Interactive Model-Centric Systems Engineering (IMCSE)

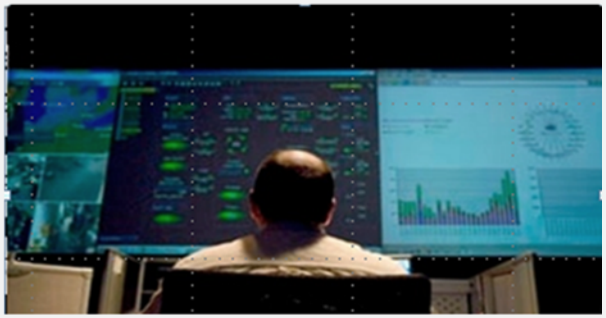
Research Review

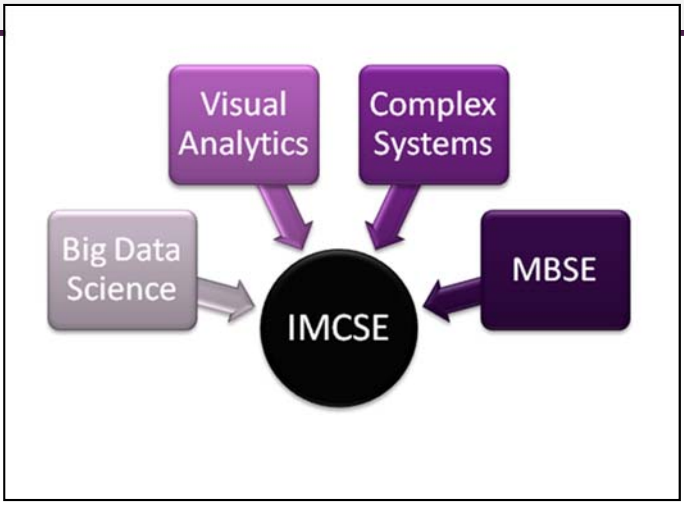
By
Dr. Donna H. Rhodes and Dr. Adam M. Ross, MIT
7th Annual SERC Sponsor Research Review
December 4, 2015

www.sercuarc.org

IMCSE Goal

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 / BACKGROUND

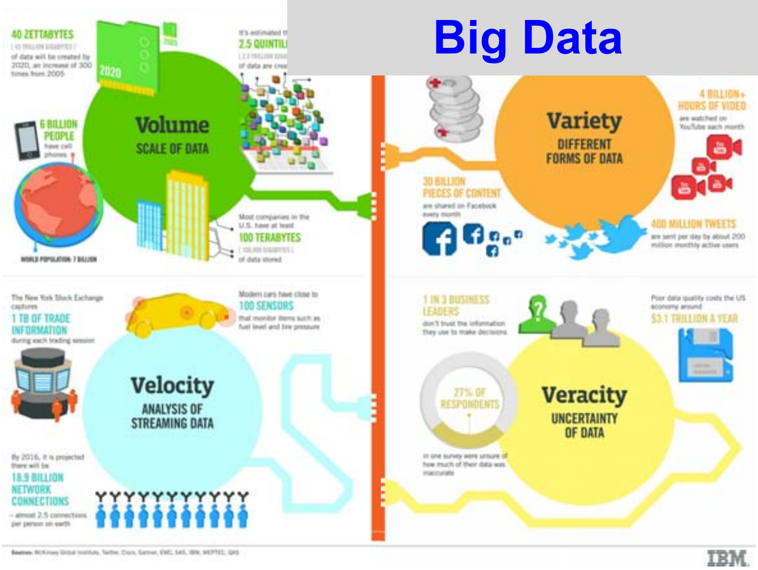
Research Challenges

Models have significantly changed systems engineering practice over the past decade and continue to do so…

- Model-based systems engineering (MBSE) methods and tools are increasingly used throughout the entire system lifecycle
- While substantial benefits have been achieved, the most impactful application of models in systems engineering has yet to be realized
- Truly transformative results in methods, processes and tools are necessary to fully achieve a model-centric paradigm

