle packing layout, from [86]

Example implementation and evaluation of goals

Figure 24 shows an example implementation, again using the NGCS dataset. Given a particular hierarchical sequence of epoch variables, the circles represent that sequence in decreasing radius of the packed circles. As shown in the figure, VUAV can take on two values and is represented as two circles in the left pane. The next level down the hierarchy shows the three levels of EngineEmissions, represented by the three circles contained within each VUAV circle. The right pane shows a zoomed in version of one of the VUAV circles to highlight the contained circles.

86 http://bl.ocks.org/mbostock/raw/4063530/

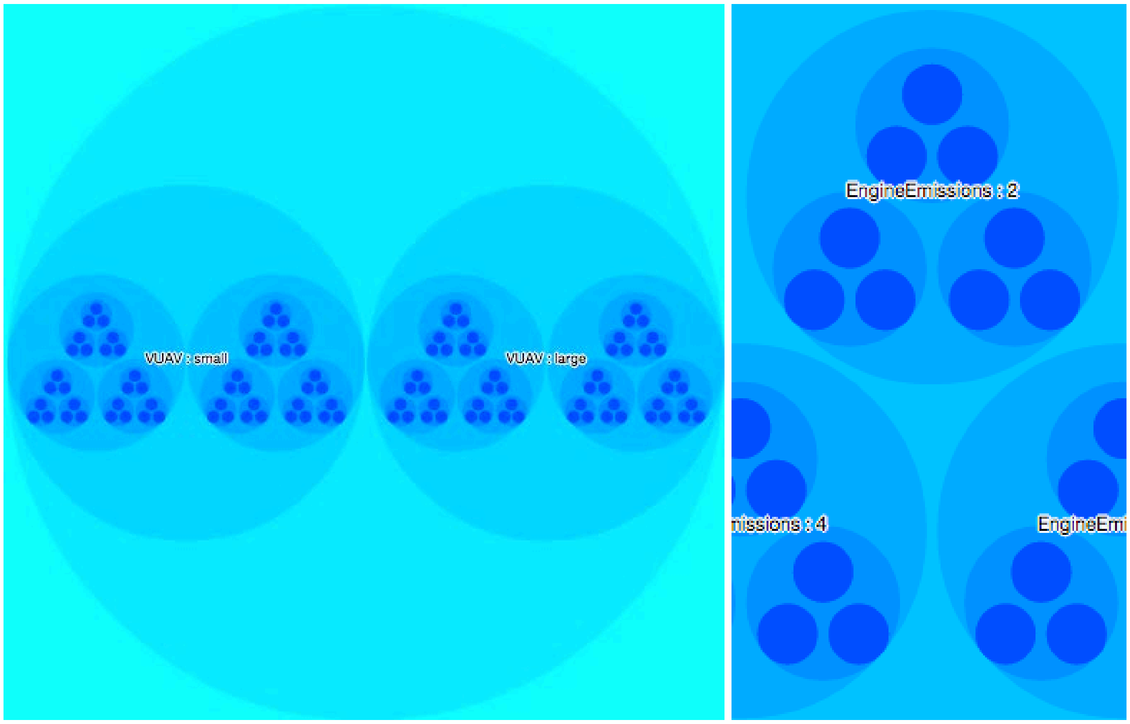

Figure 24. Circle packing visualization of NGCS epochs as seen at different zoom levels

As with treemaps, circle packing easily lends to the accomplishment of Goal #3, allowing the user to get a sense of the whole epoch space (as well as how many variables go into each epoch – encoded by the number of circle layers), as seen in the left pane of the figure. Our particular implementation of the circle packing visualization actually also allows users to zoom to any portion by clicking on corresponding circles, as seen in the right pane. Through this, a user can click through to any particular epoch based on the variable values from higher levels, helping with Goal #2. Finally, if for some reason a user is very zoomed in to a particular epoch and wants to understand the variables that went into creating it, s/he can easily zoom out layer by layer to discover them (meeting Goal #1).

<u>Other Comments</u>

While both the treemaps and the circle packing visualizations provide the opportunity to view the entire epoch space at a glance, it is easier to recognize levels in circle packing, as the boundaries for rectangles overlap, whereas the boundaries of circles do not. It should be noted that the ability to zoom can also be implemented on treemaps, but for the fully enumerated epoch data, as the rectangles are all still the same size, their shared boundaries will not make this feature as useful as it is for circle packing.

EVALUATION OF PROPOSED IMPLEMENTATIONS

This section summarizes the evaluation of the various considered visualizations techniques for use in Epoch Sampling. To review, the evaluative criteria are as follows:

1) Is the visualization good for two epoch variables?
2) Is the visualization good for more than two epoch variables?
3) Does the visualization help the user understand specific epoch definitions? (Goal #1)
4) Does the visualization help the user find and select epochs? (Goal #2)
5) Does the visualization help the user understand a) epoch space size, b) fraction available to explore, and c) fraction already explored? (Goal #3)

The three possible answers to these questions are:

- "Yes" – This visualization achieves the goal.
- "Ok" – This visualization is mediocre; does not actively help nor hurt to achieve the goal.
- "No" – This visualization hinders the achievement of, or does not achieve, the goal.

Criteria 2-5 are answered assuming there are greater than two epoch dimensions. Table 1 summarizes the relevant features of the proposed implementations from the discussion above in the context of our IEEA Epoch Sampling goals. The best alternative, as reviewed for the Epoch Sampling module, for each row is highlighted.

Table 1: Summary of characteristics for each visualization, with best alternative for each row indicated.

Visualization Type:	**Scatter Plot**	**Parallel Coordinates**	**Tree**	**Treemap**	**Circle Packing**
Good for **two** dims	<u>Yes</u>	Ok	Ok	Ok	Ok
Good for **multi** dims	No	Yes	<u>Yes</u>	Yes	Yes
Goal #1 (understanding)	Ok	Ok	<u>Yes</u>	No	Yes
Goal #2 (find & select epochs)	Ok	No	<u>Yes</u>	No	Yes
Goal #3 (view epochspace/fracs)	Ok	No	Yes	Yes	<u>Yes</u>

As seen, for the case of two epoch variables, the scatter plot is best available option (note that the scatter plot meets all goals in the two-dimensional case). For multiple dimensions, the tree visualization meets all three of our defined goals, making it the single best alternative. However, the most promising visualization technique for epoch sampling among these choices seems to be a coordinated combination of the circle packing with the expandable tree, as the circle packing surpasses the tree in its ability to facilitate Goal #3, in order to optimize the abilities of both of these visualizations individually.

NEXT STEPS

Immediate next steps will be integrating aspects of scatter plots, trees, and circle packing into a demonstration implementation, as well as developing prototypes for the other parts of IEEA and evaluating their functionality based on user goals for these modules. Informal user interviews may be conducted to ensure module goals stay accurate. While we have been able to evaluate functionality of various visualizations as described, future studies should test them on users from the population of decision-makers/analysts who would actually need to use such a tool.

USABILITY AND FUTURE CONSIDERATIONS

Functionality is only one attribute of a system. Analogous to Ricci and Schaffner's concepts of "trust" and "truthfulness" in a model (Ricci 2014)[87], flawless functionality of a system ("truthfulness") does not guarantee usability ("trust"). This usability can only be earned with good interface design. Now that we have presented and evaluated the functional visualization techniques based on a particular module's goals, we next consider the usability criteria for evaluating the interfaces that display these visualizations to users. These criteria include learnability, efficiency, and error-tolerance (based on Miller 2011)[88].

LEARNABILITY

When evaluating the learnability of visualizations, some questions to consider include:

- Is it easy to learn at first?
- How helpful is the interface?
- Can tasks be completed and mastered without outside help?
- Does it have built-in instructions or guidance?

While many pieces of technology were developed with the assumption that users would read a manual or take a class first, that is increasingly not the case. More often than not, users are goal-oriented, and will learn to operate a system by way of exploring how to complete tasks (learning by *doing*) or by seeing others complete a task (learning by *watching*). If users need help from the system along the way for whatever reason, the help must be searchable and *goal-oriented* in order to be most effective. As visual cues are much easier to aid in user memory ("*recognition*" – knowledge in the world) than no such help ("*recall*" – knowledge in the head), it is important that systems somehow help the user rather than require the user to remember everything about its operation. As mentioned in the previous section with functionality, *consistency* is important within the interface as well as externally (so perhaps users can transfer existing knowledge from other applications to aid in using this interface). Quick, visible system *responses* are also critical so that the user can get immediate feedback on whether or not they have actually done something. If an interface has multiple states or modes, these should also be very apparent to the user (and their transitions, if applicable). Finally, the interface should provide *affordances*, or the ability of an object to appear that it can be used in a certain way. For example, a text box

[87] 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.

[88] Miller, R. 6.831 User Interface Design and Implementation, Spring 2011. (Massachusetts Institute of Technology: MIT OpenCourseWare)

offers the affordance that a user can click into it and type. Ideally, an object's perceived properties to the user should match its actual properties, so the user knows exactly what s/he is to do with the object (Miller 2011).

EFFICIENCY

When evaluating the efficiency of visualizations, some questions to consider include:

- Once learned, is it fast to use?
- How long does it take to complete common tasks?
- Does the interface feel efficient to users?
- Are there bottlenecks or shortcuts?

Once a user is familiar with a system, s/he tends to group parts of it in a unit of memory. This is called "*chunking*," and good interfaces should present information in such chunks that are easily recognizable by the user. The interface should also be fast to navigate, in terms of *pointing* and *steering*. Fitts's Law, T = a + b*log(D/S+1) = RT + MT, represents the time T it takes to move your hand to a target of size S and distance D, or the reaction time RT plus the movement time MT. This law for pointing has many implications for interface design to speed up pointing time, such as the fact that targets at the edge of the screen are easy to hit, whereas unclickable margins require increased accuracy. To aid with pointing efficiency, it is good to make frequently-used targets bigger and put them near each other. There is a similar law for steering, T = a + b*D/S, representing the time T that it takes to move your hand through a tunnel of length D and width S. The index of difficulty, represented by the constant b, is now linear instead of logarithmic, showing that steering is much harder than pointing. Thus things like requiring the user to steer through narrow tunnels on the screen will severely damage efficiency. Keyboard *shortcuts* or anticipating the user's next movement (e.g., autocomplete) also help users to perform tasks faster (Miller 2011).

ERROR-TOLERANCE

When evaluating the error-tolerance of visualizations, some questions to consider include:

- Are errors few and recoverable?
- Does the design help to prevent errors?
- Does it help when errors occur?

Human error is unavoidable. Slips (failure of execution) and lapses (failure of memory) are fairly common simply due to inattention, but interfaces should take measures to prevent complete mistakes (using the wrong procedure for a goal). Some ways of accomplishing this are avoiding actions with similar descriptions, avoiding habitual action sequences with identical prefixes, and/or adding confirmation dialogs, clearly marked exits, manual overrides, error messages or the ability to undo (Miller 2011).

FUTURE CONSIDERATIONS

The marriage of functionality and usability does not necessarily cause user satisfaction, just as with truthfulness and trust, but ensuring that these questions are addressed by any interface will greatly boost the chances. Immediate next steps in this area will be to evaluate interfaces holistically on these criteria, conducting informal user studies if possible. As with functionality, usability questions can be answered subjectively for any interface, but for more thorough and accurate evaluations, future efforts should aim to conduct user studies drawing from the population at which this tool is directed.

ADDITIONAL INTERACTIVE EEA VISUALIZATION PROTOTYPES

Collaborative web-based tools similar to the IEEA demonstration prototypes described in the following sections are not a new concept and have previously been discussed in works by Heer[89] and in applications specific to engineering design by Liu[90]. As noted previously, Spero[91] performed a holistic review of 81 existing tradespace exploration tools and found wide variability in the implementations and types of functions performed by various existing tools. The Framework for Assessing Cost and Technology (FACT), currently in use by the U.S. Marine Corps Systems Command (MCSC), is the only extensively developed, web-based systems engineer implementation reviewed by Spero and has been described in detail in other literature[92,93,94]. FACT is a sophisticated tool for performing tradespace exploration that allows designers to explore tradeoffs in system attributes for user-selected restrictions on design variables and performance variable ranges. The prototypes described here provide a proof of concept for additional capabilities for IEEA that specifically consider multiple stakeholder needs and future changes in context and/or mission.

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89 Heer, J. and Agrawala, M., “Design Considerations for Collaborative Visual Analytics,” Information Visualization, 7(1):49–62, 2007.

90 Liu, Xiaoqing Frank, Samir Raorane, and Ming C. Leu. 2007. "A Web-Based Intelligent Collaborative System For Engineering Design," In Collaborative product design and manufacturing methodologies and applications, pp. 37-58. Springer London.

91 Spero, E., Bloebaum, C., German, B., Pyster, A.,and Ross, A., "A Research Agenda for Tradespace Exploration and Analysis of Engineered Resilient Systems," 13th Conference on Systems Engineering Research, Redondo Beach, CA, March, 2014.

92 O’Neal, M., Ender, T., Browne, D., Bollweg, N., Pearl, C.J., and Brico, J., “Framework for Assessing Cost and Technology: An Enterprise Strategy for Modeling and Simulation Based Analysis.” MODSIM World 2011 Conference and Expo, Virginia Beach, VA, October 14.

93 Ender, T., Browne, D., Yates, W., and O'Neal, M., "FACT: An M&S Framework for Systems Engineering." The Interservice / Industry Training, Simulation & Education Conference (I/ITSEC), vol. 2012, no. 1. National Training Systems Association.

94 Browne, D., Kempf, R., Hansen, A., O’Neal, M., and Yates, W., "Enabling Systems Modeling Language Authoring in a Collaborative Web-based Decision Support Tool." Procedia Computer Science 16: 373-382, 2013.

EARTH-IMAGING SATELLITE CONSTELLATION CASE STUDY

Preliminary work exploring techniques from visual and big data analytics with applicability to EEA has been investigated through application to a previously developed case study. The case study implements parametric models of an Earth-imaging satellite constellation to analyze trades in performance and cost. Design variables such as number of satellites per orbital plane, number of planes, optics size, and altitude are evaluated against measures of performance such as optical resolution, target revisit time, percent global coverage, and lifecycle cost. A summary of the integrated, multidisciplinary system model used for this case study is shown in Figure 25. For brevity, details of the case study will not be repeated here, but interested readers are referred to the earlier paper for detailed descriptions of the case study implementation[95].

The original case study, analyzed using traditional tradespace exploration (TSE) and multidisciplinary optimization (MDO) techniques, was extended to demonstrate EEA. To that end, 3 different system stakeholders (military, commercial and earth science users), each with differing value functions, and 2 possible future contexts were considered. This results in 6 unique epochs. The lone context variable evaluated whether a disturbance event occurs that results in the loss of a percentage of the satellites within the constellation and thus diminished value delivery of the overall system.

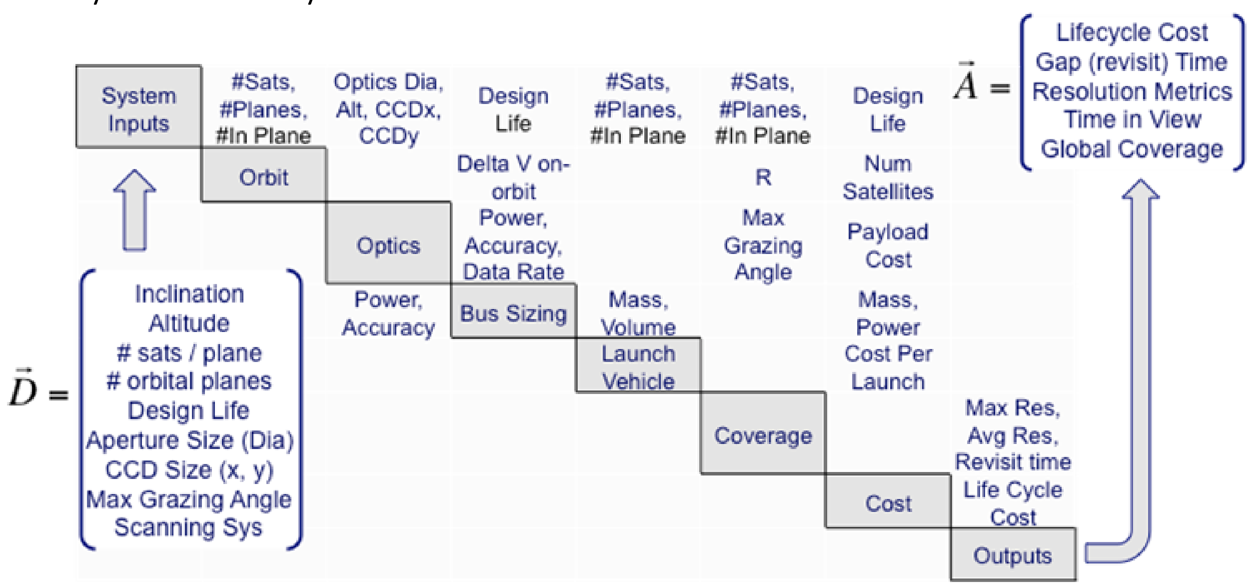

Figure 25. N² diagram representing integrated multidisciplinary parametric models of an Earth imaging satellite constellation

WEB BROWSER-BASED TOOL IMPLEMENTING COORDINATED VISUALIZATIONS

Implementation of an IEEA demonstration needs to draw on a combination of the techniques described. This means that IEEA needs to take into account the practicality of representing large

[95] Curry M, La Tour P, Slagowski S., "Multidisciplinary Design Optimization For A High-Resolution Earth-Imaging Constellation," IEEE Aerospace Conf 2015. Big Sky, MT, March, 2015.

amounts of data effectively given scarce communication resources (e.g., limited spatial or temporal resolutions due to hardware or software constraints)[96]. Given the volume and complexity of the data that will need to be analyzed, IEEA methods and tools should be capable of providing data to the decision-maker in a way that enhances cognition. A demonstration of the above discussed techniques for coordinated visualization, OLAP and data reduction methods was implemented in several prototype web browser-based tools similar to those described by Sitterle et al.[97]. To improve information cognition by the user, guidelines for effective coordinated visualization[98] and animated data transition[99] were applied.

Figure 26 below shows a screenshot of scatterplot representations of the utility (value) versus lifecycle cost of available design alternatives. The two scatter plots correspond to design values evaluated in epoch 1, the baseline case, and epoch 5 which represents a situation in which stakeholder preferences for individual performance attributes has changed. The left-hand plot shows the utility versus cost of the alternatives evaluated in epoch 1. The right-hand plot shows the same alternatives evaluated in epoch 5 and it is clear that the resulting tradespace has been distorted, relative to epoch 1, due to a change in the stakeholder preferences. To further convey that information to the user, histograms of cost and utility are displayed with each plot.

If a decision-maker believes that it is possible that the system will experience both epoch 1 and 5 over the course of its lifetime, then they might prefer a design to be Pareto efficient in both epochs. However, since the shape of the tradespace has changed between epochs 1 and 5, a decision-maker should not necessarily expect designs that were previously on the Pareto front to remain there in the new epoch. Applying the concepts of brushing and linking between coordinated visualizations, the user can interactively draw a lasso around Pareto efficient designs of interest in epoch 5 and receive immediate feedback on where those same designs appear in epoch 1.

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[96] Keim D., “Designing Pixel-Oriented Visualization Techniques: Theory And Applications,” IEEE TVCG (2000); 6(1): 59–78.

[97] Sitterle V, Curry M, Ender T, Freeman D., “Integrated Toolset And Workflow For Tradespace Analytics In Systems,” INCOSE Int’l Symp 2014. Las Vegas, NV, 2014.

[98] Scherr M., “Multiple And Coordinated Views In Information Visualization,” Media Informatics Advanced Seminar on Info Vis. 2008/2009.

[99] Heer J, Robertson G., “Animated Transitions In Statistical Data Graphics,” IEEE Trans on Vis and Comp Graphics (2007); 13(6): 1240-1247.

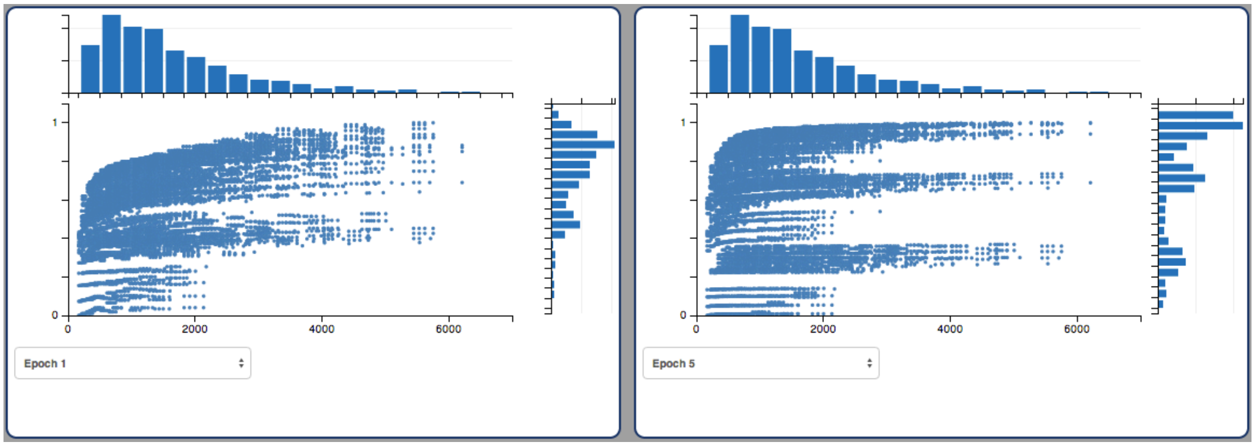


Figure 26. Web-based tool showing coordinated scatter plots and histograms

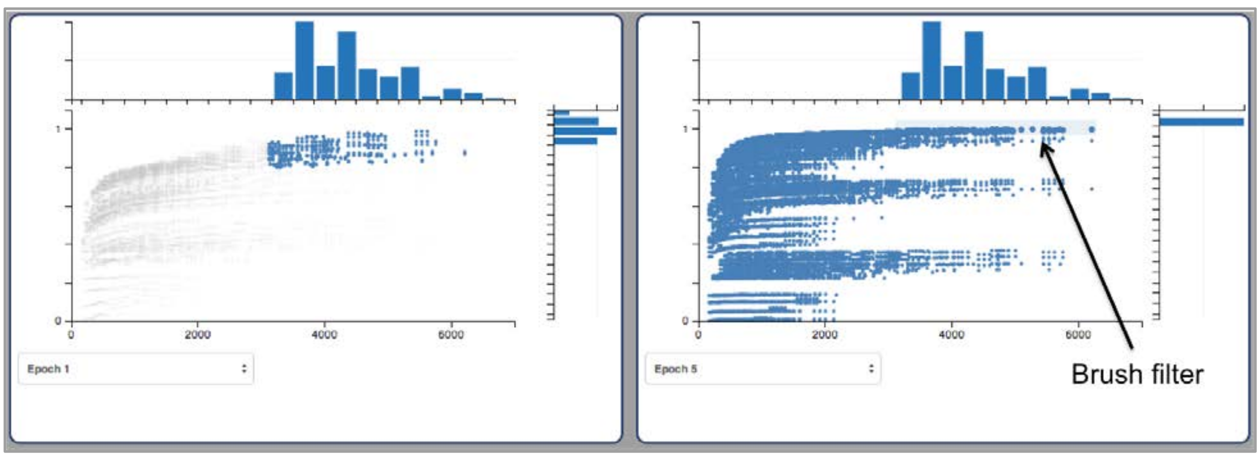


Figure 27. Brushing to filter designs across coordinated views

As shown in Figure 27, all of the coordinated visualizations (e.g., epoch 1) are updated simultaneously to reflect only the designs selected through brushing (in epoch 5). It is clear from the combined visualizations that while the selected points are Pareto efficient in epoch 5, some of them deviate from the Pareto front in epoch 1. User cognition of this conclusion is reinforced by the utility histograms to the right of each scatter plot that show that the tight distribution of utilities in epoch 5 are now more spread out in epoch 1. In addition to brushing, a user can also interactively filter data by clicking on the histogram bars to effectively filter out all but a selected slice of the data. As shown in Figure 28, by clicking on the y-axis histogram of the right hand figure, data not associated with those bars is grayed out in the coordinated views.

Enhanced understanding of the impacts of a decision on multiple epochs can be very powerful as demonstrated in this example. Much of that power is driven by the rapid response between visualizations provided to the user interacting with them. As previously discussed, OLAP techniques can be applied to slice, dice, drill down, roll up or compute pivots of the hyper-dimensional data cube representing design alternatives over epochs and eras. For the example presented here, Crossfilter, a JavaScript library which functions like a client-side OLAP server, has been used to allow rapid filtering between scatterplot views and to accelerate grouping of the thousands of data points into the aggregated histogram views. Latency between user interactions with any visualization and the resulting updates in corresponding visualizations is on the order of milliseconds. This provides a seamless interactive experience, which should facilitate improved user cognition of the data on which they will base their decisions.

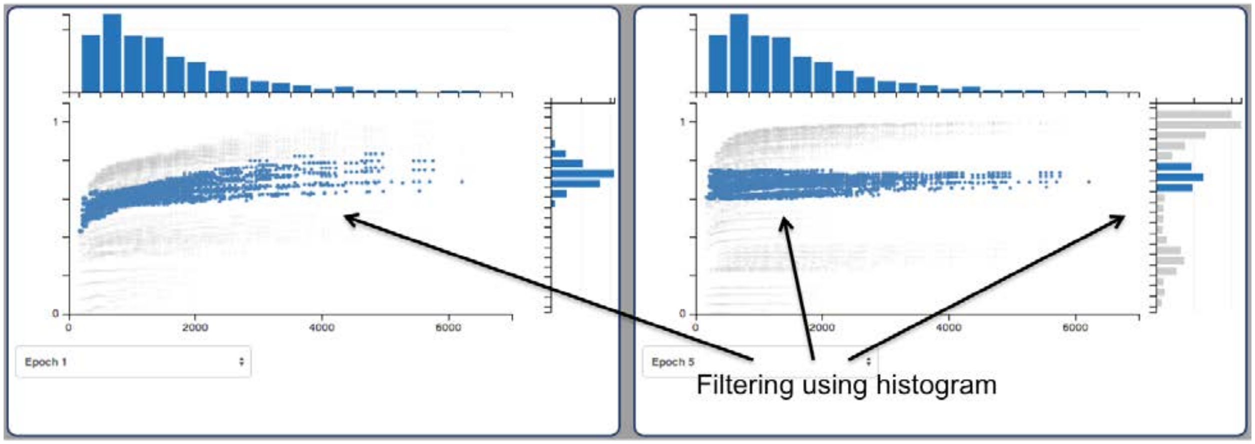


Figure 28. Coordinated views using histogram bin selection to slice data using OLAP

As the number of design alternatives and epochs grow, interactive coordinated visualizations can slow, as processing and rendering of the data becomes the limiting factor. Data reduction techniques can be applied in these situations to keep the large amounts of data from becoming unduly burdensome. Some past examples of EEA case studies utilizing filtering or sampling approaches include applications in the transportation[100] and space domains[101]. Since these approaches have the possible implication of concealing important information, we would prefer to use methods that allow us to represent all of the data. Binned aggregation can allow us to accomplish this aim.

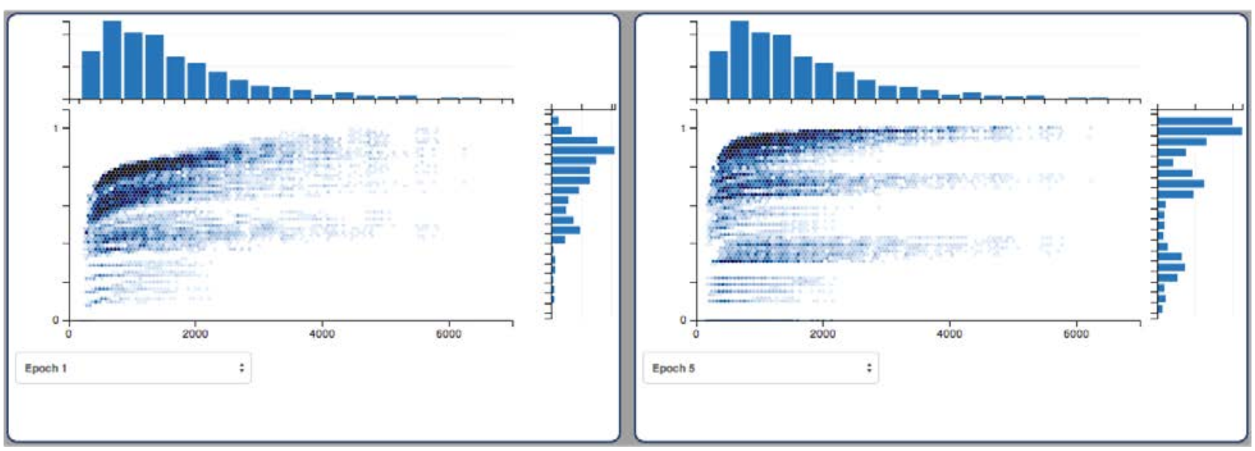


Figure 29. Coordinated X-Y scatterplot views with 2-D binned aggregation

[100] Nickel J., Using Multi-Attribute Tradespace Exploration For The Architecting And Design Of Transportation Systems, SM in Engineering Systems. Cambridge, MA: MIT, 2010.
[101] Roberts, C., Richards, M., Ross, A., Rhodes DH, Hastings DE., "Scenario Planning In Dynamic Multi-Attribute Tradespace Exploration," 3rd Annual IEEE Sys Conf. Vancouver, Canada, March 2009.

In the prior examples, histograms were a type of binned aggregation, since they reduced the larger set of points to a smaller set of rectangular bars reflecting the amount of data in each bin. This required projection of the 2-D data into a 1-D space. To allow a decision-maker to more fully appreciate the underlying features of the tradespace, we would ideally like to represent the 2-D data with fewer polygons, while simultaneously not reducing the number of dimensions. One technique for accomplishing this is to group data into rectangular bins and encode the density of points using color hue[102,103]. Some researchers have argued that hexagonal bins can better represent data over rectangular bins, to aid a user's interpretation[104]. A key rationale is the fact that hexagons have more sides and thus look more like circles, while providing a regular tessellation of a 2-D surface. Implementing the hexagonal binning approach on the running example significantly reduces the number of polygons required, and thus speeds up interactive rendering. A screenshot of the example implemented with hexagonal binning is shown in Figure 29.

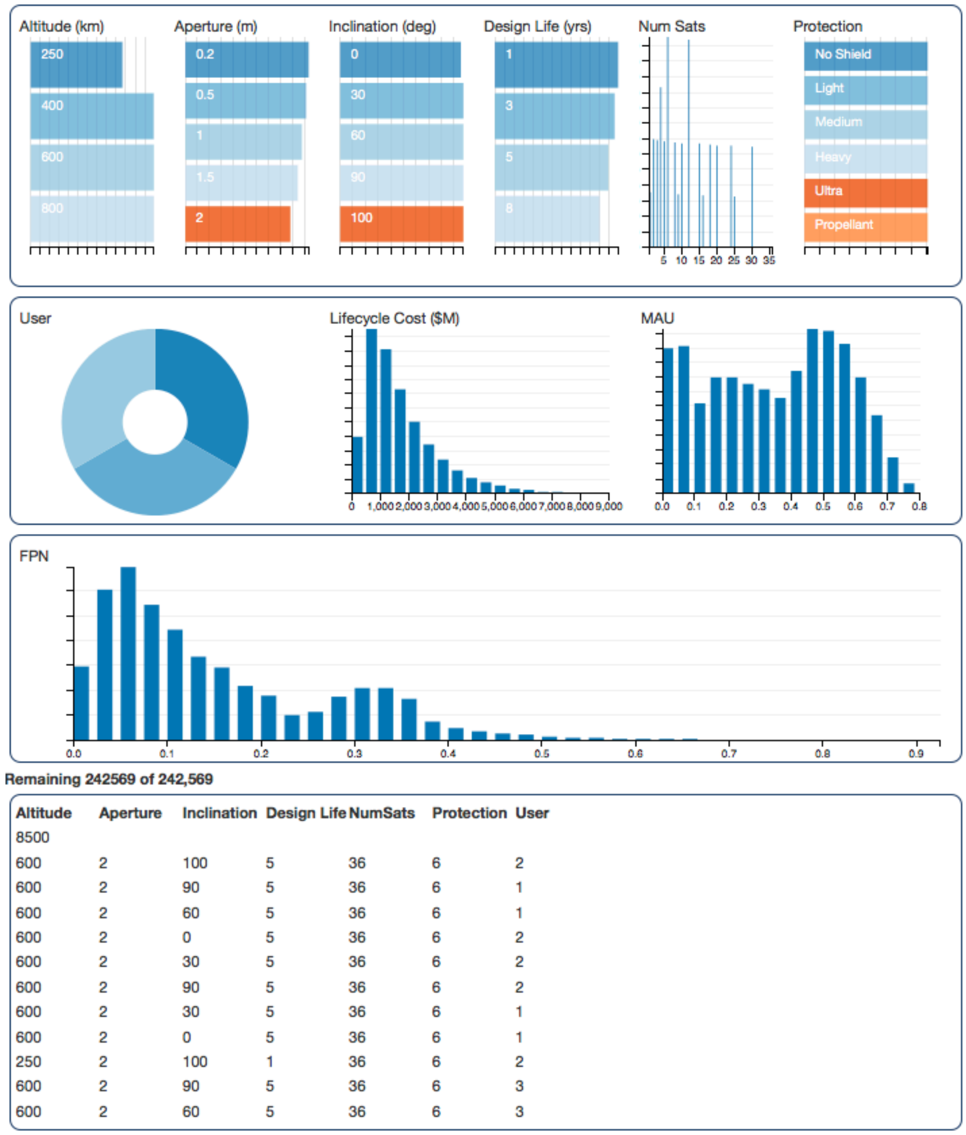
INTERACTION WITH LARGE DATASETS

The previous interactive example provides a relatively simple demonstration of the usefulness of coordinated visualizations and OLAP techniques for analyzing EEA problems. However, realistic problems, like those currently posed by the DoD as part of the ERS research initiative, will likely require the analysis of large numbers of designs, epochs and eras to provide insights to decision makers. A logical next question is therefore, "Do these interactive coordinated viewing techniques scale to larger data sets?". To test scalability, an interactive application with 10 coordinated displays was developed. The application, shown in Figure 30 and Figure 31, was tested using the previously described satellite constellation case study for a multi-epoch analysis case using almost a quarter million design/epoch pairs. This is several orders of magnitude larger than the previous example that only considered on the order of 10,000 design/epoch pairs and also significantly larger then EEA case studies described in previous literature.

[102] Liu Z, Jiang B, Heer J., "ImMens: Real-Time Visual Querying Of Big Data," Eurographics Conference on Visulization (EuroVis). 2013.

[103] Cleveland W, McGill R., "The Many Faces Of A Scatterplot," *Journal of the American Statistical Association* (1984); 79(388): 807-822.

[104] Carr D, Littlefield W, Littlefield J., "Scatterplot Matrix Techniques For Large N," *Journal of the American Statistical Association* (1987); 82(398): 424-436.



Altitude	Aperture	Inclination	Design Life	NumSats	Protection	User
8500						
600	2	100	5	36	6	2
600	2	90	5	36	6	1
600	2	60	5	36	6	1
600	2	0	5	36	6	2
600	2	30	5	36	6	2
600	2	90	5	36	6	2
600	2	30	5	36	6	1
600	2	0	5	36	6	1
250	2	100	1	36	6	2
600	2	90	5	36	6	3
600	2	60	5	36	6	3

Figure 30. Interactive Application with Multiple Coordinated Views

This application displays a summary of several key design variables in histogram charts on the top row. The middle row contains charts summarizing breakdowns of each system user (e.g. military, commercial and earth science), lifecycle cost for each design alternative, and the multi-attribute utility (MAU) of each design/epoch pair. The third row provides a histogram summary of the Fuzzy Pareto Number (FPN) of each design/epoch pair. The FPN of a particular design/epoch pair can be thought of as a percentage distance away from the Pareto Front[105]. Thus, as designers, we would ideally want a design to have an FPN of zero, indicating that the design is on the Pareto Front, across all epochs.

[105] Smaling, R., "Fuzzy Pareto Frontiers in Multidisciplinary System Architecture Analysis", 10th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference, Albany, NY, September 2004.

Much like the previous example application described above, this application allows the designer to apply filters to the data set by clicking on histogram bars, dragging a filter window across the bars or clicking on a section of the pie chart. A filter action within any particular chart automatically links to the other charts and updates them according to show only the filtered in data. The bottom row of the application provides a data table that summarizes the designs remaining within the data set after filters have been applied. The example shown in in the figure shows filters applied to design variables for protection (e.g. shielding or maneuvering propellant), epoch variables for user preference, and overall system performance as quantified by lifecycle cost, utility and FPN. The interpretation of this example is that the designer is leaving filtered in only designs that have no shielding, corresponding to only the military system user, system lifecycle costs below $1 billion, utility scores above 0.5 and FPN below 10%. This filters the number of designs under consideration quickly down from 242,569 to only 727 alternatives as shown in the summary table at the bottom. After application of the filters, updates of all charts and table elements take place in ~100 milliseconds which is generally regarded as sufficiently fast enough to maintain user engagement while they interact with the large data set.

Remaining 727 of 242,569

Altitude	Aperture	Inclination	Design Life	NumSats	Protection	User
1000						
800	0.2	60	1	18	1	3
600	2	60	3	4	1	3
400	1.5	90	1	6	1	3
400	1.5	100	1	6	1	3
600	1.5	100	1	6	1	3
600	1.5	60	1	6	1	3
600	1.5	90	1	6	1	3
800	1.5	100	1	6	1	3
800	1.5	60	1	6	1	3
800	1.5	90	1	6	1	3
400	0.2	100	1	15	1	3

Figure 31. Interactive Application with Coordinated Views showing use of data filters

ADVANCED VISUALIZATIONS FOR SINGLE AND MULTI-EPOCH ANALYSIS

The previously described interactive prototypes provide good demonstrations of some of the capabilities needed for IEEA such as multiple coordinated views, OLAP and data reduction techniques such as filtering and binned aggregation. Some exploratory work has also been performed on more compact coordinated visualizations that may improve the speed with which a designer can extract insights from data. As distances between user interface (UI) items on the screen get further apart the time it takes to interact with them should go up, thus slowing discovery and decision-making. Fitt's Law, a descriptive model of human movement primarily used in human–computer interaction (HCI) research, tells us that interaction time will go up logarithmically with increasing distance of required movement across the UI on the screen (Fitts

1954)[106]. The interaction time is also a function of the size of the UI item, such as a button, slider or data point on a graph. This is true for increasing distance between mouse clicks on controls and for eye movement between complementary UI charts or visualizations that a designer must use concurrently to reach a conclusion. Another important UI design concept often used in HCI work is the steering law. The steering law can be derived directly from Fitt's law and describes the amount of time it takes a user to move along a defined path using a pointing device, like their eyes, finger or mouse cursor (Rashevsky 1959)[107], (Drury 1971)[108]. This is an important concept to consider when a user is expected to interact, for instance, with nested menus, scroll bars or pop-up context menus.

As research on IEEA progresses, these and other UI design concepts will be considered when developing future demonstrations. A set of metrics that evaluate the usability and effectiveness of a particular prototype application for decision-making may also be developed using UI design concepts such as affordance, efficiency, safety and learnability. That a user interface should be safe and easy to learn may seem obvious, but they can be difficult concepts to measure. The affordances of a UI, which refers to an attribute of an object that allows people to know what do with it, may similarly be difficult to evaluate. An example of the concept of affordance would be the handles on a door that tell a person at a quick glance whether they should push or pull to open it. Efficiency may be the most straight-forward of these concepts and refers to how quickly a user can interact with a UI to accomplish a task. Each of these concepts provides important usability considerations that facilitate improved collaboration between a human decision-maker and an interactive computer application designed to aid them. A review of recent literature in the are of HCI is necessary to determine the most effective way of evaluating metrics for these concepts. Note that usability is a concept distinct from the effectiveness or usefulness of an interface. An application can be very usable, but still fail to be useful for decision-making. Both the usability and usefulness of interface must be considered in future IEEA research.

When visualizing large sets of multi-dimensional data an often applied approach is to use scatter plot matrices that plot each variable against each other variable in a grid of scatter plots[109,110,111]. This allows a designer to detect patterns in the data that may be difficult to train an algorithm to detect and is common in exploratory data analysis. For data of high-dimensionality, like the data sets that may be required for IEEA, this may require increasingly larger amounts of screen "real-estate" that may slow interaction. Alternative visualizations, such as the one shown in Figure 32, may be able to accomplish similar functionality to scatter plot matrices with reduced interaction

[106] Fitts, P., "The information capacity of the human motor system in controlling the amplitude of movement". Journal of Experimental Psychology 47 (6): 381–391, June 1954.

[107] Rashevsky, N., "Mathematical biophysics of automobile driving". Bulletin of Mathematical Biophysics, 21, 375–385, 1959.

[108] Drury, C., "Movements with lateral constraint. Ergonomics", 14, 293–305, 1971.