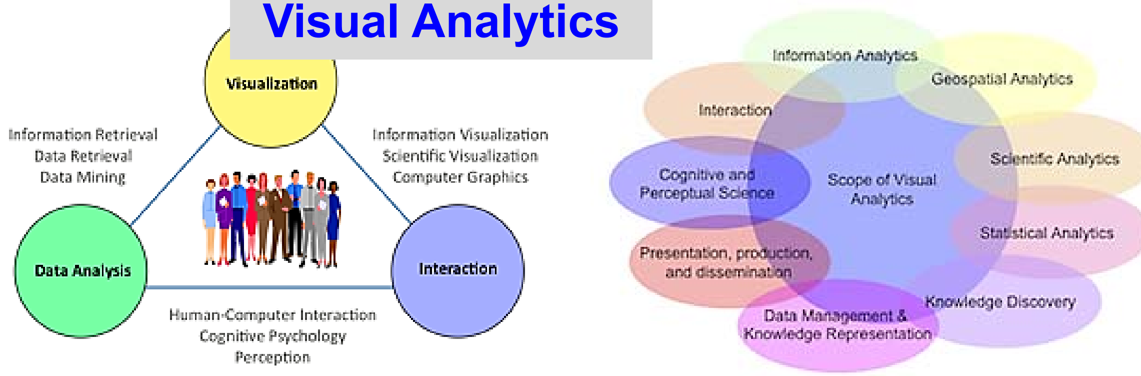
Nexus of Transformational Ideas

Big Data



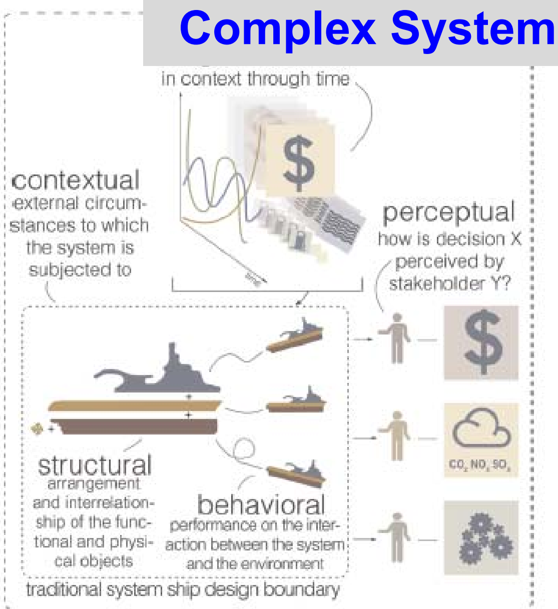
http://www.ibmbigdatahub.com/sites/default/files/infographic_file/4-Vs-of-big-data.jpg

Visual Analytics



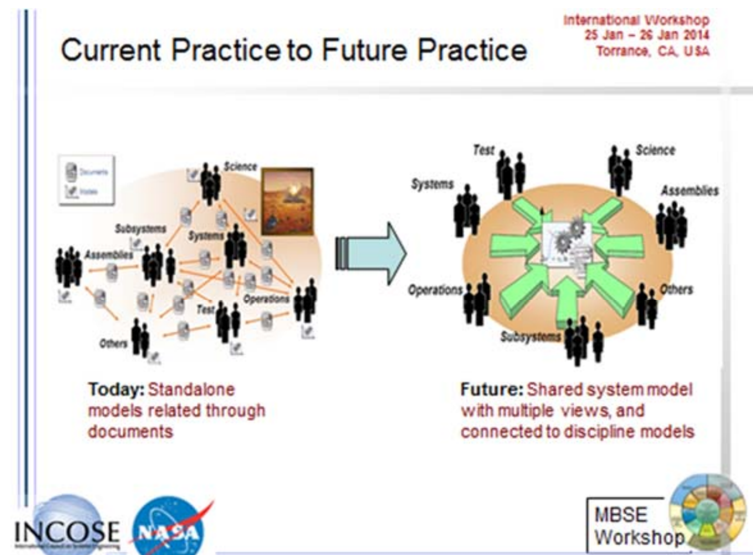
www.visual-analytics.eu/faq/

Complex Systems



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.

Model-based Systems Engineering



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

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Merging the Four:
Interactive Model-Centric Systems Engineering

SEARI Systems Engineering Advancement Research Initiative

- Big Data + Visual Analytics…
  + Complex Systems + MBSE = IMCSE
  - Volume, variety, velocity, and veracity of data
  - Collect data, visualize, interact, model, find patterns, generate insights, repeat
  - Structural, behavioral, contextual, temporal, and perceptual complexities
  - Integrated models including requirements, structure, behavior, parametrics

Interactive Model-Centric Systems Engineering	MBSE	STRUCTURAL	form of system components and their interrelationships	**Existing "state of practice"** systems architecting and model-based systems engineering
		BEHAVIORAL	function/performance, operations, and reactions to stimuli	
		CONTEXTUAL	circumstances in which the system or enterprise exists	**Emerging "state of art"** *Epoch Modeling* *Multi-Epoch Analysis* *Epoch-Era Analysis* *Dynamic Tradespace Exploration* *Multi-Stakeholder Negotiations* *Comprehension of Complex Datasets* *Studies of Decision Making* *and more….*
		TEMPORAL	dimensions and properties of systems over time	
		PERCEPTUAL	stakeholder preferences, perceptions and cognitive biases	

- Potential use for this merged capability for decision support within and across systems engineering throughout lifecycle

On the power of humans with computers:

"statistics (computing) + humans is much more powerful than statistics alone or humans alone"
– Professor Remco Chang, Tufts University
Visual Analytics Lab, Aug 2013

Developing complex systems necessitates an approach to generate, manage, and analyze artificial data across these five aspects, which result in improved SE decision making