[109] Liu Z, Jiang B, Heer J. Immens: real-time visual querying of big data. Eurographics Conference on Visulization (EuroVis). 2013

[110] Sitterle V, Curry M, Ender T, Freeman D. Integrated toolset and workflow for tradespace analytics in systems. INCOSE Int'l Symp 2014. Las Vegas, NV, 2014

[111] Scherr M. Multiple and coordinated views in information visualization. Media Informatics Advanced Seminar on Info Vis. 2008/2009

time. This particular example uses two coordinated views, a scatter plot and a parallel coordinate plot that maps design variable, performance attributes, cost, utility and FPN for each design/epoch pair. The interface also includes a control panel below the parallel coordinates that allows each of the variables to be assigned to the various data dimensions within the scatter plot. The controls allow variables to be assigned to the X-Y position of points on the scatter plot as well as the radius of the dot and its color. The interface presents the same information as the traditional scatter plot matrix in a much more compact form that facilitates user interaction, data filtering and visualization.

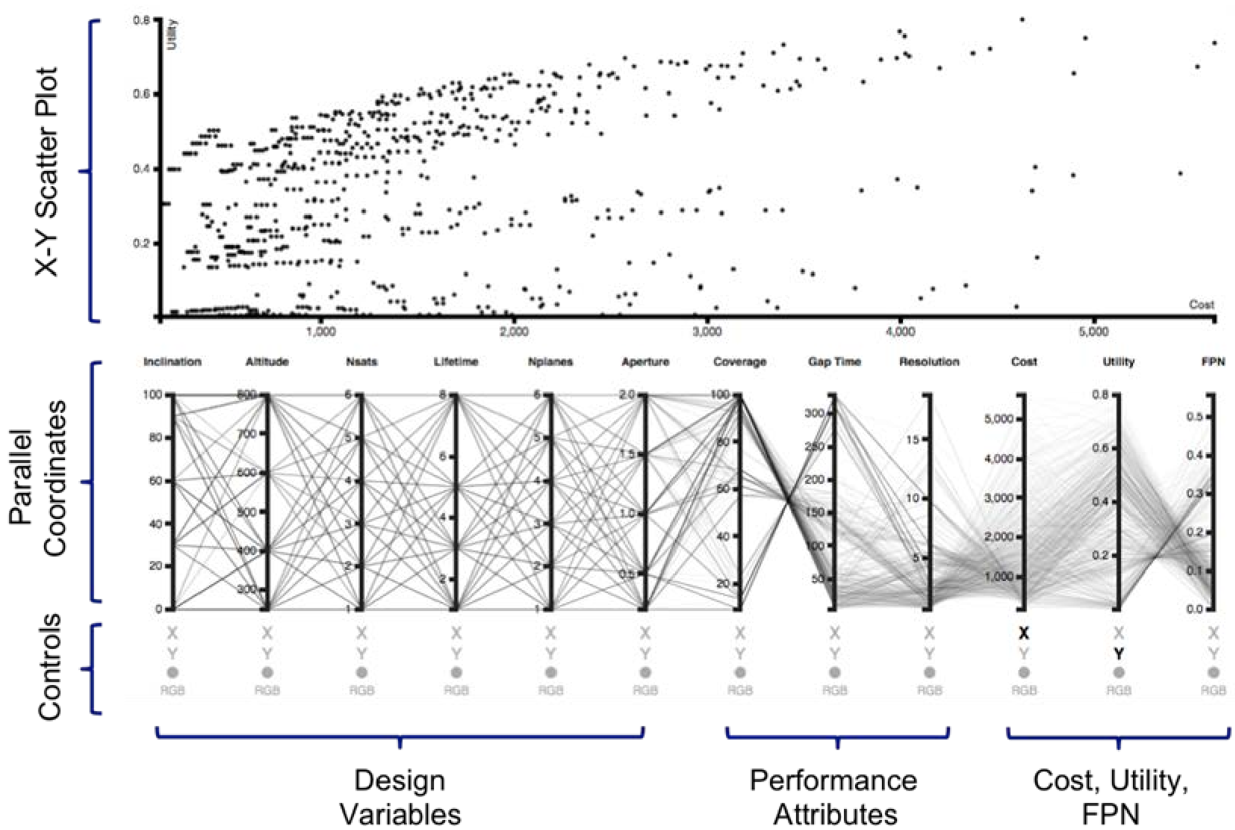


Figure 32. Coordinated multiple views of single epoch results using X-Y scatterplot and parallel coordinates

As mentioned, in addition to the position (e.g. x,y coordinates) of elements within the scatter plot, other attributes of a visualization can also be used to display other data dimensions. In Figure 33, additional data dimensions are encoded using color and circle radius. In this example x, y, radius and color correspond to cost, utility, aperture size and gap time respectively. The user can control which variables are assigned to which visualization elements using the control panel at the bottom. This provides the user a convenient way to visualize the highly dimensional data much more quickly to gain insights and make decisions.

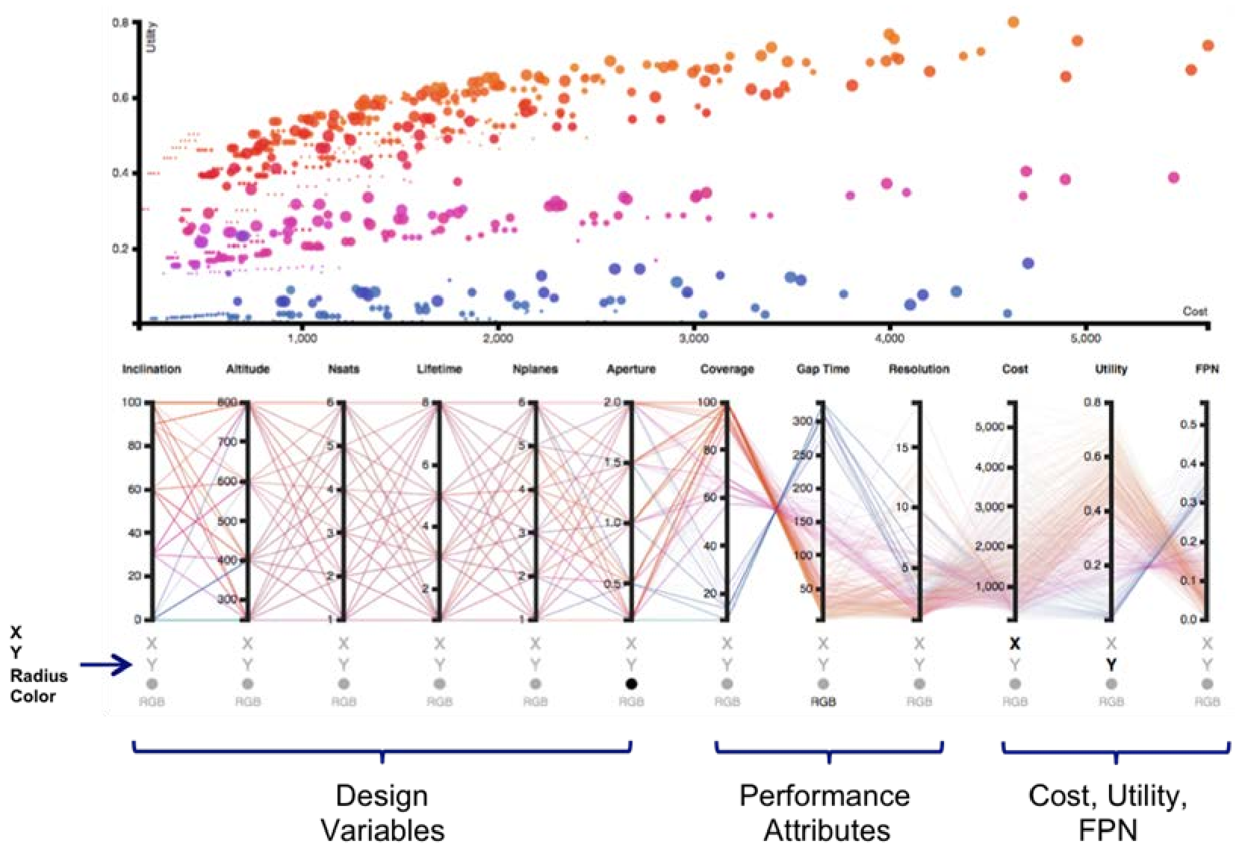


Figure 33. Visualization with additional data dimensions encoded using color and circle radius

To gain a deeper understanding of the data, however, a user needs to be able to interactively explore and filter the data. As shown in Figure 34, this prototype interface allows a designer to interactively set filters by dragging a box around values on the axes of the parallel coordinate plot. In this example filters are set to keep FPN less than 10%, cost less than $1B and utility greater than 0.5. The designs remaining are biased towards near polar inclination constellations at high altitudes, near 100% global coverage and low gap times. This is a relatively straightforward example, but it demonstrates how a designer can use more advanced coordinated visualizations to understand high-dimensional data. This is an important proof of concept for capabilities that can be applied to future IEEA demonstrations that will require analysis of high-dimensional data.

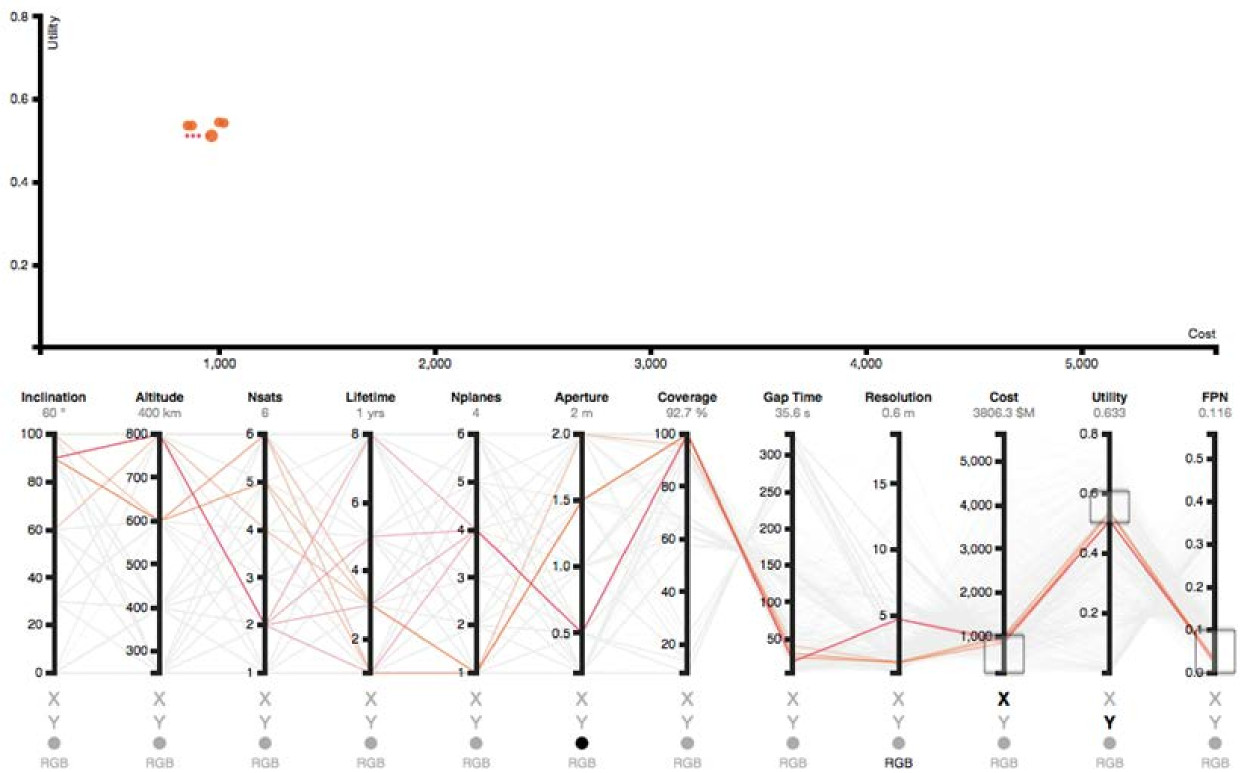


Figure 34. Visualization showing applied filters

NEXT STEPS

Recent advances as well as ongoing efforts by various researchers and industry practitioners create new opportunities for the development of advanced systems engineering methods, processes and tools. Developments in computing, visual analytics and statistical algorithms all provide techniques that could potentially be applied to the field of systems engineering. This could result in better ways to design complex systems to handle a wide range of operational contexts and future stakeholder needs while effectively controlling the escalating costs associated with acquiring, operating and maintaining such systems.

An ultimate goal for this research effort is to demonstrate end-to-end applications of IEEA on several case studies. These case studies could include both multi-epoch and multi-era analysis and serve as demonstrations of how IEEA enables a decision-maker to design systems with the ability to respond to new or changing conditions through modified tactics, reconfiguration, or replacement. Leveraging recent work in visual analytics and coupling it with new applications of EEA constructs using improved processes are seen as enablers of this goal. IEEA will allow designers to better inform the identification of relevant questions, uncover patters, discover regions of interest within the tradespace and potential model errors, and ultimately allow the decision-maker to make better informed decisions with higher levels of confidence and trust. Several areas of ongoing investigation may contribute to this end goal.

First, structured approaches for querying, manipulating and visualizing the types of large data sets generated through EEA must be matured further. As part of this effort so far, several prototypes have demonstrated capabilities necessary for IEEA such as massive parallelization, multiple coordinated interactive visualization and OLAP for faster data handling. Additional research may further extend our ability to use EEA constructs and higher interactive rates. Examples include demonstrating methods to allow a decision-maker to interact with their data at multiple resolutions or levels of abstraction, real-time surrogate modeling and predictive prefetching of data possibly based on user modeling. All of these methods have the potential of relaxing the requirement that an interactive system must have all data in memory at once. On larger problems, like those posed by the DoD ERS initiative, it may not be possible to hold all data associated with a design problem in the memory of a personal computer or workstation at the same time.

Second, additional research is necessary to refine the process defining the IEEA framework. One potential key to improving interactive collaboration between a human analyst and an interactive application (or ensemble of applications) is recognition of the importance of the process the human follows. The interactive process may in fact be more important than the sophistication of the application or the experience of the analyst. Thompson (2010)[112] provides an example of human chess players using simple computer tools to play against a sophisticated super computer built by IBM. The case study showed that the super computer could easily outmatch a human grandmaster, but if the human was augmented with a basic software application running on a simple laptop they could consistently beat the more powerful super computer. More surprisingly, the case study revealed that amateur players that used a superior process for interacting with simple computer tools could beat both the super computer and human grandmasters that was also augmented with computer tools but following an inferior interaction process. The key take-away is that the process through which the human and computer interact strongly influences the effectiveness of their collaboration.

In addition to the interactive process, research on improvements to the IEEA framework should also investigate how to effectively apply iteration within the revised process. Noted mathematician John Tukey described exploratory data analysis as "an open-ended, highly interactive, iterative process" (Jones,1987)[113]. IEEA is seen as an extension of previous methods like RSC (Ross 2009)[114] but with specific emphasis placed on a more iterative, interactive process.

A third and final candidate area of research is the development of user models to improve human-computer collaboration. As also noted by Tukey, "nothing can substitute here for the flexibility of the informed human mind", but user models may be useful to facilitating a more effective collaboration during design/epoch-space exploration. User models may be useful when

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[112] Thompson, C. (2010, February 1). Garry Kasparov, cyborg. Retrieved February 27, 2015, from http://www.collisiondetection.net/mt/archives/2010/02/why_cyborgs_are.php

[113] Jones, L., "The Collected Works of John W. Tukey: Philosophy and Principles of Data Analysis", 1965-1986, Volume 4, CRC Press, May 15, 1987.

[114] Ross A., McManus, H., Rhodes D., Hasting, D., and Long, A., "Responsive Systems Comparison Method: Dynamic Insights into Designing a Satellite Radar System", AIAA Space 2009, Pasadena, CA, September, 2009.

coupled with machine-learning techniques to offer the human analyst recommendations on what they may be looking for based on past data. This can be thought of in the same way search engines algorithms like those used by Google and Amazon offer suggestions based on past data and initial queries. User models may also be helpful for predicting data that must be pre-computed or pre-fetched from a remote database by predicting what the user will want to look at next. As previously discussed, predictive approaches like these could be particularly important when working on problems where it is not possible to store all design data locally at the same time.

Investigations into each of these research areas should culminate in an eventual end-to-end demonstration of IEEA on several relevant case studies. These cases should clearly demonstrate how IEEA empowers decision-makers to make better decisions that are either faster, more trustworthy and/or of a higher quality. They should also demonstrate how IEEA enhances the ability to understand and communicate data through the design of new interactive systems for data visualization and analysis.

The research team will mature the approach for evaluating systems under dynamic uncertainty, with further development of the extended framework to for interactive capability and scaling to big data. This work extends the Phase 2 effort on a demonstration prototype, using the MIT IVTea Suite, applying IMCSE principles to enhance the user interface, data handling and analysis widgets. In Phase 3 the research team will enhance the method and degree of interactive capability, focusing specifically on the Epoch-Era Analysis method, a novel method for value-driven tradespace exploration and analysis. The maturing prototype framework with associated supporting tools will be applied to a case analysis including various types of uncertainties. This case application will be used to elicit feedback on relevance, ease of use, feasibility and tractability of data scaling and visualization techniques. The research team will extend the Phase 2 prototype efforts for Interactive Epoch-Era Analysis (IEEA) and test using case applications, along with preliminary supporting infrastructure. This will inform the transition strategies, additional case application and prototype user testing.

Value-Model Choice and 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.

Introduction

As evidenced by the recent rise of model-influenced systems engineering efforts, including Model-Based Systems Engineering, Model-Based Engineering, and Interactive Model-Centric Systems Engineering, the role of models in engineering activities has been increasing in scope (Rhodes and Ross 2014)[115]. Models have always been used as tools to augment human ability to make predictions or sense of information, encapsulating existing knowledge, as well as automating its application. The rapid rise of low expense computational ability has increased the accessibility of numerical models and the roles they can play in engineering, including both analysis and synthesis. Leveraging models in an effective way for engineering decision support necessitates understanding the role that model choice plays in the generation and analysis of data for decision making. This is especially true when seeking to identify system solutions in early design that are robust across uncertainties (Spero et al. 2014)[116]. This report section describes preliminary research in helping to frame this challenge and potential insights that might be gained when actively trading models as a part of a study.

Motivation/Background

There are several key concepts involved during design decision making in early phase design. Figure 35 depicts the general relationship between decision problems and decision solutions as they relate to data and models in early phase engineering analysis. 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 needed 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 the cost and performance measures), or complex (e.g. aggregate perceived benefit and cost under uncertainty of a large number of measures), with many possible implementations (Lee et al. 2014)[117]. Each of these models, and the artificial data generated by them, can be potentially

[115] Rhodes DH, Ross AM. Interactive Model-Centric Systems Engineering (IMCSE) Phase 1 Technical Report. SERC-2014-TR-048-1; September 2014.

[116] Spero E, Avera MP, Valdez PE, Goerger SR. Tradespace exploration for the engineering of resilient systems. *12th Conf on Sys Eng Research. (CSER14).* Redondo Beach, CA, March 2014.

[117] Lee BD, Binder WR, Paredis CJJ., "A Systematic Method For Specifying Effective Value Models," *CSER14.* March 2014.

altered by changes in the epoch space (i.e., 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).

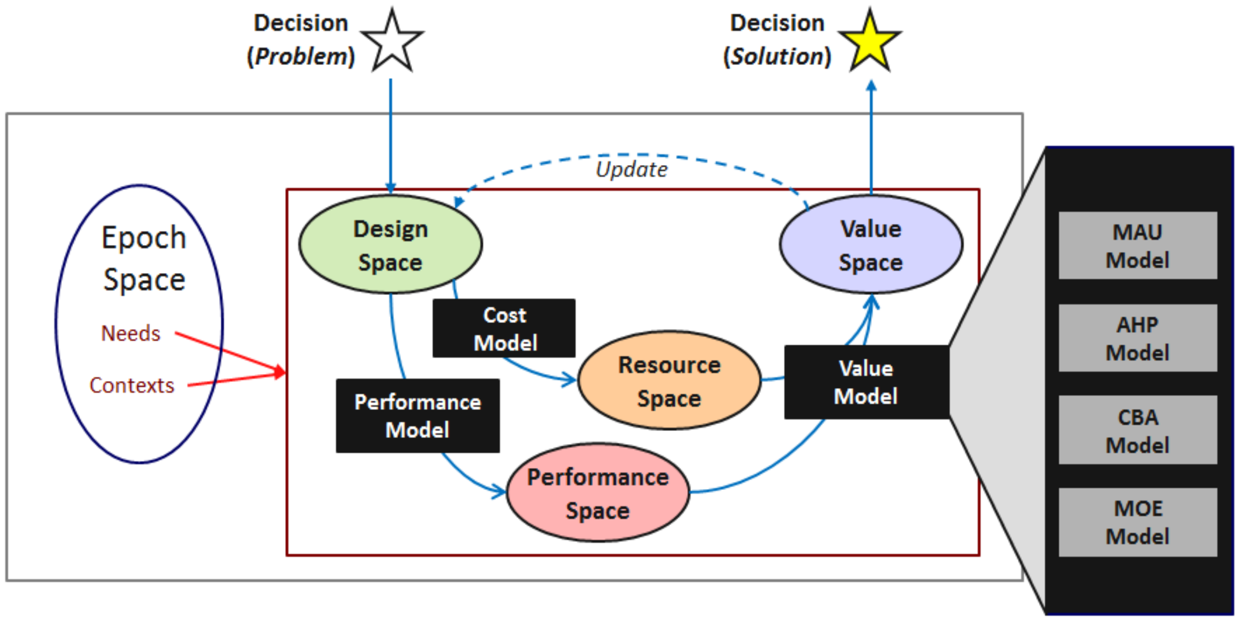

Figure 35. Role of key models for supporting system decision making, with alternative value models use in demonstration case

Since the role of models is central in the depicted decision framework, it is essential that engineers and analysts understand not only the sensitivities of their proposed solutions, but also of the models from which the data for decisions are generated. This includes understanding the impacts of key assumptions and model formulations on the data. One means for conducting this investigation is through "model trading" (i.e., model selection) where data is generated using alternative models with the resulting data compared.

In this research, the team has begun exploratory work defining model types and formulation of how model trading might be implemented. Leveraging insights from earlier work (Ricci at al. 2014)[118], which described the role of interactivity in refining a user's captured value model, we generalize the concept as "value model trading." This ranges from tuning parameters within a particular value model (e.g., utility function shapes and weights for a Multi-Attribute Utility value model) to also include trading of value model formulations themselves. There are many possible

[118] Ricci N, Schaffner MA, Ross AM, Rhodes DH, Fitzgerald ME. Exploring stakeholder value models via interactive visualization. *CSER14*. March 2014.

value models (Ross et al. 2010)[119]. For this demonstration, four alternative value model formulations were used: Multi-Attribute Utility (MAU), Analytic Hierarchy Process (AHP), Cost-Benefit Analysis (CBA), and Measure of Effectiveness (MOE). Recall, a value model attempts to predict how a particular decision maker might perceive net benefits and costs for alternatives under consideration. Different value models treat the mapping of raw data to perceived benefits and costs 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 across MAU, AHP, CBA, and MOE. The results of this variation were analyzed in terms of how the set of perceived benefit versus cost efficiency changed. This was calculated as the Pareto efficient set (i.e., non-dominated solutions across the two high level objectives) for the 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 being developed internally at MIT to support value-driven tradespace exploration and analysis.

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 of a system). But he is 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 previously addressed (Ricci et al. 2014)[120], while the first and third questions are investigated in this study. The approach in this study is to 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; and find solutions that perform well across the alternative value models.

[119] Ross AM, O'Neill MG, Hastings DE, Rhodes DH. Aligning perspectives and methods for value-driven design. *AIAA Space 2010*. Anaheim, CA, September 2010.
[120] Ricci N, Schaffner MA, Ross AM, Rhodes DH, Fitzgerald ME. Exploring stakeholder value models via interactive visualization. *CSER14*. March 2014.

The design alternatives and performance and cost models for Space Tug are relatively straightforward, consisting of the rocket equation and some linear relationships (McManus and Schuman 2003)[121]. The value models 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) (Keeney and Raiffa 1993)[122]. 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). The set of single attribute utility functions is then aggregated via a multi-linear function into a multi-attribute utility score. The equation for MAU is:

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

Here K is the normalization constant, $U(\hat{X})$ is the aggregate MAU value across the multiple single attributes X_i and their respective single attribute utilities $U_i(X_i)$; k_i is the elicited swing weighting factor for attribute X_i; n is the number of attributes. Figure 36 illustrates the three single attribute utility functions (i.e., capability, delta V, response time), along with their k_i weights for the MAU 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.

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[121] McManus H. Schuman T. Understanding the orbital transfer vehicle trade space. *AIAA Space 2003*. Long Beach, CA, September 2003.

[122] Keeney RL, Raiffa H. *Decisions with Multiple Objectives: Preferences and Value Tradeoffs*. New York: Cambridge University Press; 1993.

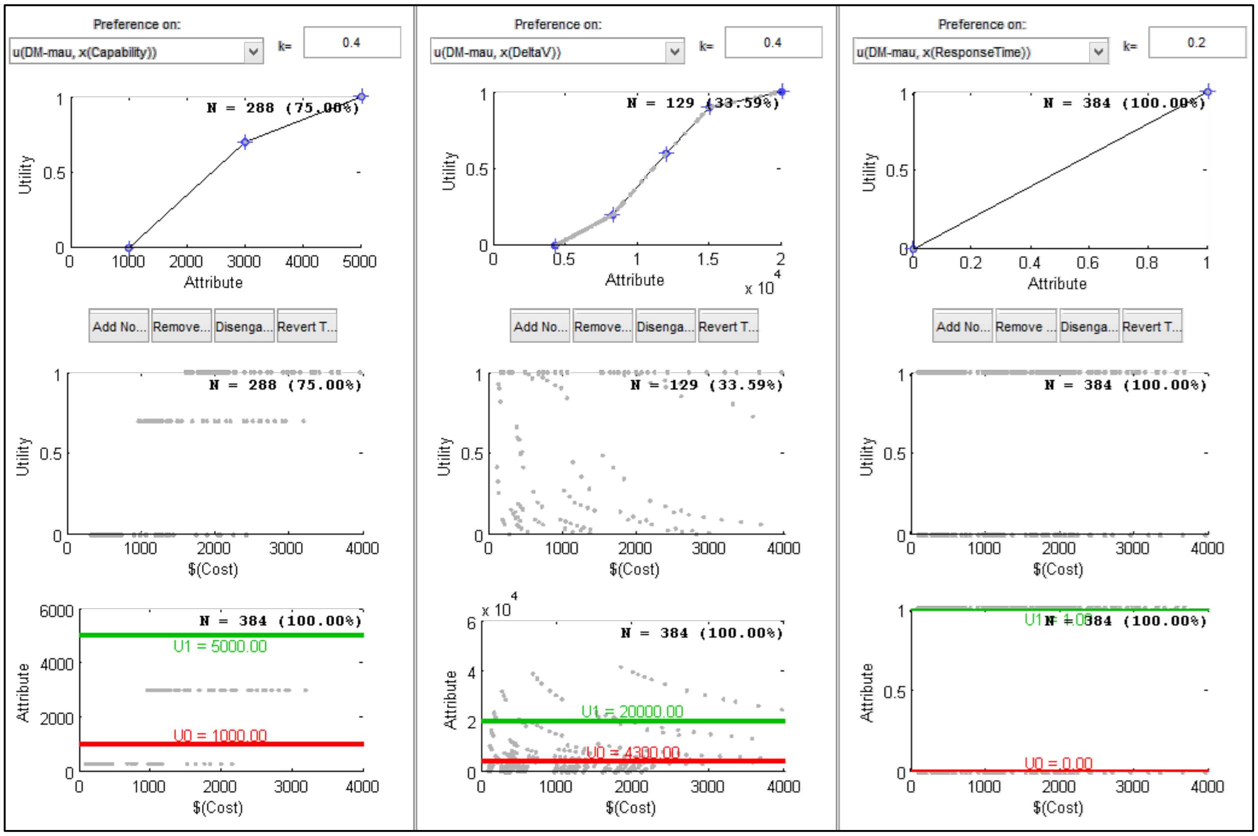


Figure 36. Single attribute utility functions for the MAU value model.

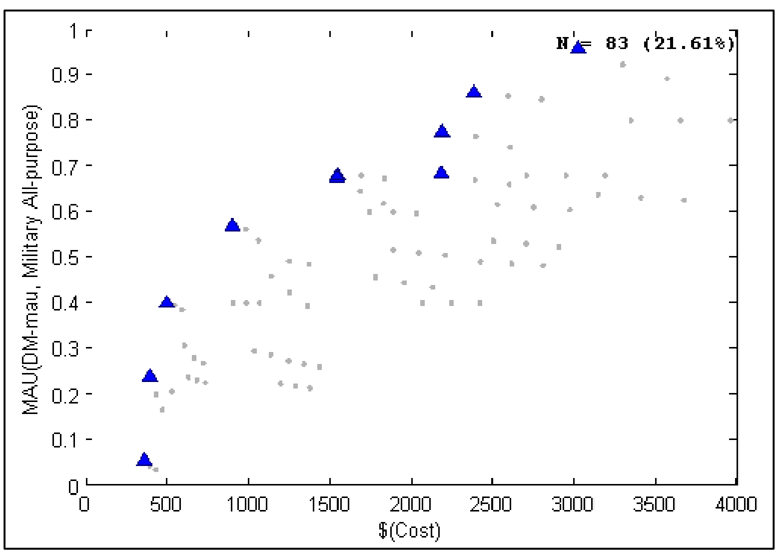


Figure 37. MAU benefit vs. cost tradespace (with Pareto efficient set indicated)

Each of the Space Tug design alternatives were then evaluated in terms of the MAU benefit and cost and are plotted in Figure 37. 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 MAU, 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).

Analytic Hierarchy Process (AHP)

Analytic Hierarchy Process value model generates an aggregate measure across multiple criteria (Saaty 2004)[123]. Each of the criteria are evaluated pair-wise to determine relative value contribution. The aggregate AHP score is determined using a linear-weighted sum, with the weights derived from the pairwise comparisons. The AHP value equation is:

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

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

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

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

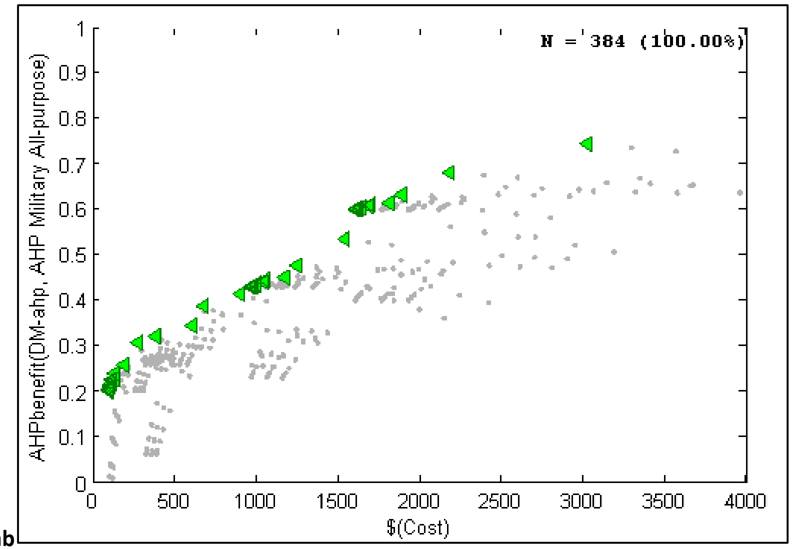
Higher is Better ⇨

Lower is Better ⇨

Figure 38. Matrix of comparisons for the AHP value model.

Figure 38 illustrates the pair-wise comparison matrix for the three criteria (capability, delta V, and response time), which resulted in calculated k_i weights of 0.4, 0.4, and 0.2 respectively.

[123] Saaty TL. Decision Making — The Analytic Hierarchy and Network Processes (AHP/ANP). *Journal of Systems Science and Systems Engineering* 2004; **13**(1): 1-35.



ab

Figure 39. AHP benefit vs. cost tradespace (with Pareto efficient set indicated).

Each of the Space Tug design alternatives were then evaluated in terms of the AHP benefit and cost and are plotted in Figure 39. Additionally, the Pareto efficient set of designs 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 obvious pattern except they never have electric propulsion (type 3).

Cost-Benefit Analysis (CBA)

Cost-Benefit Analysis value model converts multiple criteria into a common currency (typically dollars) in order to simplify comparisons (Mishan 2007)[124]. In order to construct this model, one must create monetization (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:

$$CBA(\hat{X}) = \sum_{i=1}^{n} CBA_i(X_i),$$

$$CBA_i(X_i) = \frac{m_i}{r_i}\left(1 - e^{-r_i \cdot X_i}\right), \text{ when } X_i \geq X_{i,min}; \text{ or } CBA_i(X_i) = 0, \text{ when } X_i < X_{i,min}$$

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, the CBA function is simply a linear function of (i.e., $Y = m_i X_i$.)

[124] Mishan EJ. *Cost-Benefit Analysis*. 5th ed., New York: Routledge; 2007.

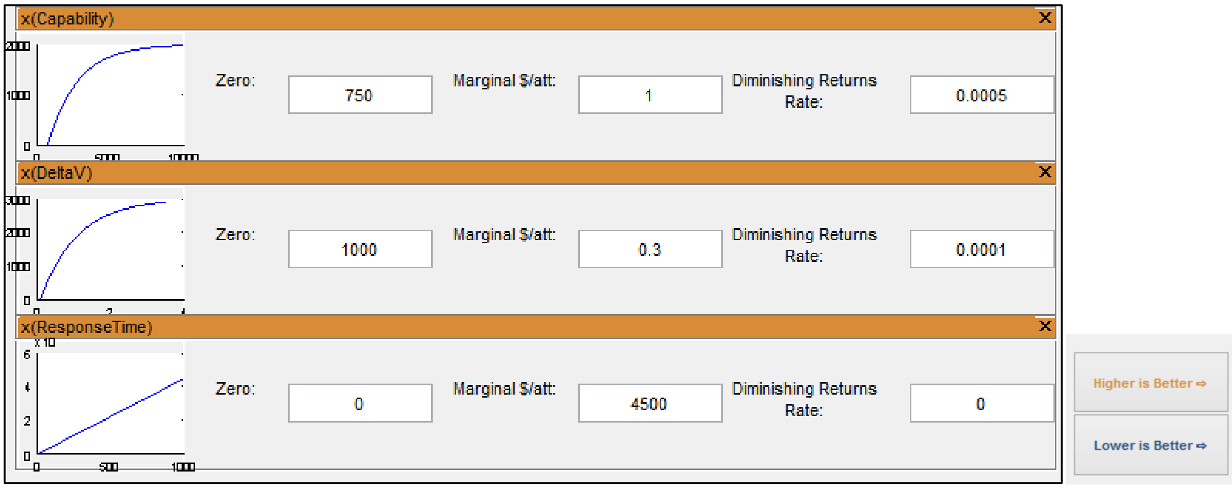


Figure 40. Attribute monetization functions for the CBA value model.

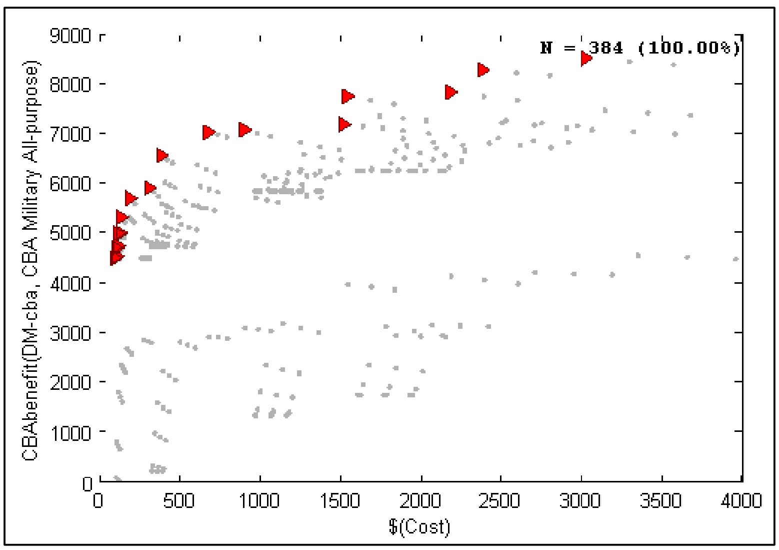


Figure 41. CBA benefit vs. cost tradespace (with Pareto efficient set indicated)

Each of the Space Tug design alternatives were then evaluated in terms of the CBA benefit and cost, and are plotted in Figure 41. Additionally, the Pareto efficient set of designs 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 and never have electric propulsion (type 3).

Measure of Effectiveness (MOE)

Delta V was used as a single dimension Measure of Effectiveness (OAS 2008)[125] since it represents the fundamental capability for transferring target vehicles from one orbital slot to another. For clarity we use a single MOE, but one could use all three attributes, each as a measure of performance (MOP) and perform multi-dimensional Pareto analysis to identify the non-

[125] Office of Aerospace Studies. *Analysis of Alternatives (AoA) Handbook: A Practical Guide to Analyses of Alternatives*. AFMC OAS/A9, www.oas.kirtland.af.mil, July 2008.

dominated solutions. Using a performance metric as the MOE might be considered equivalent to "not having a value model." However, a value model is always being used when a study is synthesizing information to form the basis of a decision, even if a decision maker does not explicitly acknowledge a value model as such.

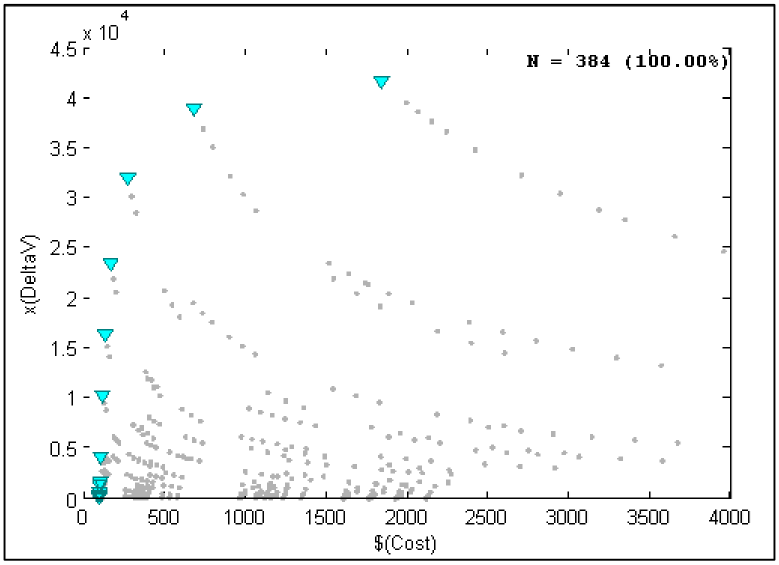


Figure 42. MOE (Delta V) benefit vs. cost tradespace (with Pareto efficient set indicated).

Each of the Space Tug design alternatives were evaluated in terms of the MOE benefit and cost and are plotted in Figure 42. Additionally, the Pareto efficient set of designs 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 will result 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.

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 43 illustrates the four perceived benefits versus costs 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 designs that appear in three out of four of the sets.

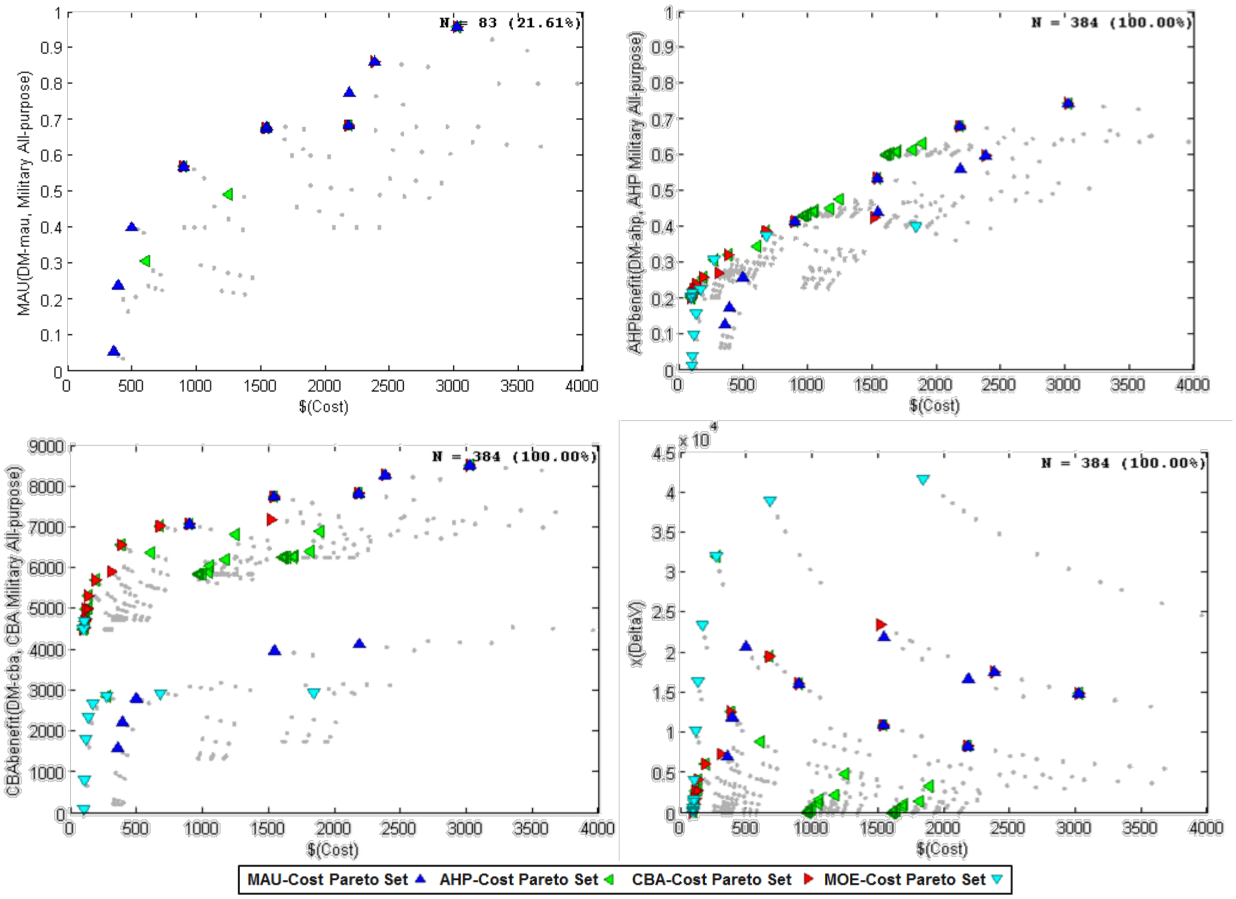


Figure 43. Comparison of four value tradespaces.