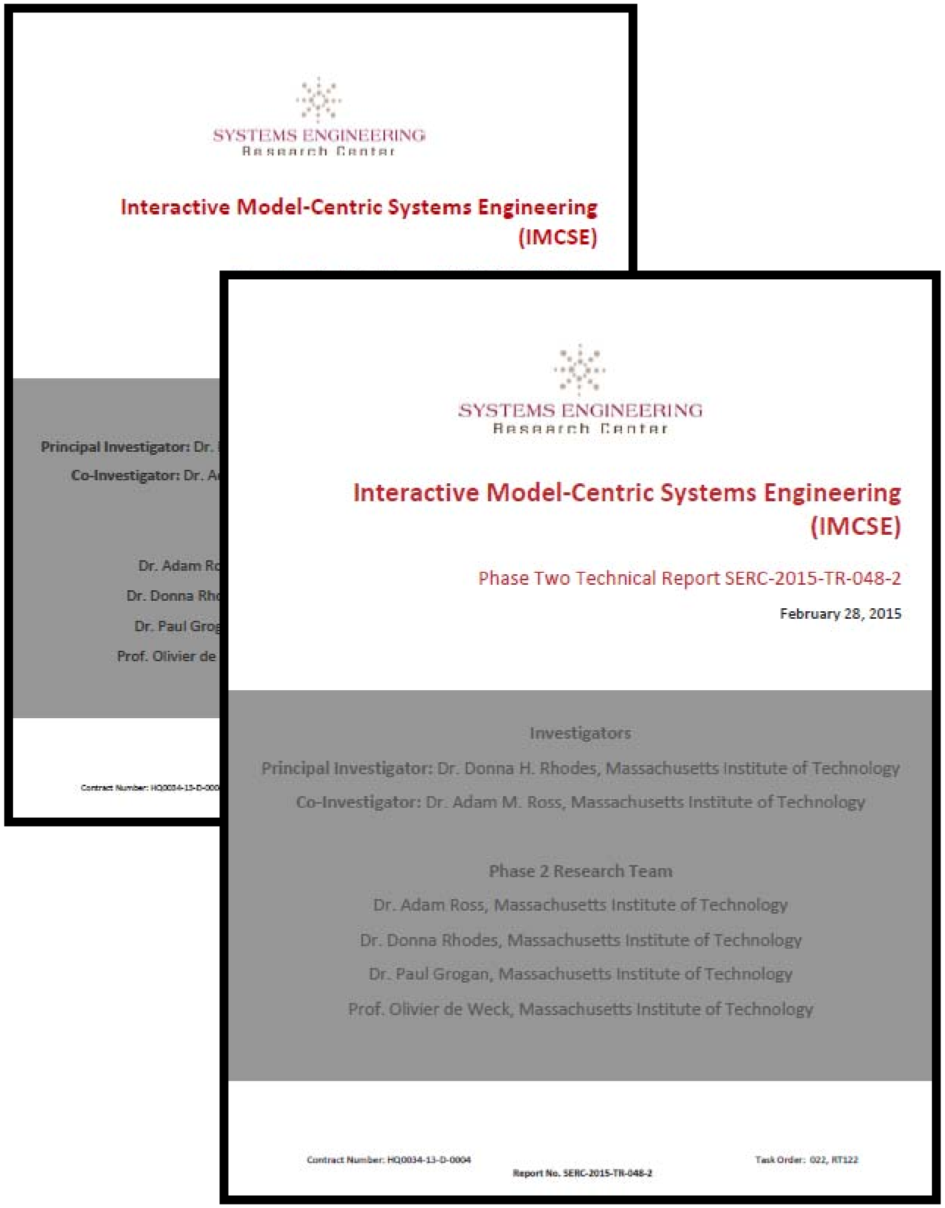
Overall IMCSE Project Objectives

OBJECTIVES

- Formulate and mature a shared IMCSE research agenda and roadmap
- Encourage a focus on human-model interaction within model-centric engineering community
- Create and disseminate IMCSE knowledge assets, prototypes, demonstration cases and empirical studies
- Develop synergistic partnerships and transition strategies to achieve impact

PHASE 3 RESEARCH

Project Overview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Interactive Model-Centric Systems Engineering (IMCSE)

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Interactive Model-Centric Systems Engineering (IMCSE)

Phase Two Technical Report SERC-2015-TR-048-2

February 28, 2015

Investigators

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

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

Phase 2 Research Team

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Contract Number: HQ0034-13-D-0004 Task Order: 022, RT122

Report No. SERC-2015-TR-048-2

RT-122 Phase 1 May 2014-Sep 2014
RT-122 Phase 2 Oct 2014-Feb 2015
RT-143 Phase 3 Mar 2015 – Feb 2016

YEAR 2 Activities (Phase 3)

1. **Pathfinder Research Roadmap**
2. **Model Choice and Trading Models**
3. **Interactive Epoch-Era Analysis (IEEA)**
4. **Cognitive and Perceptual Considerations in Human-Model Interaction**

IMCSE Year 2 (Phase 3) Areas

Pathfinder: Collaboratively-Derived IMCSE Research Roadmap

- derive an IMCSE research roadmap, in collaboration with other SERC researchers and the broader systems community
- build partnerships for research within and external to SERC

Human-Model Interaction

- preliminary cognitive and perceptual heuristics/design principles synthesized toward a guidance document for model developers, users, decision makers
- Investigations on multi-stakeholder negotiation, model curation, non-technical challenges of digital system models

Model Choice and Trading Models

- expand model choice and tradeoff framework and demonstration case beyond value models, to trading of other types of models including performance and cost models

Interactive Epoch-Era Analysis

- apply maturing prototype framework with associated supporting tools to a case analysis including various types of uncertainties
- case application to elicit feedback on relevance, ease of use, feasibility and tractability of data scaling and visualization techniques

PATHFINDER

Expected Outcome: Collaboratively developed research agenda used as a means to enable research collaboration and partnerships with early adopters

PATHFINDER PROJECT AND 2015 WORKSHOP

IMCSE Pathfinder

IMCSE Pathfinder project brings together the relevant stakeholders to develop a research vision and research priorities, and a roadmap to achieve them

- Investigate current practice and emerging state of the art through literature and discussions with subject experts
- Face-to-face gatherings to define a research agenda
- Tap into the broader research community to develop a collaboratively-derived research agenda
- Build a community of interest and collaboration partners

The ultimate goal is to build a community of interest around the IMCSE research agenda, establish partnerships for research, and to foster collaboration in addressing the emerging challenges at the intersection of the four pillars.