The next step in the study is a more formal joint Pareto set analysis to determine the specifics of apparently attractive designs. This type of analysis uses standard multi-objective optimization techniques along with set theory and has been implemented within the IVTea Suite (MATLAB®-based) software mentioned earlier.

Joint Pareto Analysis

The joint Pareto analysis entails 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 (indicated as “0% PARETO”) is indicated in Figure 44. It is important to notice that there are zero “joint” designs. Here, “joint” means that the design appears in all individual Pareto sets. Instead, there are six “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.

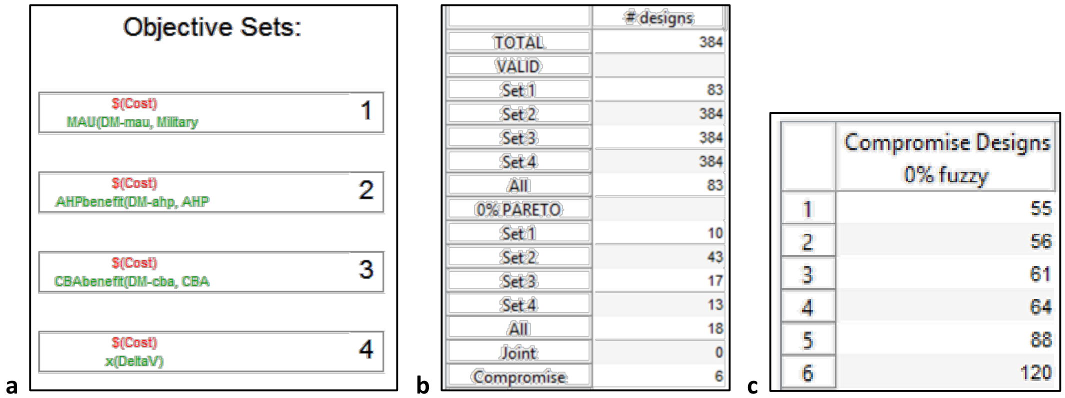


Figure 44. Joint Pareto analysis with (a) four objective sets of two objectives each; (b) analysis results; (c) list of six compromise designs.

Upon closer inspection, we find that there are also six designs that are in three out of four Pareto sets. These are listed in Table 2, 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). These designed are considered "promising" if efficiency across three out of four value models is sufficient.

Table 2. Promising designs that are joint Pareto efficient across three out of four value models.

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	

The details of the promising designs are described in Figure 45. 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 nuclear propulsion (type 4), and a large amount of fuel. Each of these four designs are highly attractive across the value models, and are most benefit-cost efficient for three out of four. These are, however, very expensive systems (as determined by the nuclear propulsion and large amount of fuel). Finding less expensive alternatives that are also robust to value model choice would be attractive at this point.

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 (Fitzgerald and Ross 2012)[126]. 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 the design is within 7% of Pareto efficiency for all four value models. An additional attractive feature of this fuzzy Pareto design is its lower cost.

[126] Fitzgerald ME, Ross AM. Mitigating contextual uncertainties with valuable changeability analysis in the multi-epoch domain. *6th Annual IEEE Systems Conference*. Vancouver, Canada, March 2012.

	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 45. Details on the "promising" designs.

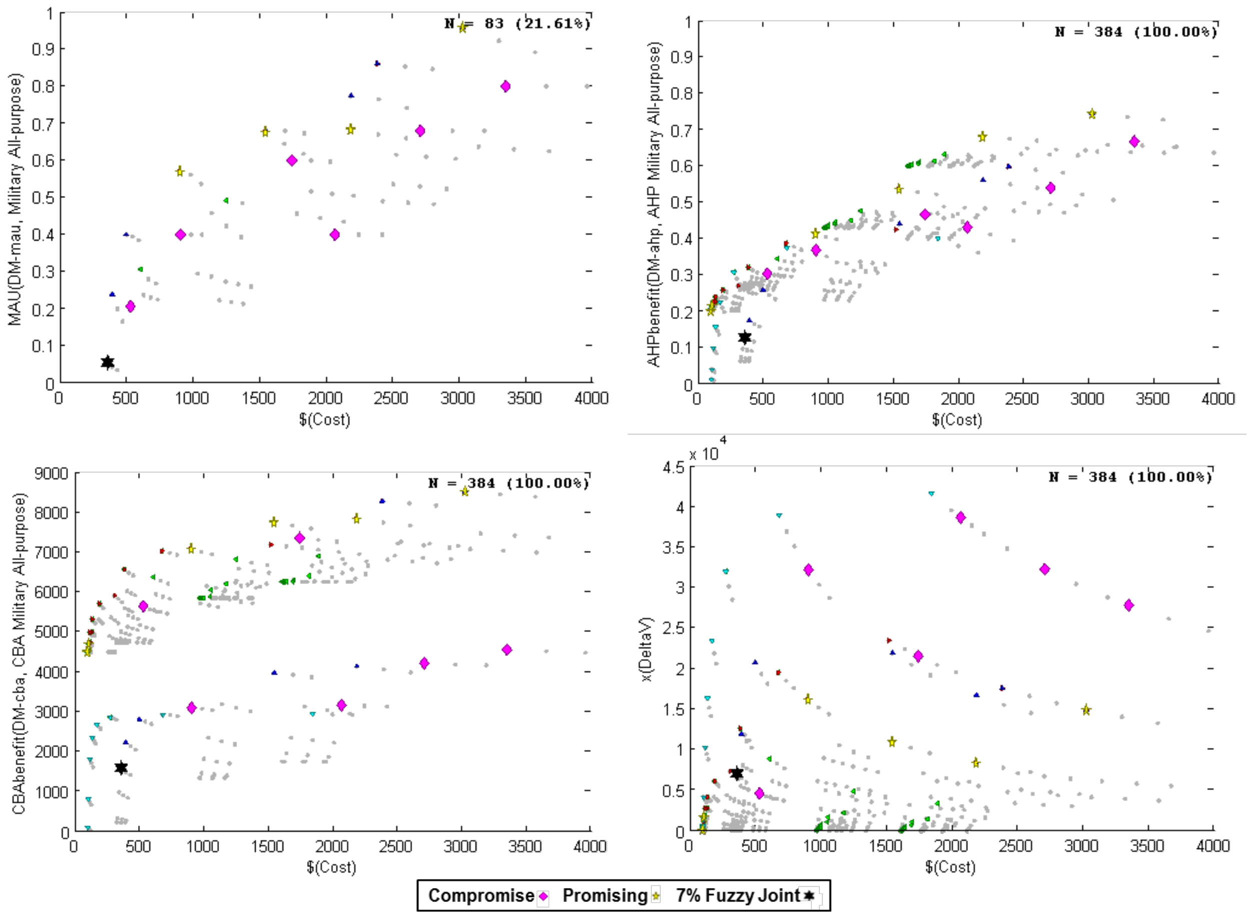


Figure 46. Comparison of benefit versus cost tradespaces with compromise, promising, and fuzzy joint designs indicated.

Figure 46 illustrates the four tradespaces, with the compromise, promising, and 7% fuzzy joint designs. Design 52 is the 7% fuzzy joint Pareto design and represents the most robust choice if the decision maker is unsure of which value model best captures his preferences. Interestingly this design uses electric propulsion, which was a design choice absent from the AHP and CBA Pareto sets. Appealingly, this design is in the low cost region of the tradespaces. The joint Pareto analysis identified designs that are most efficient across 3 out of 4 value models (tending to high performance, high cost solutions), as well as balanced efficiency across all 4 value models (lower performance, lower cost solution). Ultimately the foregoing value model trade analysis doesn't prescribe the "best" solution, but rather highlights several key points: 1) the choice of value model matters since it determines the attractiveness of each solution; 2) each value model will likely highlight different systems; 3) it is possible to identify systems that do well across multiple value models; 4) this type of analysis is useful if the most appropriate value model to use is uncertain or likely to change. One could theoretically wrap an optimizer around the joint Pareto analysis to identify a "best" solution; however, this would obfuscate the pedagogical aim of this study.

Discussion

Much of the modeling literature tends to focus on model formulation and validation in pursuit of finding "best" solutions (e.g., optimization-based approaches) (Rhodes and Ross 2014)[127]. Model types include performance, cost, as well as value models. As pointed out earlier (Ricci et al. 2014)[128], there is an asymmetry when validating performance models as opposed to value models. The former could have ground truth as a basis for validation, while the latter attempts to put structure on something that may be fundamentally subjective (i.e., human interpretation). As model-centric methods proliferate, and the pursuit of robust and resilient solutions becomes strategically important, analysts and engineers need to explore more than just the accuracy and sensitivity of their model results; they must also explore the impact of model choice itself. Where ground truth might be available, model validation is possible, and the impact of model choice may be interpreted as error introduced into the data. Where ground truth may be unavailable, as may be the case for value models, understanding the impact of model choice on data could become an essential part of studies. The demonstration case for value model trading was intended to help identify key tasks and supporting infrastructure for value model trading capabilities. The case did result in the ability to use different value model formulations on a common data set. The next phase of the research will continue analyzing value model trades in this case, and will develop a more complete framework and process for conducting value model trades in general.

Next Steps

The research team will build on the Phase 2 work on value model trades to further evolve the framework and process. In Phase 3, the research team will build on prior phase results to further evolve the framework and process for conducting value model choice and tradeoffs and apply this through an expanded case application set, to validate the framework and identify workflow considerations. The model choice and tradeoff framework will be expanded including demonstration cases beyond value models (to include trading of other types of models including performance and cost models). The expanded framework will consider alternative use cases for the impact of model choice and tradeoffs on decision-making. For example, this includes the context of multi-stakeholder negotiations using tradespace exploration, where the data source(s) (i.e. "models") strongly impact the trust and framing of the shared decision problem

[127] Rhodes DH, Ross AM. *Interactive Model-Centric Systems Engineering (IMCSE) Phase 1 Technical Report*. SERC-2014-TR-048-1; September 2014.
[128] Ricci N, Schaffner MA, Ross AM, Rhodes DH, Fitzgerald ME. Exploring stakeholder value models via interactive visualization. *CSER14*. March 2014.

Supporting MPTs

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.

IVTea Suite

During this phase, work on IVTea Suite (Interactive Value-Driven and Tradespace Exploration and Analysis Suite) was deferred in order to focus on developing demonstration prototypes for IEEA, as described in earlier sections. It is envisioned that new MPTs will emerge from the IEEA prototype implementation work during Phase 3 and beyond. These may be compatible with IVTea Suite, or constitute a new complementary MPT, focusing on facilitating aspects of IMCSE research and help with transition to practice.

Next Steps

Going forward, IVTea Suite will undergo refinement of user interface, data handling, as well as development of additional widgets that support ongoing research, as research resources allow. Further development of demonstration prototype standalone and integrated IEEA MPTs will also occur during the next phase.

INTERACTIVE SCHEDULE REDUCTION MODEL

The applications thrust in this phase focused on the Interactive Schedule Reduction Model project (ISRM).

Leveraging prior work from DARPA META, the Schedule Reduction Model was extended with interactivity as a central aspect, promoting sensitivity analyses and benchmarking to be the central use case. This report describes progress on the ISRM completed as of the end of Phase 2 of the IMCSE project[129].

INTRODUCTION

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 GAO report[130] highlights 74 instances of cost breaches in 47 of 134 major defense acquisition programs since 1997. 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. A GAO report calls[131] for early and continued systems engineering analysis aim to identify and intervene before significant overruns occur. Increased effort to consider design alternatives and evaluate achievability of objectives during design reviews ensure the project meets requirements with available resources.

Earth and space science missions share similar features. A NRC report[132] of NASA missions shows average cost and schedule growth exceeds 20 percent and 13 of 40 recent missions experienced excessive cost growth. Commonly identified factors contributing to cost and schedule growth include optimistic and unrealistic estimates, project and funding instability, instrument and technology development problems, and launch service issues. Other contributing factors include cost growth induced by schedule growth due to staffing and cost growth due induced by cost growth in another project due to re-planning. Most cost growth accumulates from development issues after critical design review (CDR), even though CDR is intended to mark the final stage of design.

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[129] Portions of this report also appear in: Grogan, P.T., O.L. de Weck, A.M. Ross, and D.H. Rhodes, “Interactive models as a system design tool: Applications to system project management,” Proceedings of the 2015 Conference of Systems Engineering Research, Hoboken New Jersey, March 2015

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

[131] 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. Washington, D.C.; March 2011.

[132] National Research Council (NRC). Controlling Cost Growth of NASA Earth and Space Science Missions. Washington, D.C.: The National Academies Press; 2010

The META II Complex Systems Design and Analysis (CODA) project (Murray et al. 2011)[133] investigated new design techniques relying on engineering software models for early design activities without physical testing. Key components of the META design process include deliberate use of layers of abstraction, development and use of a component model library (C2M2L), and virtual verification and validation processes. Past work (de Weck 2012)[134] developed the Design Flow Model (DFM) as a prototype system dynamics (SD) tool to evaluate the feasibility of a five-fold speedup in system development under the META-enabled process, showing potential for a five-fold speedup for projects.

The IMCSE program builds on these ideas to create, validate, and transition methods, processes, and tools to rapidly model the critical aspects of systems, especially those that facilitate collaborative system development. IMCSE aims to develop transformative results in engineering projects through intense human-model interaction. The Interactive Schedule Reduction Model (ISRM) is one of three activities in the first and second phases of IMCSE to demonstrate web-based technologies as new methods for human-model interaction enabling rapid sensitivity analysis of various factors. It uses the DFM as a use case to explore alternative systems development processes and resource allocations and determine their potential impact on program schedule.

Background and Objectives

The Role of Design Tools

As discussed above, aerospace and defense projects are particularly afflicted by cost and schedule overruns. A variation of this pattern has been popularized by Augustine's Law XVI[135] which observes that aircraft unit costs increase exponentially while budgets increase linearly, leading to the seemingly-absurd case where the entire defense budget affords just one aircraft by 2054. Investigating the source of cost growth in fixed-wing aircraft, a RAND study (Arena et al. 2010)[136] estimates economy-driven factors contribute only about a third of cost growth. Customer-driven factors attribute the remaining two-thirds with major contributions from complexity of performance characteristics and airframe material.

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

[134] de Weck OL. "Feasibility of a 5X Speedup in System Development Due to META Design." DETC2012-70791. International Design Engineering Technical Conferences & Computers and Information in Engineering Conference. Chicago, Illinois: August 2012.

[135] Augustine NR. Augustine's Laws. Sixth Edition. Reston, Virginia: AIAA; 1997.

[136] Arena MV, Younossi O, Brancato K, Blickstein I, Grammich CA. Why Has the Cost of Fixed-Wing Aircraft Risen? MG696-1.2. The RAND Corporation. Santa Monica, California; 2010.

There are many descriptions and definitions of complexity in literature; however, a unifying perspective (Suh 1999)[137] for system design relates it to uncertainty in meeting functional requirements (FRs) within cost and schedule constraints. Sources of complexity (Rhodes and Ross 2008)[138] include structural (components and interrelationships), behavioral (functional response to inputs), contextual (outside circumstances), temporal (time dynamics), and perceptual (stakeholder preferences) factors. Most efforts to quantify complexity focus on structural features where information- or entropy-based methods (Sinha and de Weck 2012)[139] define a complexity metric as a function of system components, their interconnections, and overall architecture. Application-specific studies (Deshmukh et al. 1998)[140] (Frizelle and Woodcock1995)[141] show systems with higher complexity measures can provide higher levels of performance than simpler systems if they are optimally managed.

Downsides of complexity arise from limitations in individual and social cognition. To emphasize this distinction, consider descriptive and perceived dimensions (Schlindwein and Ison 1994)[142]. Descriptive complexity is the objective system property related to information content as described in entropy-based measures. Perceived complexity is the subjective property related to uncertainty in meeting FRs due to an observer's incomplete knowledge of required information. This project assumes perceived and descriptive complexity are correlated, and constitute a tradeoff between efficiency and robustness generally observed[143] in systems architecting (Doyle and Csete 2011). Descriptive complexity can improve efficiency of meeting a given set of FRs under expected (nominal) conditions while perceived complexity reduces robustness by adding uncertainty to achieving FRs within cost and schedule constraints. Due to perceptual limitations, seemingly-efficient designs may realize poor performance and produce "robust-yet-fragile" conditions(Alderson and Doyle 2010)[144].

The notional tradespace of system architectures in the figure below illustrates the efficiency-robustness relationship. The ideal design (upper right) is limited by constraints on descriptive and

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[137] Suh NP. "A Theory of Complexity, Periodicity and the Design Axioms." Research in Engineering Design 1999; 11(2):116-131.

[138] Rhodes DH, Ross AM. "Five Aspects of Engineering Complex Systems: Emerging Constructs and Methods." 4th Annual IEEE Systems Conference. San Diego, California: April 2008.

[139] Sinha K, de Weck OL. "Structural Complexity Metric for Engineering Complex Systems and its Application." 14th International DSM Conference. Kyoto, Japan: September 2012.

[140] Deshmukh AV, Talavage JJ, Barash MM. "Complexity in Manufacturing Systems Part 1: Analysis of Static Complexity." IIE Transactions 1998; 30(7):645–655.

[141] Frizelle G, Woodcock E. "Measuring Complexity as an Aid to Developing Operational Strategy." International Journal of Operations & Production Management 1995; 15(5):26–39.

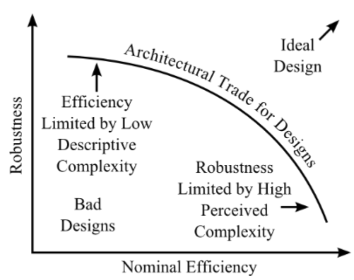
[142] Schlindwein SL, and Ison R. "Human Knowing and Perceived Complexity: Implications for Systems Practice." Emergence: Complexity and Organization 2004; 6(3):27-32.

[143] Doyle JC, Csete M. "Architecture, Constraints, and Behavior." Proceedings of the National Academy of Sciences of the United States of America 2011; 108(3):15624-15630.

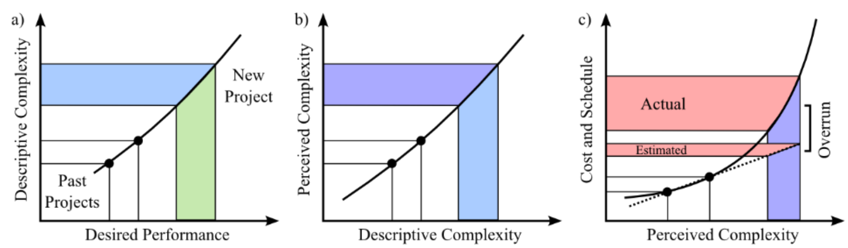
[144] Alderson DL, Doyle JC. "Contrasting Views of Complexity and Their Implications for Network-Centric Infrastructures." IEEE Transactions on Systems, Man, and Cybernetics – Part A: Systems and Humans 2010; 40(4):839-852.

perceived complexity. Robust designs (upper left) tend to be inefficient due to constraints on descriptive complexity required to anticipate responses to uncertainties (e.g. consider the KISS principle: “keep it simple stupid” reportedly coined by Kelly Johnson). Efficient solutions (lower right) tend to be fragile due the inability to anticipate responses to uncertainties caused by high perceived complexity.

Design studies (Hershi and Frey 2002),[145] (Singha 2014),[146] (Flagler et al. 2014),[147] (Grogan 2014)[148] consistently show a super-linear relationship between objective complexity measures and effort to complete a design with fixed requirements. Although perceived complexity cannot be observed as a hidden intermediate variable, this project hypothesizes it to be a contributing mechanism for cost and schedule overruns. Consider the illustrative example in the figure below . A new project seeks to increase performance over past projects with an increase in descriptive complexity (a). Perceived complexity is assumed to be related to descriptive complexity by a monotonically-increasing function dependent on the system and its observers (b). Differences in function slope and shape, for example, distinguish between VLSI and mechanical design (Whitney 1996)[149]. Project cost and schedule is a super-linear function of perceived complexity (c) which assigns higher cost and schedule to deal with high perceived complexity.