Pathfinder Workshop
20 January 2015

Key Emergent Themes

- Characteristics of Models
- Ease of Interaction
- Enabling Informed Decisions
- Enabling Human-Human Interaction
- Guided Interaction
- Model Re-Usability
- Trusted Models

Imagine an Ideal World

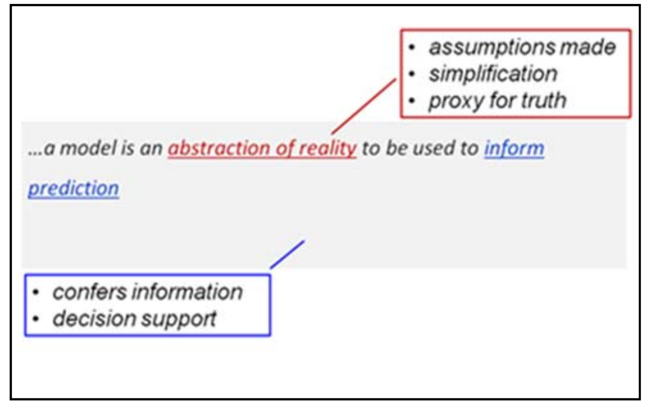
An intuitive experience that generates deep insights across the area of relevant decisions that balances time, resources and the desired confidence in the decision outcome.

Pathfinder Workshop Report published 28 Feb 2015

Who Interacts with models?

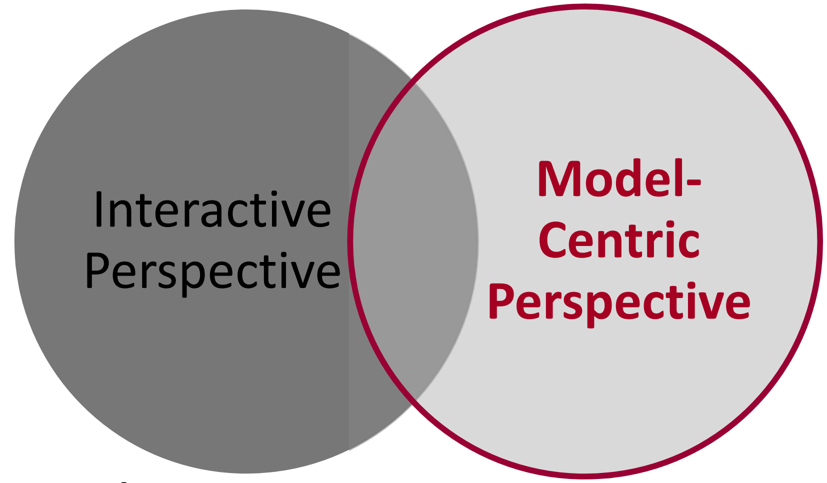
multitude of users, used for many reasons

- model developers
- engineers/designers
- system testers
- resource analysts
- senior decision makers
- policy analysis
- developers of model-based toolsets



Model-Centric Perspective

Potential topics might include:



- how information is displayed
- what forms models take
- how models generate information
- how models accept user inputs
- how models are developed and maintained
- how models are reused, formalisms and platforms used
- how sensitivity analysis is performed
- how models are integrated with other models
- how model-related information affects trust and reuse
- how model development is iterated
- how models are bundled with validation information
- how models are interoperable, etc.

Trusted Models

- The individual will trust models, with supporting evidence underlying that trust.
- There will be an **established pedigree/heritage at variable levels of fidelity**.
- A rich set of **information (for example, test cases) will be bundled with a model**.
- **As needed for a given role, models may be "invisible" such that non-essential detailed information is hidden, or have increasing levels of "transparency" for the individual who needs to examine inner workings of the model**.
- Uncertainty in model output is apparent, as framed by specific context/use.
- The development environment and model libraries will foster a high trust, collaborative relationship between the model users and the model developers.
- Individuals will trust that sharing models will not jeopardize the need for their personal expertise.