Efficiency versus robustness as an architectural trade in design.



Hypothesized mechanisms of cost and schedule overruns: new projects increase descriptive complexity to meet performance goals (a), which increases perceived complexity (b), and leads to cost and schedule overruns of linear extrapolation from past projects (c).

This theoretical model highlights three potential sources of cost or schedule estimation errors: 1) errors in the level of descriptive complexity to meet target performance, 2) errors relating descriptive and perceived complexity, and 3) errors relating perceived complexity and cost and schedule. Errors in (3) are particularly biased towards cost and schedule under-estimation. Humans have difficulty in estimating geometric or exponential growth, instead using linear

[145] Hirschi NW, Frey DD. “Cognition and Complexity: An Experiment on the Effect of Coupling in Parameter Design.” Research in Engineering Design 2002; 13(3):123-131.

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

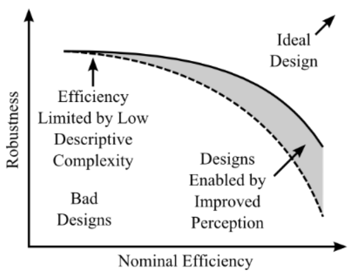
[147] Flager F, Gerver DJ, Kallman B. “Measuring the Impact of Scale and Coupling on Solution Quality for Building Design Problems.” Design Studies 2014; 35(2):180-199.

[148] Grogan PT. Interoperable Simulation Gaming for Strategic Infrastructure Systems Design, PhD thesis. Cambridge, Massachusetts: Massachusetts Institute of Technology, 2014.

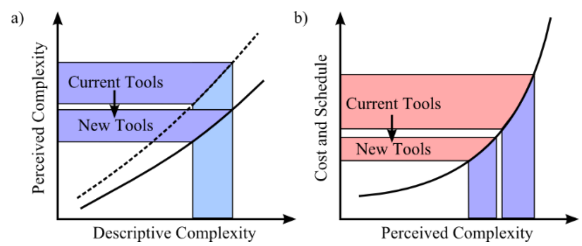
[149] Whitney DE. “Why Mechanical Design Cannot be like VLSI Design.” Research in Engineering Design 1996; 8(3):125-138.

extrapolations in intuitive assessment (Stango and Zinman 1995)[150]. Linearizing results of past projects, as shown above, (c) leads to under-estimations characteristic of large or complex projects beyond existing experience.

There are two approaches to address cost and schedule growth in engineering projects: pursue more conservative designs with lower descriptive complexity (at the cost of lower performance) or improve the designers' perception. This project seeks improved perception to achieve desired performance of descriptively-complex systems at lower cost, expanding the space of feasible designs in the figure below (left).



Improved perception enables new designs outside the previously-feasible region.



. Proposed role of design methods and tools: new tools reduce perceived complexity (a) leading to lower cost and schedule (b).

Design methods and tools are proposed to reduce perceived complexity and help designers acquire knowledge to manage descriptively-complex systems. Methods such as filtering, abstraction or generalization, and automation reduce a problem to its essential features and apply pre-defined procedures at lower levels. Computational tools provide extensive memory, rapid communication, and new human-computer interfaces for advanced visualization. The figure above (right) illustrates the effect of design tool innovations on the functional relationship between descriptive and perceived complexity (a), ultimately reducing cost and schedule (b). In summary, tools improving designer perception are hypothesized to reduce design effort by anticipating product performance under a wider range of conditions.

MODELING TOOLS IN SYSTEMS ENGINEERING

Recent SE practices show increased focus on model-centric tools to support design activities. Model-based systems engineering (MBSE) is defined by INCOSE (2007)[151] as a "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." MBSE aims (Friedenthal et al. 2012)[152] to replace labor-

[150] Stango V, Zinman J. "Exponential Growth Bias and Household Finance." The Journal of Finance 2009; 64(6):2807:2849.

[151] International Council on Systems Engineering (INCOSE). Systems Engineering Vision 2020 Version 2.03. TP-2004-004-02. September 2007.

[152] Friedenthal S, Moore A, Steiner R. A Practical Guide to SysML. Second Edition. Waltham, Massachusetts: Elsevier; 2012.

intensive, error-prone, and cumbersome document-based processes with model-based methods to improve specification and design quality, specification and design reuse, and development team communications. In addition to efficiency gains commonly-identified, evidence (Sterman 1994)[153] of active participation in model-building leading to more effective learning may allow MBSE efforts to reduce perceived complexity of descriptively-complex systems.

The META II Complex Systems Design and Analysis (CODA) project (Murray et al. 2011)[154] explored use of model-based techniques in design activities. It developed three key mechanisms to reduce cost and schedule overruns. First, multiple layers of abstraction allow concepts to be quickly developed and assessed at a coarse level and refined during detailed design. Second, designers develop and maintain a trusted component model library (C2M2L) to limit costly model-building and validation exercises. Third, re-design cycles take place in virtual environments, allowing designers to rapidly evaluate concepts and find required changes sooner.

Past work (de Weck 2012)[155] developed the Design Flow Model (DFM) as a system dynamics (SD) model to assess differences between traditional sequential stage-gate development processes and the flexible META-enabled design methods for projects in the Adaptive Vehicle Make (AVM) program portfolio. The SD model formalism defines stock (accumulations) and flow (rates of change) variables as functions of other model components. Numerical techniques integrate stocks as a system of differential equations in a time-stepped simulation. DFM stocks are SE activity products from requirements elicitation, architectural exploration, design and integration, verification, and validation. DFM flows quantify factors influencing work products such as change generation, time pressure, and efficiency.

Past 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 (i.e. problems arising from limits on perception), however, a realistic project requires 70 months and $51.9M in NRE costs (65% schedule growth and 86% cost growth). An equivalent 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.

PLATFORMS FOR MODELING AND SIMULATION

While initial results are promising, the DFM requires additional work to evaluate sensitivity to key input parameters and determine its applicability beyond the AVM program portfolio.

[153] Sterman JD. "Learning In and About Complex Systems." System Dynamics Review 1994: 10(2-3):291-330.

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

[155] de Weck OL. "Feasibility of a 5X Speedup in System Development Due to META Design." DETC2012-70791. International Design Engineering Technical Conferences & Computers and Information in Engineering Conference. Chicago, Illinois: August 2012.

Interactive "what-if" planning models have been shown (Sharon et al. 2009)[156] to provide benefits in similar project management contexts and may be effective to allow practitioners to understand and evaluate benefits of applied MBSE efforts such as META. More importantly, the DFM serves as a microcosm of the broader challenges to model-based design and serves as a use case for new methods to generate and analyze large data sets. Advancing these broad objectives revisits underlying tools and techniques for contemporary modeling.

The DFM was implemented in Vensim[157], an industry-standard tool for SD model development and execution. Vensim provides high-performance simulation with sensitivity analysis, data import, and optimization capabilities. However, it follows a paradigm where models are usually developed by one designer with one formalism for use by one individual to carry out one experiment. Some Vensim products provide supplementary features for broader interaction with models such as:

- Command scripts: allow a licensed user to automate model executions,
- Open Database Connectivity (ODBC): allow a licensed Windows user to read from or write to an ODBC-supported database,
- Dynamic Data Exchange (DDE): allow a licensed Windows user to exchange information with other DDE-supported applications, and
- Dynamic Linked Library (DLL): allow a licensed user to integrate Vensim functionality in other applications.

Licenses restrict redistribution of Vensim executables and libraries. While most users can license a free Vensim Model Reader to execute (but not edit) models, the Vensim tool cannot be modified to integrate new capabilities without developing a separate application and linking the DLL which is separately licensed. These limitations constrain the ability to share, refine, and customize model-based tools.

A new modeling paradigm (Jacobs 2005)[158] emphasizes collaborative modeling among multiple designers for multiple users and multiple applications. However limited progress has been observed to date. For example, a survey (Boer et al. 2009)[159] shows little use of interoperable simulation standards outside defense applications due to the complexity and cost of runtime applications and incompatibility with commercial packages common in industry. In contrast, innovations in web- and browser-based technologies in recent years represent the most advanced techniques to share and use data and could form the basis of collaborative modeling. ISRM intends to transition core features of web-based applications---open-source core libraries

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

[157] Ventana Systems Incorporated. Vensim version 6.3. http://vensim.com, accessed 22-Sept 2014.
[158] Jacobs PHM. The DSOL Simulation Suite: Enabling Multi-formalism Simulation in a Distributed Context. PhD thesis. Delft, Netherlands: Technische Universiteit Delft; 2005.
[159] Boer CA, de Bruin A, Verbraeck A. "A Survey on Distributed Simulation in Industry.," Journal of Simulation 2009: 3(1):3-16.

and loosely-coupled interfaces based on HTTP-based data exchange---to modeling and simulation.

There exist several SD modeling tools on web platforms. Forio Simulate[160] is a commercial web-based service addressing similar goals of this project; however it is closed-source and proprietary. Insight Maker[161] is a similar open web-based modeling tool but it provides a graphical tool as a stand-alone modeling environment rather than a general-purpose library. Lower-level libraries such as SIM.JS[162] support discrete event simulation with features such as random number generation but do not support the SD formalism. Other mathematical computing libraries such as Numeric Javascript[163] and Sylvester[164] implement vectors and matrixes but do not provide integrators required for the SD formalism.

Development Approach

Based on limitations of existing SD platforms, Figure 47 below outlines ISRM objectives as six tasks in two phases.

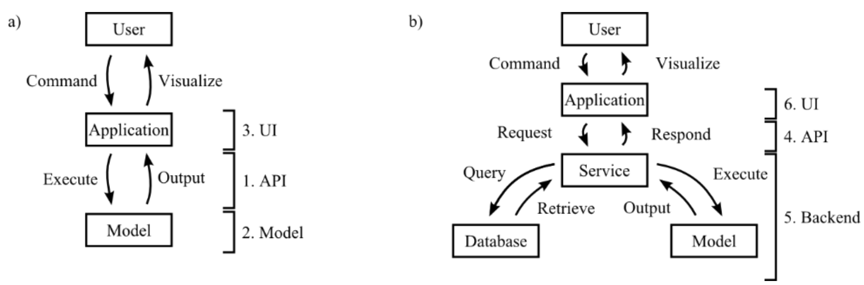


Figure 47 ISRM development approach in Phase 1 (a) and Phase 2 (b) with six tasks.

Phase 1 of this project transformed the existing DFM into a browser-based tool to facilitate interaction and extension. It allows users to run simulation executions, view or export numerical results, and override input parameters. Task 1 develops an application programming interface (API) to execute a model and interpret results in a browser. Task 2 ports the existing DFM from Vensim to JavaScript using the API. Task 3 develops a user interface (UI) to allow interactive model exploration in a browser environment.

Phase 2 developed a service-based application to compose and query datasets across model executions. It allows users to specify ranges of input parameters, aggregate existing datasets, and execute models to generate and store new data. Task 4 develops a service API to collect and query results across model executions. Task 5 implements the backend components to interact

[160] Forio Simulate. http://forio.com/simulate, accessed 22-Sept 2014.
[161] Insight Maker. http://insightmaker.com, accessed 22-Sept 2014.
[162] SIM.JS version 0.26. http://simjs.com, accessed 22-Sept 2014.
[163] Numeric Javascript version 1.2.6. http://www.numericjs.com, accessed 22-Sept 2014.
[164] Sylvester version 0.1.3. http://sylvester.jcoglan.com, accessed 22-Sept. 2014.

with the services. Finally, Task 6 develops a UI to provide allow users to command model execution under conditions of interest and show and interpret large quantities of information.

STANDALONE ISRM TOOL

The standalone ISRM tool seeks to replicate the Vensim-based DFM in a browser environment. This section reviews the tasks to define a model application programming interface (API), implement and validate the model, and design the user interface (UI).

JAVASCRIPT MODELING AND SIMULATION (MAS) API

The JavaScript language was not originally intended for numerical computation and no existing libraries are applicable to time-evoked simulation. This section defines a JavaScript Modeling and Simulation (MAS) API for a portion of the system dynamics (SD) formalism shown as an object class diagram in Figure 48.

SD components descend from a common `Entity` class which establishes required attributes (unique `id`) and methods to initialize (`init`), and advance time (`tick`/`tock`). The two-step time advance avoids order dependence by pre-computing (`tick`) and then committing (`tock`) state changes. In comparison, Vensim sequences the order of equations to eliminate dependence. The tick/tock method can approximate simultaneous equations; however it is currently limited to single-iteration numerical integration methods such as explicit (forward) Euler. `Utils` provides utility functions such as generating a globally-unique identifier (`guid`) and replicating the integer-part method from Vensim (`intPart`).

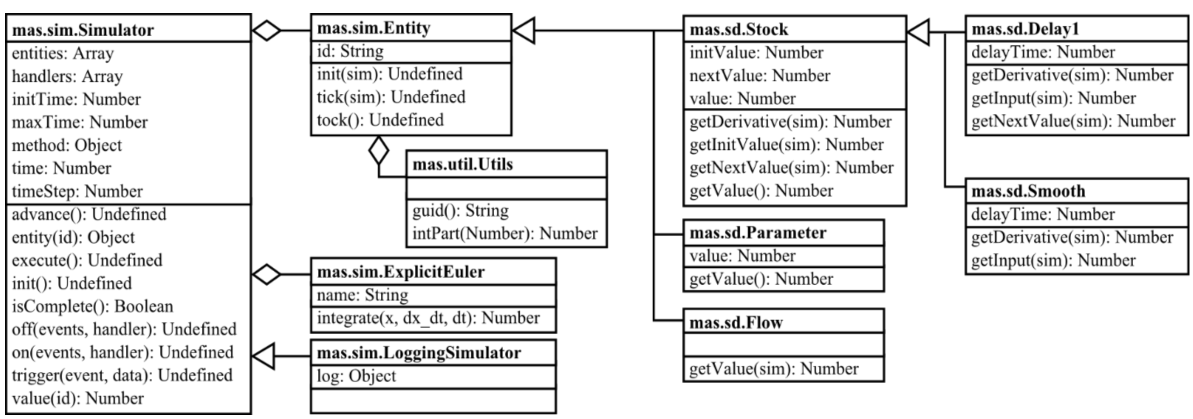


Figure 48. Class diagrams for the JavaScript API for SD models

`Entity` subclasses define components in the SD formalism. `Parameter` defines components with a constant value. `Flow` defines components with value dependent on other components, functionally defined by overriding a method (`getValue`). `Stock` defines components with a state variable numerically integrated during a simulation with derivative specified by overriding a method (`getDerivative`). `Delay1` and `Smooth` define first-order exponential delay and smoothing of an input signal specified by overriding a method (`getInput`). The `sim` argument provides access to the simulation context including integration method (`sim.method.integrate(…)`), time (`sim.time`), or entity values (`sim.value(…)`).

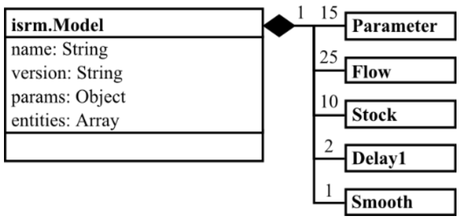
`Simulator` aggregates `Entity` objects to perform a time-managed simulation. The initialize method (`init`) initializes all entities and triggers an "init" event. The advance method (`advance`) ticks/tocks all entities, increments simulation time, triggers an "advance" event, and triggers a "complete" event if complete. The default completion check method (`isComplete`) compares the current simulation time against the specified maximum time (`maxTime`). Finally, event handling methods bind handlers to events (`on`), remove handlers (`off`), and trigger events (`trigger`). Similarly, `LoggingSimulator` logs time-based attribute values.

MODEL IMPLEMENTATION

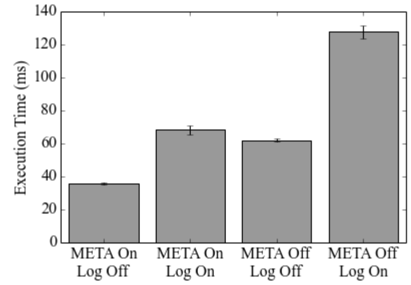
The JavaScript port of the DFM instantiates SD entities composed in a separate object instance. The `Model` class (figure below left) shows attributes to identify the model version and override parameter values and component SD entities. Each model component includes additional attributes to define semantic names, descriptions, and units as documentation. For example, the following defines the NRE Cost stock:

```
new mas.sd.Stock({
        id: 'nreCost',
        name: "NRE Cost",
        desc: "Non-recurring engineering cost.",
        units: "$",
        getDerivative: function(sim) {
                return sim.value("spendRate");
        }
})
```

This component overrides the default `getDerivative` method to access the Spending Rate flow value.



The ISRM model class instantiates required simulation entities for the SD formalism.



ISRM standalone model performance benchmark under four conditions. Error bars show 95% confidence interval over 100 trials.

The Vensim DFM and JavaScript ISRM are cross-validated by comparing outputs at each time step under both the META and no-META conditions. Differences in numerical precision (JavaScript uses double-precision while most versions of Vensim only use single-precision) restrict identical results. The no-META condition produces approximately equal results in both tools. The META condition produces small differences in intermediate variables which can appear as large relative differences for small quantities. For example, the JavaScript model shows -0.068 pending changes at time 1.5 while the Vensim model shows -0.038, a relative difference of more than 80%. Despite some transient values, the relative difference in final outcomes between the two tools is less than $6.9 \cdot 10^{-5}$ for all variables.

A performance benchmark the figure above (right) evaluates baseline execution time using Google Chrome version 39 with an Intel Core i5-760 CPU. Test conditions vary META input conditions and logging of intermediate values. Results range between 35 and 130 milliseconds for a 120-month simulation with 0.25 month time steps. Higher execution times arise from longer project durations without META processes and from data operations due to logging. Although results cannot be compared to Vensim due to license and application limitations, the small magnitude of around 10 executions per second provides a compelling case that JavaScript-based models are suitable for interactive interfaces.

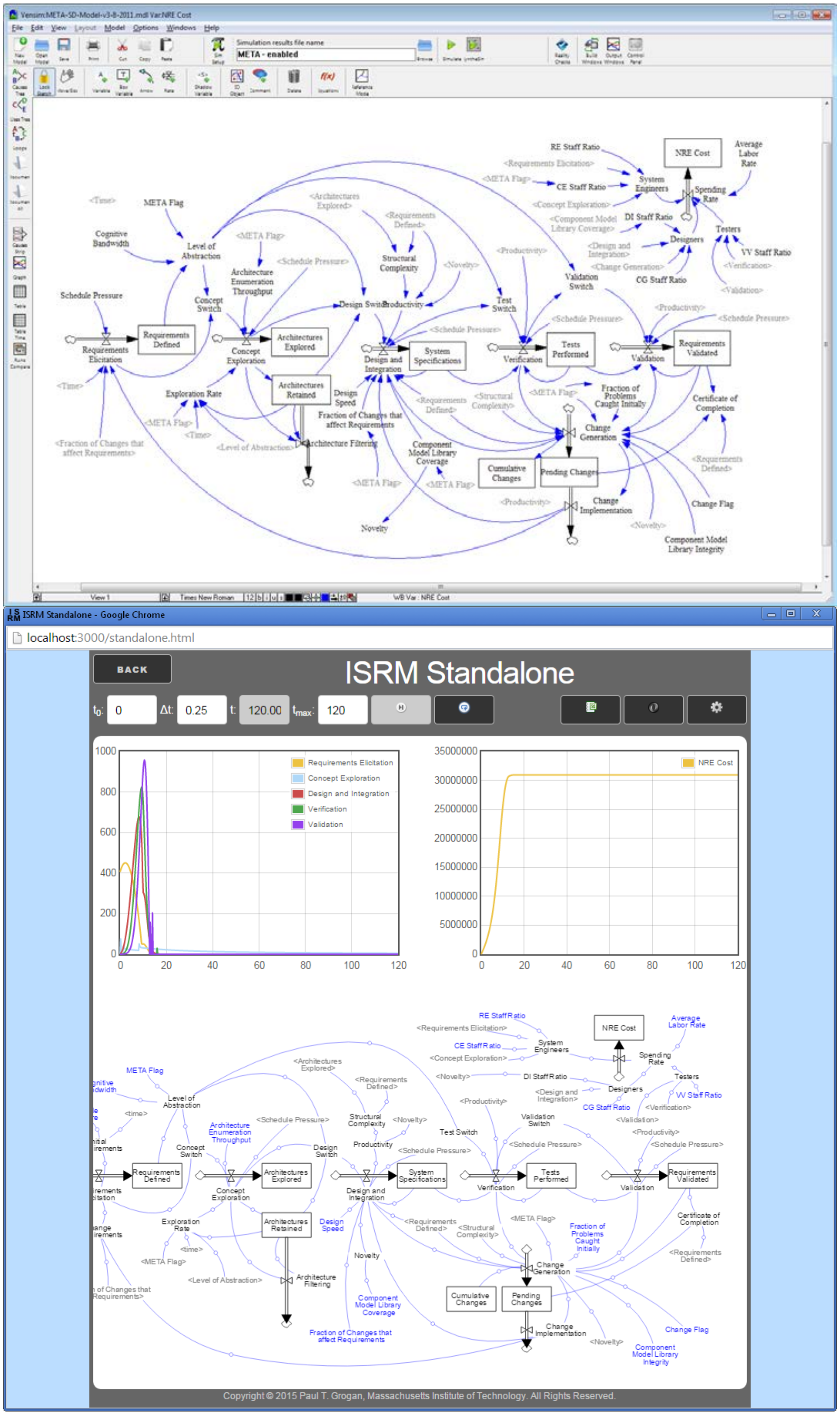


Figure 49. Screen captures comparing user interfaces for the Vensim-based DFM (top) and browser-based ISRM (bottom).