Imagine an Ideal World

Model Re-Usability

Model Re-Usability

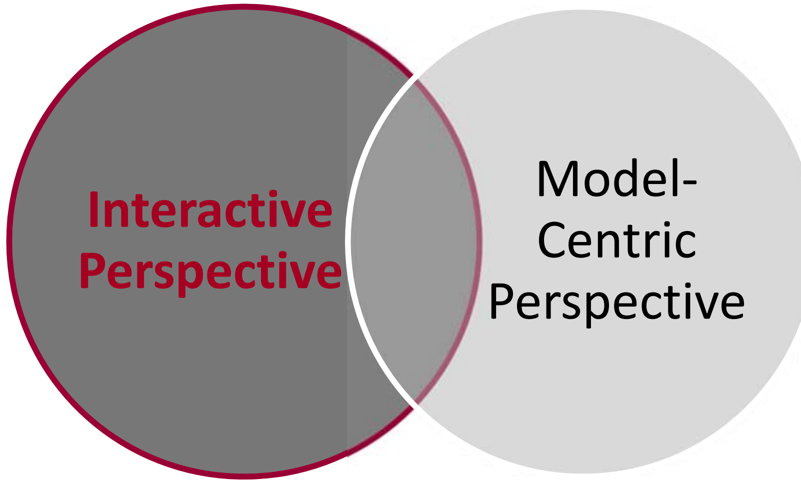
- The individual using an interactive model-centric environment will have some capability to **retain history of changes in the models over time, including ability to track change propagation and capture usage pattern**.
- The environment will be adaptable for the culture of the organization to **enable effective reuse with confidence in the model** and its appropriateness for the situation.
- Finding suitable models and reusing them in the individual's environment will be easily accomplished.
- Models will transparently capture a user's values, communicate them clearly, and allow changes as more information is made available.
- An individual will easily be able to document risks and uncertainties with the models themselves, and retrieve this information when reusing models.
- **Effective approaches for model sharing will mitigate Intellectual property concerns** and will not jeopardize perceived competitive advantage

Imagine an Ideal World
Characteristics of Models

Characteristics of Models

- Models will have **associated information that characterizes the development history of the model over time, how it has been used, and specific individuals who developed the model**.
- There will be support provided to understand the model limitations, risks and uncertainties.
- The environment will provide support to the individual that will help in understanding model limitations.
- Models will be designed to be intuitive for decision making.
- Role-based permissions/views will provide appropriate access and abilities for the modeling development and use.
- **Models will adapt to personal logic, evolving context, and changing questions.**

Interactive Perspective



Potential topics might include:

- explore a tradespace
- input data into a model
- query a model
- perceive of the interaction
- use a model to make design choices or investment decisions
- perceive accuracy of a model
- perceive whether a model works correctly
- validate their decisions with models
- avoid cognitive biases
- develop trust in models
- how stakeholders decide what models to use, etc.

Imagine an Ideal World
Ease of Interaction

Ease of Interaction

- The individual interacting with a model will find it an intuitive and the effort involved will be commensurate with the value the model provides.
- **Novice users will be able to rapidly learn and benefit from** use of modeling environments.
- Model users will find that changes to a model can easily be implemented within the modeling environment.
- **Models will be easily tailorable for levels of abstraction, for different stakeholder types, and different purposes**.
- Modeling environments will have human error tolerance.
- An individual would be able to look at a given level of abstraction of a model, as well as have the ability to dig into a deeper level within a particular view.
- The **speed of making queries will be in tune with exploration**, and there will be minimal latency in query responses.

Enabling Informed Decisions

- The individual will find that the model-centric environment enables more informed decision making.
- Modeling environments enable decisions based on rich context information that spans the space of relevant parameters.
- **Models will be effective for evaluating systems under alternative contexts, for example policy context**.
- Environments will provide the capability to contrast and compare results with ease.
- The individual will be able to intuitively judge the models, and **uncertainty in the model output will be easily apparent.**
- There will be the means to assess and/or judge the goodness of a model-enabled decision.

Guided Interaction

- Interactions with models will provide guided assistance for viewing models from standpoint of other stakeholders.
- A model will take imprecise input from the individual, and **offer a guided experience prompting interaction where the individual might not even know what question to ask**.
- The guided experience will aid the individual in dynamically interacting with the models, **functioning as an "AI colleague"**
- Individual will feel as if the environment "understands where the individual is coming from and what they are concerned about."
- There will be **assisted capabilities and wizards for model composability, model interrogation, and stakeholder role playing**.

Imagine an Ideal World
Enabling Human-Human Interaction

Enabling Human-Human Interaction

- The behavior of each individual in the modeling process will be captured, and enable understanding of the whole system behavior in regard to meeting system objectives.
- **Model-centric environments will support collaborative decision making and design with near real-time human to human interaction**.
- Individuals will find it easy to compare their own values with those of other individuals so that they can calibrate their own values.
- Models will enable value-centric engineering, providing a means to make those values explicit as part of the collaborative decision process.

Promising Research

As cited by the pathfinder workshop participants, there are promising areas of emerging research found in the systems community. Some examples include:

- Cataloging/ formalizing human experience into patterns that can be queried
- Uncovering assumptions in existing processes
- Decision support research on techniques for visualization of data
- Analytic mental models based on the analyst themselves
- Innovations in commercial tools to enable human-model interaction
- Visualizations for showing ranges of outcomes from each decision outcome based upon doing exploratory modeling in the background
- Crowdsourcing of mental models elicited in an unbiased fashion
- Modeling environment to detect usage patterns and pull relevant information for users

IMCSE research team is spearheading effort to create a shared research roadmap with emerging research mapped to researcher needs … looking for collaborators and pointers to ongoing research

HUMAN-MODEL INTERACTION

Expected Outcome: Impactful studies on key topics leading to heuristics and prescriptive guidance, and informing policy and standards development

Toward a "Science" of Human – Model Interaction

- Progress has been made on standards, methods and techniques for model-based systems engineering, yet little focus has been given to the **complexities of human-model interaction**
- Previous investigation of human-model interaction mostly limited to mechanistic aspects
- Related "science" …
  - Science of ***human-systems integration*** **(HSI)** has emerged (Pew and Mavor, 2007), but focuses on humans and operational systems, while models are abstractions of reality.
  - Science of ***human-computer interaction*** **(HCI)** is relatively mature and offers valuable insights for the future (Harper et al., 2008); however its focus is on designing computer interfaces for effective human use.
  - Science of ***visual analytics*** is emerging

Open area of inquiry relates to the various aspects of humans interacting with models:

- individual interacting with a model
- human to human interaction via models
- facets of human interaction with data, and related fundamentals such as model purpose and model handling

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Cognitive and Perceptual Aspects of Human-Model Interaction

Systems Engineering Advancement Research Initiative

Pathfinder Workshop Findings: confirmed progress has been made for model-based systems engineering, yet little attention has been given to ***human-model interaction***

Lacking a specific body of empirical evidence, we investigate relevant findings and lessons learned from the experience of aircraft pilots transitioning to use of glass cockpits and virtual displays.

Analogy Case

Transition to Glass Cockpit:
investigate challenges and lessons learned from ***human interaction*** with highly automated cockpit systems and displays that may inform IMCSE

Analogy Case Findings
Transition to Glass Cockpit

Glass Cockpit Impact: use of advanced technology in cockpits manifests itself primarily through an increase in autonomy that not only changes the role of pilots, but also adds an fundamentally changed piloting by adding an additional role, manager of systems

Cognition
- Coherence: maintain accurate "picture of reality"
- Means of Disrupting Coherence
  - Automation Bias
  - Complacency
  - Mode Error

Mitigations
Accountability
Transparent Systems
Human-Centered Design

Perception
- Human-Computer Interface
  - Effectively present information for task at hand
- Preference-Performance Dissociation
  - User's preferences not matching up with performance

Study of Human-Automation Induced Accidents: Nagoya, Strasbourg, Cali

We postulate that relevant similarities exist to the experience of system designers and decision makers transitioning to immersive model-centric environments, with increased abstraction of systems information.

We are investigating cases to look for implications for heuristics and biases of relevance for interactive model-centric engineering theory and practice.

Submitted: German, E.S. and Rhodes, D.H., Human-Model Interactivity: What can be learned from the experience of pilots transitioning to glass cockpit?, CSER 2016

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Digital System Models
Investigating Non-Technical Challenges

MIT Systems Engineering Advancement Research Initiative

Technical challenges understood; being worked by government , industry, and academia. If left unaddressed, non-technical challenges (e.g., IP and KA) could substantially reduce effectiveness of DSM

- Knowledge assessment (KA) issues include “buy-in” (i.e. trust) both by technical staff directly creating the models and by decision-makers in the acquisition and operation processes, as well as inter-model validity assessment in the cases of multiple models operating in the same domain

Model Package Development	Pros	Cons
DoD Developed	• Reduces Intellectual Property (IP) disputes • Can maintain access • Eliminate inter-model comparisons	• Does not utilize industry expertise • Requires DoD to maintain and update
Heterogeneous Models Privately-Developed	• Fully leverages competitive industry • Minimizes DoD work	• Does not resolve IP disputes directly • Requires inter-model comparison • Potential lack of continued access
Homogenous Models Privately-Developed	• Reduced IP disputes • Partially leverages competitive industry • Reduces DoD work • Eliminates inter-model comparisons	• Introduces miniature monopolies • Potential lack of continued access • Does not fully leverage industry expertise • Does not minimize DoD work

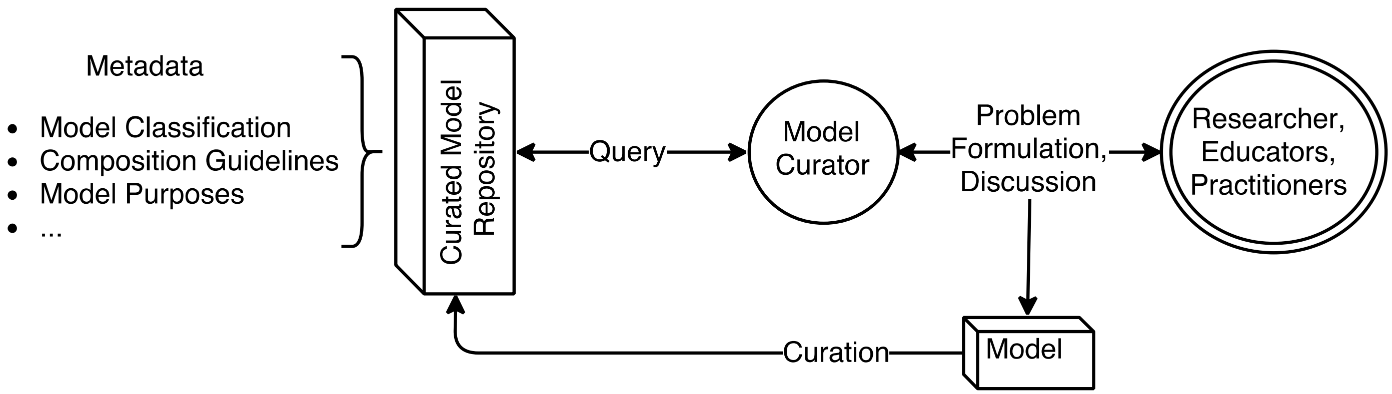
Model Package Use	Pros	Cons
Centralized – Single Copy	• Reduces IP disputes • Reduces security risks	• Difficulty in updating • Hampers iterative design
Centralized – Multiple Copy	• Allows for iterative design	• Few firms can host full DSM • Increases security risk • Does not address IP disputes
Distributed	• Reduces IP disputes • Partially leverages competitive industry • Reduces DoD work • Eliminates inter-model comparisons	• Requires transition to centralized during hand-off to DoD • Potentially technically difficult • Increases simulation-run times • Increases cyber-security issues/security risk