STANDALONE USER INTERFACE

The standalone ISRM user interface (UI) is a web page structured and styled with HTML and CSS and controlled with JavaScript. Figure 49**Error! Reference source not found.** compares the Vensim UI (top) to the ISRM UI (bottom). Buttons on the top section control simulations, the middle section plots data, and the bottom section visualizes a stock-and-flow diagram. jQuery[165] handles form inputs and event handling, Flot[166] plots data, and kinetic.js[167] manages the stock-and-flow diagram. Users click and drag stocks (rectangles), flows (black labels), parameters (blue labels), and shadow variables (gray labels) to customize the display. Double-clicking a field opens a jQuery UI[168] dialog widget to edit parameter values, view flow values, view/edit stock values, toggle plotting, and view documentation.

STANDALONE TOOL LIMITATIONS

The biggest limitation of standalone tool compared to existing SD tools arises from a fixed model structure in the UI where the user can only change parameter values. A few flag-based parameters such as META features or Change Generation toggle some features, but all other parameters such as Productivity, Model Library Coverage and Integrity, and Staff Efficiency only change value. Input parameters alone cannot modify the assumed model structure or behavior.

A number of assumptions in the DFM limit its applicability to broader engineering projects. For example, it does not enforce staffing level constraints for design processes and 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, the ISRM UI requires hard coding. Adding model-building activities to the ISRM will require a significant development effort to validate functional behaviors and automate layout of the stock and flow diagram.

Additionally, the tick/tock time advancement method in MAS restricts numerical integration to one-step methods such as explicit (forward) Euler. More precise methods such as fourth order Runge-Kutta (RK4) require either a centralized state update procedure or more iterative periods to estimate intermediate values. Future work should adapt the tick/tock procedure to allow for other numerical integration or simulation assumptions. Future work may also extend MAS to consider other SD functions beyond Delay1 and Smooth.

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[165] jQuery version 2.0.3. http://jquery.com, accessed 22-Sept 2014.
[166] Flot version 0.8.1. http://flotcharts.org, accessed 22-Sept 2014.
[167] Kinetic.js version 5.1.0. http://www.kineticjs.com, accessed 22-Sept 2014.
[168] jQuery UI version 1.10.3. http://jqueryui.com, accessed 22-Sept 2014.

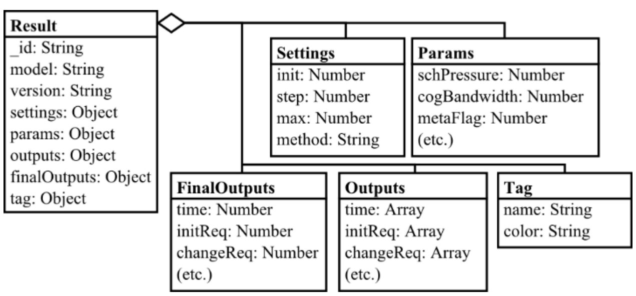
Service-based ISRM Application

The service-based ISRM application seeks to extend the capabilities of the standalone tool to compose, query, and visualize data across multiple model executions. This section reviews the tasks to define a service application programming interface (API), implement and validate the backend components, and design the user interface (UI).

Services API

The ISRM services API defines an interface to local and remote model execution and individual and aggregated data queries. Service requests and responses rely on a common JavaScript object notation (JSON) data format shown below (left). A `Result` object includes model information, simulation settings, input parameters, time-stepped outputs and final values, and a user-defined tag.

The table below (right) lists three services and corresponding routing URLs. The result service allows a user to query a particular result or submit new data from a local model execution. The execute service allows a user to submit a request for remote model execution. Finally, the data service allows a user to query aggregated data from the complete set of results. Aggregated queries overcome minimum transaction times compared to a large number of individual queries.



ISRM service-based data model used to structure and query aggregated data, individual result, and remote execution services.

ISRM data and execution services.

Method and URL	Action
GET /results/:id	Queries a result by ID.
POST /results	Submits a new local result contained in the in request body. Responds with its assigned ID.
POST /execute	Submits a remote model execution defined in the request body. Responds with its assigned ID.
GET /data	Queries an aggregated list of all data objects matching the request query.

Accessing the `GET /results` service returns a `Result` JSON object. For example:

```
REQ:    GET /results/54de7a979565b5eeced138ba
RES:    {
        "model": ...,
        "version": ...,
        "settings": {...},
```

```
        "params": {...},
        "outputs": {...},
        "finalOutputs": {...}
    }
```

To reduce the amount of data returned for a query, filtering options are available for some services. The `GET /results` and `GET /data` services can be truncated to only return portions of a complete `Result` object. For example, to only view the settings for a particular result:

```
REQ:    GET /results/54de7a979565b5eeced138ba/settings
RES:    { "init": ..., "max": ..., "step": ..., "method": ... }
```

Similarly, to view the final value of the NRE Cost variable for all results:

```
REQ:    GET /data/finalOutputs/nreCost
RES:    [
        {"_id":"54de7a979565b5eeced138ba", "nreCost": ...},
        ...,
        {"_id":"54de7aad9565b5eeced138bb", "nreCost": ...}
    ]
```

The `GET /data` service allows filtering using URL encoding with conditional operators in the table below. For example, to only view results for models with the Change Flag and META Flag parameters set to false (0):

```
REQ:    GET /data/finalOutputs/nreCost?params.changeFlag=0&params.metaFlag=0
RES:    [
        {"_id":"54de7a979565b5eeced138ba", "nreCost": ...},
        ...,
        {"_id":"54de7aad9565b5eeced138bb", "nreCost": ...}
    ]
```

. Data service conditional operators.

Encoded Operator	Operator	Condition
`=`	=	Equal to
`=$gte`	>=	Greater than or equal to
`=$gt`	>	Greater than
`=$lte`	<=	Less than or equal to

=$lt	<	Less than
=$ne	!=	Not equal to

To submit the results of a local model execution, the `POST /results` service expects a complete `Result` object (tag optional) as the request body:

```
REQ:      POST /results
        {
              "model": ...,
              "version": ...,
              "params": { ... },
              "settings": { ... },
              "outputs": { ... },
              "finalOutputs": { ... }
        }
RES:    {"_id": 54de7aae9565b5eeced138c9}
```

Similarly, the `POST /execute` service requires a partial `Result` object as the request body:

```
REQ:    POST /execute
        {
              "model": ...,
              "version": ...,
              "params": { ... },
              "settings": { ... }
        }
RES:    {"_id": 54de7aae9565b5eeced138ca}
```

Backend Implementation

The ISRM services are implemented in a Node.js[169] runtime environment with a MongoDB[170] document-based database service. These technologies define JavaScript as a common language for all application layers including the client (browser), server, and database document. Although built on a common language, browsers do not yet support the module management system used

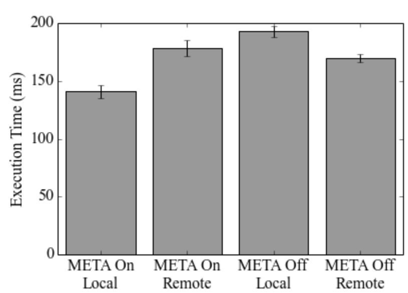
[169] Node.js version 0.10.32. http://nodejs.org, accessed 24-Oct. 2014.
[170] MongoDB version 2.6.5. http://mongodb.org, accessed 24-Oct. 2014.
RequireJS version 2.1.16. http://requirejs.org, accessed 18-Feb. 2015.

in Node so MAS and ISRM modules implement the RequireJS[171] interface for browser and server interoperability.

The Node execution uses the Express[172]**Error! Reference source not found.** framework to define a simple web server. The server provides routes for the three services (`request`, `data`, and `execute`) and otherwise serves static content as HTML pages with JavaScript applications (e.g. standalone tool, execution service, visualizations, and benchmark tools). The server application accesses a MongoDB service with the Mongoskin[173] package. `Result` objects are stored directly in MongoDB as documents.

The figure below shows results of a performance benchmark comparing local (in the browser, i.e. `POST /result`) and remote (in Node.js, i.e. `POST /execute`) model execution services using JQuery AJAX calls. All cases log time-varying data and run on the same physical machine as in the standalone benchmark. Execution services requires more time than the standalone case due to database insert/update activities. Local model execution is slightly faster for META projects while remote is slightly faster for non-META projects due to differences in data transfer quantity arising from project durations. In other words, remote model execution is preferred when generating large datasets to avoid transmitting data over services.

The service-based methods require more time than the corresponding standalone methods due to additional delays for client-web server and web server-database server communication and database actions. These examples demonstrate service overhead in a best case scenario with no network latency as about 100 milliseconds per execution. Overall, the service-based application still provides a rapid execution response, allowing about five executions per second. Querying existing data is much faster and also allows caching of commonly-accessed data to dramatically improve performance.



ISRM execution service performance benchmark under four conditions. Error bars show 95% confidence interval over 100 trials.

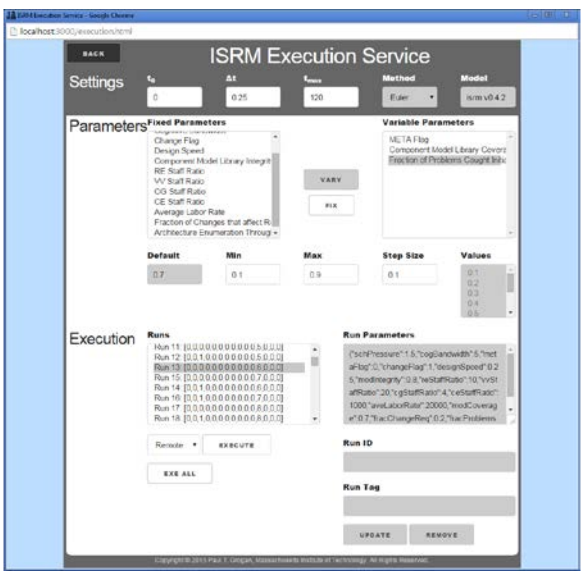
[171] RequireJS version 2.1.16. http://requirejs.org, accessed 18-Feb. 2015.
[172] Express version 4.11.2. http://expressjs.com, accessed 19-Feb. 2015.
[173] Mongoskin version 1.4.12. https://www.npmjs.com/package/mongoskin, accessed 19-Feb. 2015.

BROWSER-BASED USER INTERFACE

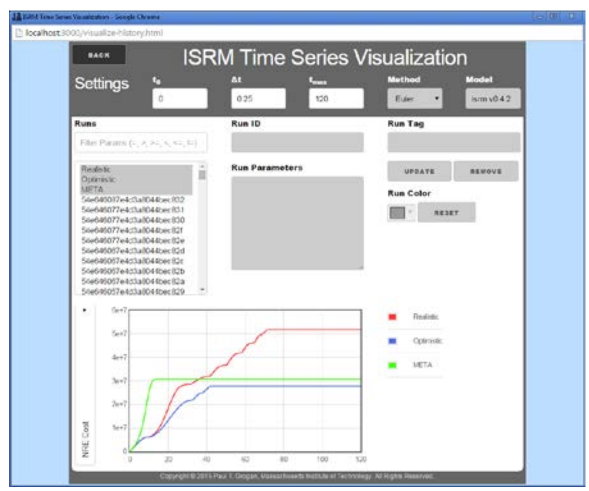
The ISRM service-based application provides UI modules with four core capabilities: batch execution, time series comparison, tradespace exploration, and sensitivity analysis. Each capability is embodied as a separate tool accessing services with JQuery AJAX methods.

The batch execution tool in the figure below (left) provides full-factorial design experiment generation with local or remote model execution. Users select and vary parameters of interest as value ranges. The tool generates list of runs which are processed with `POST /results` or `POST /execute` services. Additional UI components assign optional user tags to particular parameter sets to identify models of interest.

The time series comparison tool in the figure below (right) uses the `GET /results` service to display the simulation log data of a selected variable under various conditions. Individual results can be assigned color schemes which persist across all other visualizations. The example shown compares the time history for the NRE Cost stock under Optimistic (blue), Realistic (red), and META (red) conditions. Users can select particular model executions to display and change the y-axis to any stock or flow variable.



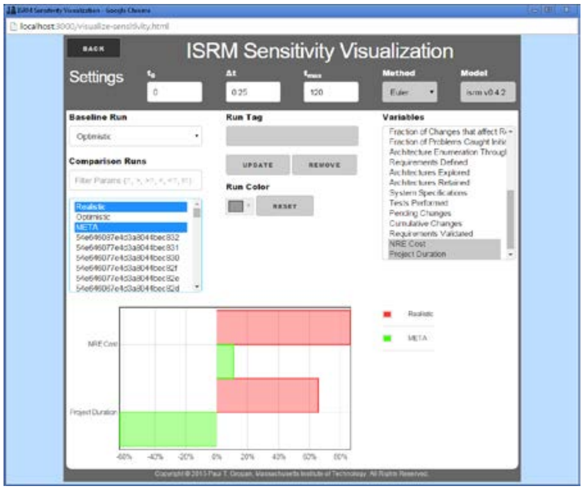
Batch execution tool. Users can run full-factorial design of experiments with local or remote model execution.



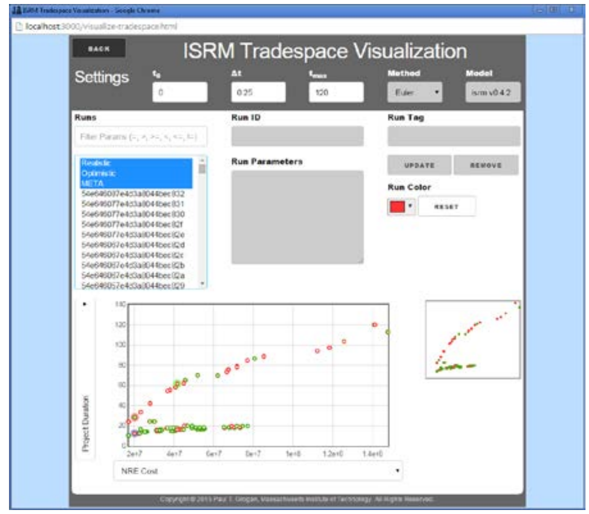
Time series visualization tool. Users visualize and compare time series of model outputs.

The sensitivity analysis tool in the figure below (left) also uses the `GET /results` service to compare final stock values or parameters as percentage differences from a baseline result. The example shown compares NRE Cost and Project Duration for Realistic (red) and META (green) conditions to the baseline Optimistic (blue) case. Users can select baseline or comparison model executions or add other stock or parameter variables to append to the sensitivity chart.

Finally, tradespace exploration in the figure below (right) uses the `GET /data` service to visualize the full set of available results plotted on two dimensions. The example shown visualizes the Project Duration-NRE Cost space and colors non-META results red and META-enabled results green. Users can select x- and y-axis variables from available stock and flow variables. A filtering option customizes a subset of results to display.



Sensitivity analysis visualization tool. Users visualize and compare final model outputs to a baseline case.



Tradespace exploration tool. Users visualize final model outputs on a two-dimensional space.

SERVICE-BASED APPLICATION LIMITATIONS

The service-based ISRM application only considers the DFM port developed under Phase 1 and does not consider changes beyond variable parameter values. Node provides shell and file system access which could be used to execute external models in future work. For example, a properly-licensed Vensim application with command line access may be coupled with the Node server to provide remote model execution. This approach benefits from optimized model execution in specialized tools but would suffer from time delays of shell and file system access rather than manipulating data in memory.

This application also only considers a single, non-malicious, local user and does not address co-modification of data. All tools query and interact with the same database but are not notified of database changes. Extensions to multi-user systems, for example distributed model execution, may require additional architectural components including improved server security and API access keys.

MongoDB allows a maximum document size of 16 megabytes which limits its generalizability to other simulations generating large datasets. This ISRM application stores log values of every stock and flow variable at each time step with document sizes on the order of 250 kilobytes which is considered large for most MongoDB applications. Models with larger outputs sets may be required to distribute a complete results document across several constituent documents.

While required for client-server interoperability, RequireJS reduces client-side performance by preventing the browser from pre-fetching JavaScript files. This causes a delay in UI display when a page is first loaded. Although not yet explored, the RequireJS optimizer or other methods such as Browserify[174] may provide improved performance at the cost of compiling JavaScript files before deploying applications.

CONCLUSION

Intense human-model interaction through new design methods and tools aim to improve perception and reduce cost and schedule to realize descriptively-complex systems. Applied to system project management, models may help assess alternative system development processes and resource allocations. ISRM extends past work to develop an extensible and interactive approach to rapidly analyze sensitivity to various factors using modern web-based technologies. Its main contributions include the standalone and service-based tools as prototypes of future interactive model development.

The standalone ISRM tool implements a JavaScript system dynamics (SD) model to demonstrate model execution and interaction capabilities in a browser-based environment. Performance benchmarks show model executions require about 100 milliseconds on consumer hardware. The tool provides user interface components similar to commercial modeling tools using open-source user interface component libraries.

The service-based ISRM application demonstrates data storage and query services using the Node.js platform and MongoDB document-based database. Performance benchmarks show services increase execution time to about 200 milliseconds but provide rapid access to stored and cached data through queries. Demonstrative applications using services include a batch execution tool, time series visualization, sensitivity analysis, and tradespace exploration.

Mirroring a core principle of other web-based technologies, ISRM tools are made available through online repositories. MAS can be accessed as the `mas` Node Package Manager (NPM) module with source code available on GitHub[175]. The standalone and service-based ISRM tools are also available on GitHub[176]. Addendum BThese prototypes could be used to help evaluate future method and tool development and may be extended in potential future projects.

There are two broad directions for potential future work. One direction aims to improve insights to system project management by refining the underlying design flow model. In particular, any future work should revisit original assumptions such as initial requirements profile and workforce constraints to improve generalizability of model results. This activity would be supported by a

[174] Browserify version 8.0.3. http://browserify.org, accessed 20-Feb. 2015.

[175] MAS version 0.0.3. https://github.com/ptgrogan/mas, accessed 20-Feb. 2015.
[176] ISRM version 0.0.1. https://github.com/ptgrogan/isrm, accessed 20-Feb. 2015.

browser-based SD model editor to replicate a larger portion of the functionality of proprietary tools for model-building activities.

Another direction of future work could be to mature methods developed in this project. The MAS library would benefit from more use cases to implement additional functions within the SD formalism or branch into other formalisms such as discrete event simulation or agent-based simulation. Extensions of service-based tools may address other limitations previously identified such as securing and synchronizing data across multiple concurrent users. Improvements to the prototype applications are also possible to improve usability and efficiency for particular tasks including options to export analysis data or figures.

ADDENDUM A. DESIGN FLOW MODEL DOCUMENTATION

This section documents components the Vensim-based Design Flow Model (DFM) adapted to the ISRM.