Considerations for Model Curation

Managing models as assets, to improve model-centric systems engineering practices and research

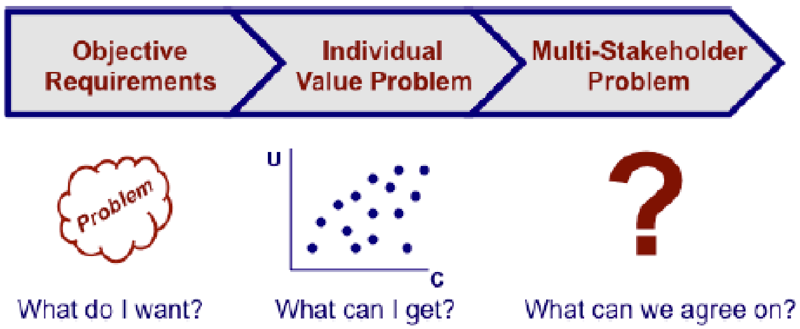
- Research needed on modelling metadata: model ontologies, modelling techniques, data rights, code of ethics, work environments, characteristics of models, composition of hybrid modelling techniques, and more
- Curator function: to authenticate, preserve, classify models; to be the keeper and advocate for the curated database of models
- Effective and timely matching of client problem needs and constraints with adequate and insightful individual, or sets of, models

A model curation function would require contributions from, and provide benefits, to the wider modeling community: practitioners, researchers, and educators … as done in digital curation and social curation practices.



Submitted: Reymondet, L., Rhodes, D.H. and Ross, A.M., Considerations for Model Curation in Model-Centric Systems Engineering, IEEE SysCon 2016

Role of Models in Multi-Stakeholder Negotiation



Models are boundary objects in negotiations, whether or not they are physical artifacts or even explicitly acknowledged

Descriptive Research

- How do stakeholders interact with each other and with models?
- Does proper negotiation occur in practice?

Prescriptive Research

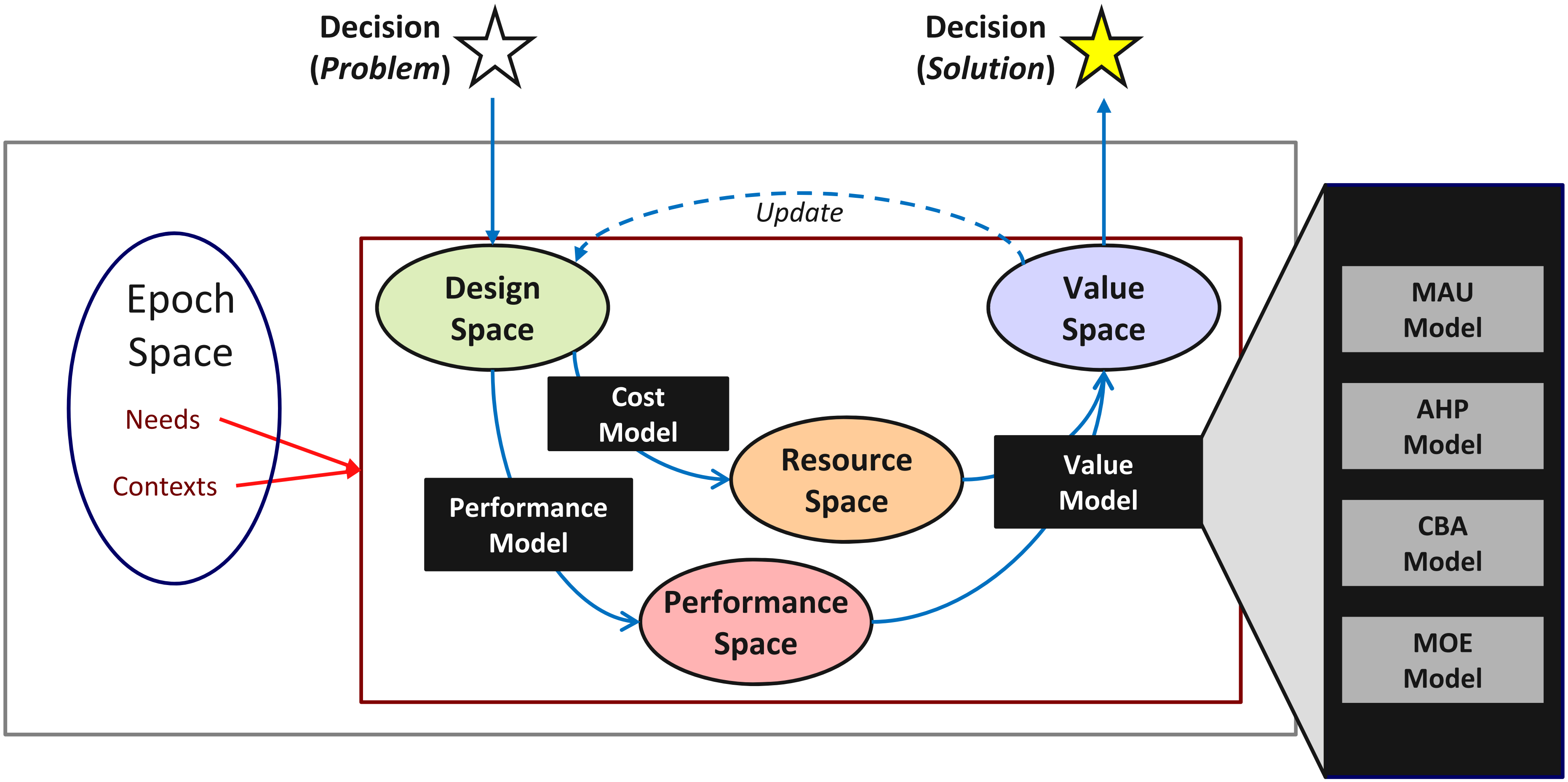
- How can we visualize models themselves, in addition to their results, in order to improve communication?