PARAMETERS

ISRM ID	DFM Name	Description	Units	Default Value
schPressure	Schedule Pressure	Multiplier for speed of several processes.		1.5
cogBandwidth	Cognitive Bandwidth	Constraint on the project team's ability to consider multiple concepts at the same time.	requirements	5
metaFlag	META Flag	Boolean to set META processes on (1) or off (0).		1 (META) 0 (non-META)
changeFlag	Change Flag	Boolean to set change generation on (1) or off (0).		1
designSpeed	Design Speed	Multiplier to set the rate of design activities.		0.25
modIntegrity	Component Model Library Integrity	Fraction of the component model library free of errors.		0.8
reStaffRatio	RE Staff Ratio	Productivity of requirements engineering staff.	requirements per person-month	10
vvStaffRatio	VV Staff Ratio	Productivity of verification and validation staff.	tests per person-month	20
cgStaffRatio	CG Staff Ratio	Productivity of change generation staff.	changes per person-month	4
ceStaffRatio	CE Staff Ratio	Productivity of the concept exploration staff.	concepts per person-month	1000 (META) 10 (non-META)
aveLaborRate	Average Labor Rate	Mean labor cost across the project team.	$ per person-month	2000
modCoverage	Component Model Library Coverage	Fraction of component models already existing in the library.		0.5 (META) 0 (non-META)
fracChangeReq	Fraction of Changes that affect Requirements	Fraction of changes which generate new requirements.		0.2
fracProblemsCaught	Fraction of Problems Caught Initially	Fraction of changes caught during design, verification, and validation to avoid generation of changes.		0.7
archThroughput	Architecture Enumeration Throughput	Rate of potential architecture generation.	architectures per month	50 (META) 10 (non-meta)

STOCKS

ISRM ID	DFM Name	Description	Units	Initial Value	Derivative Formula
reqDefined	Requirements Defined	Number of requirements defined.	requirements	0	reqElicit
archExplored	Architectures Explored	Number of architectures explored.	architectures	0	int(conExploration)
archRetained	Architectures Retained	Number of architectures retained.	architectures	0	int(conExploration – archFiltering)
systemSpecs	System Specifications	Number of system specifications generated.	specifications	0	designIntegration
testsPerformed	Tests Performed	Number of specifications tested.	tests	0	verification
pendChanges	Pending Changes	Number of changes pending completion.	changes	0	changeGen - changeImpl
cumChanges	Cumulative Changes	Number of changes generated.	changes	0	changeGen

reqValidated	Requirements Validated	Number of requirements validated.	requirements	0	validation
nreCost	NRE Cost	Non-recurring engineering cost.	$	0	spendRate
projDuration	n/a	Duration until certificate of completion is achieved.	months	0	1 - certCompletion

Flows

ISRM ID	DFM Name	Description	Units	Value Formula
initReq	Initial Requirements	Initial rate of requirements generation from design activities shaped by schedule pressure and project time.	requirements per month	max(0, -pow(2 * schPressure * time – 10 / schPressure, 2) + schPressure) * 300)
changeReq	Change Requirements	Rate of requirements generation due to change implementation.	requirements per month	fracChangeReq * changeImpl
reqElicit	Requirements Elicitation	Rate of requirements generation including initial and change components.	requirements per month	initReq + changeReq
levAbstraction	Level of Abstraction	Level of abstraction for design activities. Non-META operates at a single level of abstraction. META allows preliminary work at other levels of abstraction determined by the number of requirements and cognitive bandwidth of the team.		if(metaFlag == 1, int(log(reqDefined + 1) / log(cogBandwidth)), 1)
conSwitch	Concept Switch	Boolean to turn concept exploration on (1) or off (0). Concept exploration is always allowed at higher levels of abstraction and is also allowed under low levels of requirements elicitation.		if(levAbstraction > 1 || reqElicit < 10, 1, 0)
conExploration	Concept Exploration	Realized exploration rate of potential architectures. Exploration is limited by the maximum exploration rate and the architecture enumeration throughput. Schedule pressure acts as a multiplier for concept exploration.	architectures per month	schPressure * conSwitch * min(explorationRate, archThroughput)
explorationRate	Exploration Rate	Maximum exploration rate of potential architectures. META explores at a rate geometrically proportional to the level of abstraction and inversely proportional to the time and number of architectures retained. Non-META explores at a fixed rate and stops when one architecture is retained.	architectures per month	if(metaFlag == 1, (10 * exp(levAbstraction)) / ((0.1 * time + 1) * (archRetained + 1)), if(archRetained > 1, 0, 10))
designSwitch	Design Switch	Boolean to turn design and integration on (1) or off (0). Design is allowed at higher levels of abstraction or if concept exploration ends with at least one retained architecture.		if(levAbstraction > 1 || conExploration == 0 && archRetained > 1, 1, 0)
strComplexity	Structural Complexity	Measure of structural complexity for the current design. Complexity is proportional to number of requirements and inverse-log of the number of architectures explored		reqDefined / (log(sqrt(archExplored) + 10))

		(elegance through exploration).		
productivity	Productivity	Multiplier for the productivity of workers. Decreases with increasing novelty, proportional to requirements defined, and inversely proportional to complexity.		(1 – novelty / 4) / 2 + min(reqDefined / (strComplexity + 1), 1)
designIntegration	Design and Integration	Rate of design and integration specification. Proportional to schedule pressure. Specifications come from requirements (proportional to design speed, productivity, and fraction of unspecified requirements and inversely proportional to novelty) or change implementation.	specifications per month	schPressure * (designSpeed * productivity * designSwitch * sqrt((systemSpecs + 1) * max(0, reqDefined – systemSpecs)) / (1 – modCoverage) + (1 – fracChangeReq) * changeImpl)
novelty	Novelty	Fraction of new components.		1 – modCoverage
archFiltering	Architecture Filtering	Rate to filter out unwanted architectures.	architectures per month	if(archRetained <= 1, 0, delay1(conExploration, 1))
testSwitch	Test Switch	Boolean to turn testing on (1) or off (0).		if(levAbstraction > 1 || designIntegration < 10), 1, 0)
verification	Verification	Rate of specification tests. Proportional to schedule pressure and productivity.	tests per month	if(testsPerformed < systemSpecs, schPressure * testSwitch * productivity * sqrt((testsPerformed + 1) * (systemSpecs – testsPerformed)), 0)
changeGen	Change Generation	Rate of change generation.	changes per month	changeFlag * max((reqDefined + 1 – reqValidated) / (reqDefined + 1), 0) * delay1(strComplexity / (reqDefined + 1) * ((1 – fracProblemsCaught) * (verification + validation + designIntegration) + delay1(metaFlag * novelty * (1 – modIntegrity) * designIntegration, 4)), 1) * if(metaFlag == 1, novelty + 0.5, 1)
changeImpl	Change Implementation	Rate of changes implemented.	changes per month	smooth1(delay1(changeGen, 0.5, 1)
validationSwitch	Validation Switch	Boolean to turn validation on (1) or off (0).		if(levAbstraction > 1 || verification < 10), 1, 0)
validation	Validation	Rate of requirements validation. Proportional to schedule pressure and productivity.	requirements per month	if(reqValidated < testsPerformed, schPressure * validationSwitch * productivity * sqrt((reqValidated + 1) * (testsPerformed – reqValidated)), 0)
certCompletion	Certificate of Completion	Number of certificates of completion issued.		if(reqValidated > 0.999 * reqDefined && pendChanges < 1, 1, 0)
diStaffRatio	DI Staff Ratio	Productivity of design and integration staff.	parts per person-month	4 / novelty
sysEngineers	System Engineers	Number of system engineers.	people	int(conExploration / ceStaffRatio + reqElicit / reStaffRatio)
designers	Designers	Number of designers.	people	int(designIntegration / diStaffRatio + changeGen / cgStaffRatio)
testers	Testers	Number of testers.	people	int((validation + verification) / vvStaffRatio)
spendRate	Spending Rate	Rate of spending money.	$ per month	(sysEngineers + designers + testers) * aveLaborRate

Addendum B. Installation and Configuration

Portions of this guide are based on the following tutorials from Christopher Buecheler:

- http://cwbuecheler.com/web/tutorials/2013/node-express-mongo/
- http://cwbuecheler.com/web/tutorials/2014/restful-web-app-node-express-mongodb/

Software Repository

A GitHub software repository holds the source code for both the standalone and service-based ISRM tools. To connect, follow the following instructions.

1. Install a Git client: https://help.github.com/articles/set-up-git
2. Clone the ISRM repository: https://github.com/ptgrogan/isrm

Server Configuration

The service-based ISRM tool requires a properly-configured server. This section describes the process to set up required software on Windows. Other operating systems have not been tested but should work.

1. Download and install the latest 32-bit or 64-bit version of Node.js (version 0.10.35 as of writing): http://nodejs.org/download/
    - Node.js is released under the MIT license.

2. Download and install the latest 64-bit (preferred) version of MongoDB (version 2.6.6 as of writing): http://www.mongodb.org/downloads
    - MongoDB is released under the Free Software Foundation GNU AGPL v3.0 license.
    - Note: the 64-bit version is preferred to allow databases with more than 2 GB of data.

3. Start the database service. Open a command console and navigate to the MongoDB install directory and execute the following command to start the database service.
    ```
    cd C:\path\to\MongoDB\bin

    mongod --dbpath C:\path\to\isrm\data
    ```
    This command starts the MongoDB service on the default port 27017 using the directory path `C:\path\to\isrm\data` to store documents.

4. Install the Node.js service. Open another command console and navigate to the ISRM Server directory. Execute the following NPM command to install dependencies.
    ```
    cd C:\path\to\isrm

    npm install
    ```
    This command installs packages listed in the file `package.json`. If you receive an ENOENT error message, manually create the directory at the corresponding location (likely `C:\Users\username\AppData\Roaming\npm`) and re-issue install command.

5. Start the Node.js service:
   `npm start`

   This command starts the Node.js service on default port 3000.

6. Connect to http://localhost:3000 in any web browser. The default page in Figure 50 shows a dashboard of available tools including benchmarking applications.

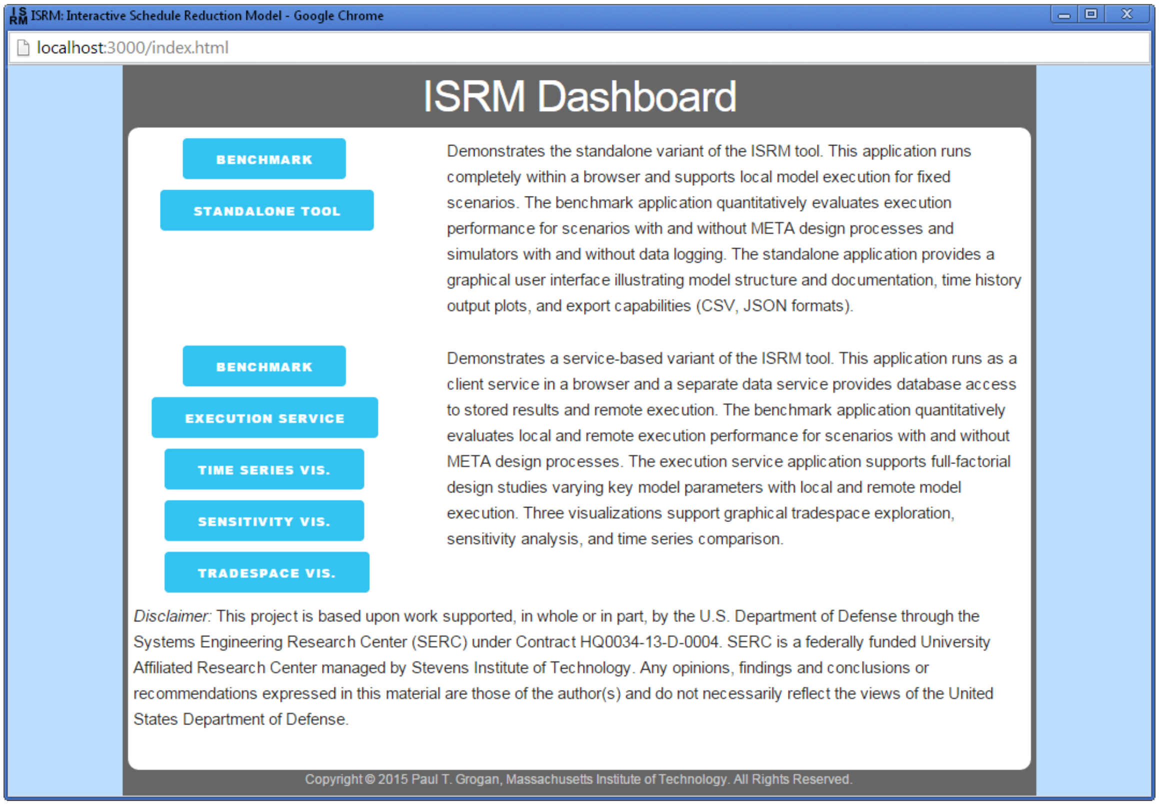


Figure 50 Default ISRM dashboard.

Addendum C. Source Code Guide

This section provides an overview of the source code for the standalone and service-based tools. The ISRM repository follow this general structure:

- `isrm\`
  - `bin\` Node scripts to start the application
  - `(data\)` MongoDB database files (create after install)
  - `(node_modules\)` Third-party Node modules (created on install)
  - `routes\` Express service routes
  - `www\` Static web files
  - `app.js` Express web server application
  - `package.json` Node package definition
  - `README.md` Information markdown file

Standalone Tool

The standalone ISRM tool emphasizes the following files:

- `isrm\www\`
  - `images\` Images for the user interface
  - `scripts\` Directory for JavaScript scripts and libraries
    - `app\` Directory for JavaScript application scripts
      - `standalone.js` Standalone application script
    - `lib\` Directory for JavaScript libraries
    - `common.js` Common configuration for RequireJS
    - `standalone.js` RequireJS loader for standalone tool
  - `styles\` Directory for CSS styles
  - `standalone.html` Standalone tool HTML page

Open the file `standalone.html` in any web browser to directly access the standalone tool. This application and the related `benchmark-standalone.html` work without the Node web server or MongoDB database components as they do not access the ISRM services.

Service-based Application

The service-based ISRM tool emphasizes the following files:

- `isrm\`
  - `bin\` Node scripts to start the application
  - `data\` MongoDB database files (create after install)
  - `node_modules\` Third-party Node modules (created during npm install)
  - `routes\` Express Service routes
    - `data.js` Data services
    - `execute.js` Execute services
    - `results.js` Results services

- `www\` Static web files
    - `images\` Images for the user interface
    - `scripts\` Directory for JavaScript scripts and libraries
        - `app\` Directory for JavaScript application scripts
            - `execution.js` Batch execution tool
            - `visualize-history.js` Time series visualization tool
            - `visualize-sensitivity.js` Sensitivity analysis tool
            - `visualize-tradespace.js` Tradespace exploration tool
        - `lib\` Directory for JavaScript libraries
        - `common.js` Common configuration for RequireJS
        - `execution.js` RequireJS loader for batch execution
        - `visualize-history.js` RequireJS loader for time series tool
        - `visualize-sensitivity.js` RequireJS loader for sensitivity tool
        - `visualize-tradespace.js` RequireJS loader for tradespace tool
    - `styles\` Directory for CSS styles
    - `execution.html` Batch execution HTML page
    - `index.html` ISRM dashboard page
    - `visualize-history.html` Time series visualization HTML page
    - `visualize-sensitivity.html` Sensitivity analysis HTML page
    - `visualize-tradespace.html` Tradespace exploration HTML page
- `app.js` Express web server application
- `package.json` Node package definition

Once the Node web server and MongoDB database service are running, access the dashboard page (`index.html`) at http://localhost:3000 in any web browser

MOVING FORWARD TO PHASE THREE

- The research team will be using knowledge and information gained in Phase 1 and Phase 2 to focus ongoing efforts in Phase 3 to further explore the identified IMCSE-related considerations within four key areas, and the challenges and opportunities at their intersection.
- The Pathfinder Workshop Report (Appendix A) will be released to elicit comments and recommendations, augmented by discussions with selected subject matter experts. This will feed into creating a collaboratively-derived research agenda. A research roadmap will be derived in collaboration with other SERC researchers and the broader systems community. A leadership summit may be conducted to support validation of research priorities, recommend pathways to accelerate research progress, and enable transition to the systems community.
- The team will perform research to mature the approach for evaluating systems under dynamic uncertainty, with further development of the extended framework to for interactive capability and scaling to big data. This work extends the Phase 2 effort on a demonstration prototype, the Interactive Value-Driven Tradespace Exploration and Analysis Suite (IVTea Suite) that applied IMCSE principles to enhance the user interface, data handling and analysis widgets. In Phase 3 the research team will enhance the method and degree of interactive capability, focusing specifically on the Epoch-Era Analysis (EEA) method, a novel method for value-driven tradespace exploration and analysis. The maturing prototype framework with associated supporting tools will be applied to a case analysis including various types of uncertainties. This case application will be used to elicit feedback on relevance, ease of use, feasibility and tractability of data scaling and visualization techniques. The research team will extend the Phase 2 prototype for interactive Epoch-Era Analysis and test it using a case application, along with preliminary supporting infrastructure, which will then be used to inform the transition strategies, additional case application and prototype user testing. The team will build on the Phase 2 work on value model trades to further evolve the framework and process, and apply this through an expanded case application.
- In Phase 3, the research team will build on prior phase results to further evolve the framework and process for conducting value model choice and tradeoffs and apply this through an expanded case application set, to validate the framework and identify workflow considerations. In this phase, the model choice and tradeoff framework will be expanded including demonstration cases beyond value models (to include trading of other types of models including performance and cost models). The expanded framework will consider alternative use cases for the impact of model choice and tradeoffs on decision-making. For example, this includes the context of multi-stakeholder negotiations using tradespace exploration, where the data source(s) (i.e. “models”) strongly impact the trust and framing of the shared decision problem.
- The research team will continue to investigate the cognitive and perceptual considerations in human-model interaction, a topic for which little research exists, though there is a body of knowledge to draw from. Preliminary heuristics/design principles will be gathered, adapted

for human-model applicability, and synthesized as a draft guidance document. The guide will be shared for review and comment by model developers, users and model-based software designers, toward publication of a validated set of guiding principles for effective human-model interaction during Phase 4. A goal is to involve one or more SERC collaborators as transition partners, to pilot use of the guiding principles during Phase 3.

- The research team will use the results of Phase 1 and Phase 2, along with ongoing Phase 3 research interim results, to develop several publishable papers for journal and conference submissions. Evolving prototype MPTs will be shared and demonstrated at one or more SERC-related events during Phase 3, including the CSER 2015. The research team will continue active knowledge exchanges with several other SERC researchers performing related work, where IMCSE outcomes can inform and/or be applied in their work.

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, and in Phase 2 have been implementing the plan. The plan includes identifying and working with transfer partners and research collaboration partners. Phase 3 will continue this work.

- In Phase 2 IMCSE research on current state of the art and practice was shared among participants in the Pathfinder Workshop held on 20 January 2015. The report will be disseminated for additional feedback and there will be subsequent exchanges extending from this workshop via teleconferences and meetings.
- The Pathfinder Project Report synthesizes the observations, findings and recommendations in current art and practice, research needs, emerging research, and an envisioned ideal world. This report issued at the end of Phase 2, will undergo a review/comment period in Phase 3. During Phase 3 the research team will submit a paper on the emerging research agenda.
- During Phase 3, the research team will evolve the list of individuals and organizations to be contacted for inputs for the activity of developing a collaboratively-derived research agenda. A working paper initiated during Phase 2 to capture the approach and lessons learned in creating this agenda will be evolved during Phase 3. A journal submission will subsequently be prepared from the working paper at the end of Phase 3.
- Results of the Interactive Schedule Reduction Model and Interactive Epoch-Era Analysis were shared with the broader SERC community, in selected meetings and workshops, including NDIA SE 2014 and INCOSE IW15. A paper on each of these projects was accepted to CSER 2015, and will be presented.
- During Phase 3, the ongoing work on the Interactive Epoch-Era Analysis and the Model Choice and Tradeoffs will be shared and demonstrated at one or more SERC events.
- One or more selected conference publications developed during Phase 2 will be evolved to journal submissions during Phase 3.
- Aspects of the IMCSE research were presented at the 2015 Complex Systems Design & Management (CSD&M) Conference, and specific discussions were held on related research efforts ongoing in Europe.
- Throughout Phase 3, synergies with other SERC tasks were 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. The research team is actively exchanging information with other SERC researchers with research relevant to IMCSE.
- The research team discussed the work with leaders of the INCOSE Model-Based Systems Engineering initiative during the INCOSE IW 2015, looking for points of connection in the work.
- In Phase 2, the research team has identified potential transition partners within and external to SERC for user-testing of methods and prototypes. During Phase 3, one or more of these partnerships will be established.

Conclusion

The research team completed the Phase 1 effort, taking place over a four month period and has now completed the Phase 2 effort, taking place over a five month period. The activities within the three thrusts – foundations, fundamentals, and applications – are on-track for the overall goals specified for Phase 1 and Phase 2, and readiness to transition to Phase 3 has been achieved.

At the end of Phase 2 the team has converged on key research topics and specific activities in support of the broader IMCSE objectives. The pathfinder workshop has validated the need for research on IMCSE, and resulted in a significant set of observations, findings and recommendations. This has provided a sound foundation for further knowledge gathering and moving forward with efforts to build a community around the IMCSE.

Phase 2 has demonstrated several ideas and technology strategies for interactive model-centric activities, and specific plans are in place for Phase 3 to build on these findings. The Interactive Epoch-Era Analysis activity has progressed and a plan is in place for the Phase 3 work.

Phase 2 investigations have revealed the importance of understanding the perceptual and cognitive considerations for human-model interaction, and a Phase 3 effort has been formulated to address this area. The research team will work toward evolving research findings to practical guidance in the form of heuristics and design principles.

APPENDIX A: REFERENCES

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