MODEL CHOICE AND TRADEOFFS

Expected Outcome: Contributing toward the development of a prescriptive framework for trading models and guiding impact for resilient systems decision making

Design-Value Loop

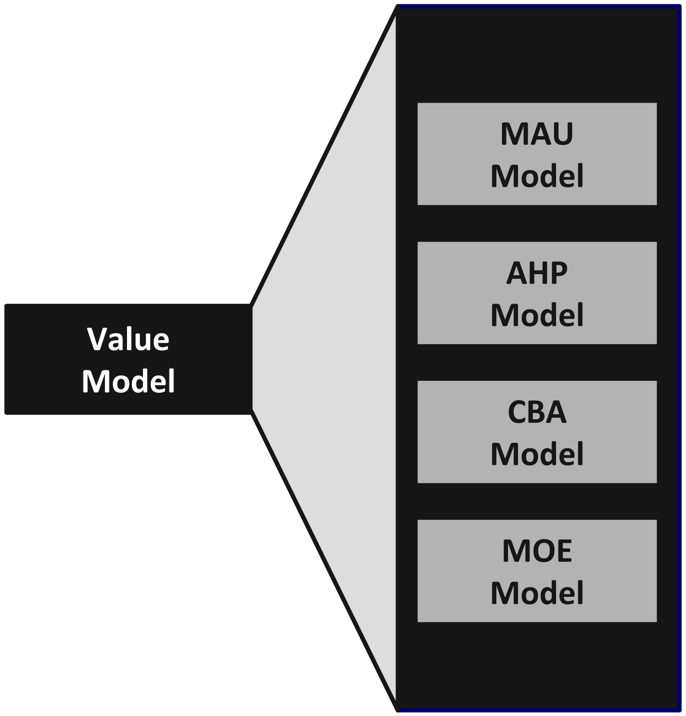
Selection of Value Model is just as important as Performance Model and Cost Model



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.

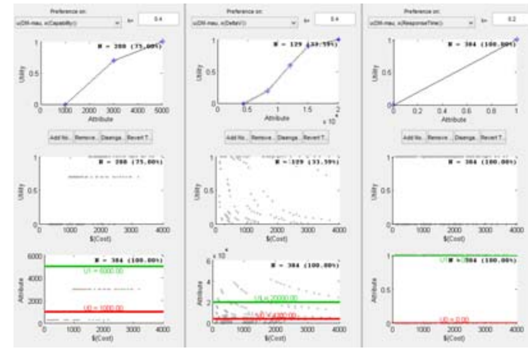
What if we had better understanding and trust in the implications of model choice?

Aggregating Information for Decisions: Value Models



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

$$K = -1 + \prod_{i=1}^{n}(K \cdot k_i + 1)$$



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

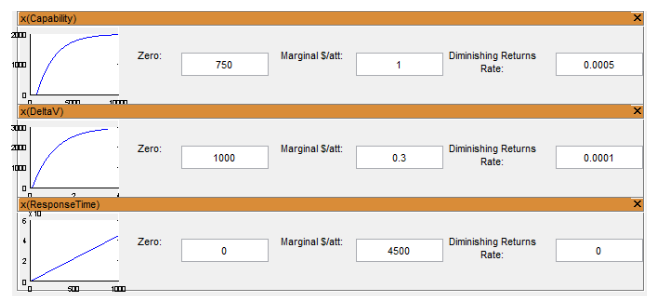
$$AHP_i(X_i) = \frac{(X_i - X_{i,min})}{X_{i,max} - X_{i,min}}$$

$$k_i = \frac{\sum_{q=1}^{n} \frac{a_{i,q}}{\sum_{p=1}^{n} a_{p,q}}}{n}$$

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

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

$$CBA_i(X_i) = \frac{m_i}{r_i}(1 - e^{-r_i \cdot X_i})$$



$X_i >= X_{i,min}$;

$CBA_i(X_i) = 0$ $X_i < X_{i,min}$

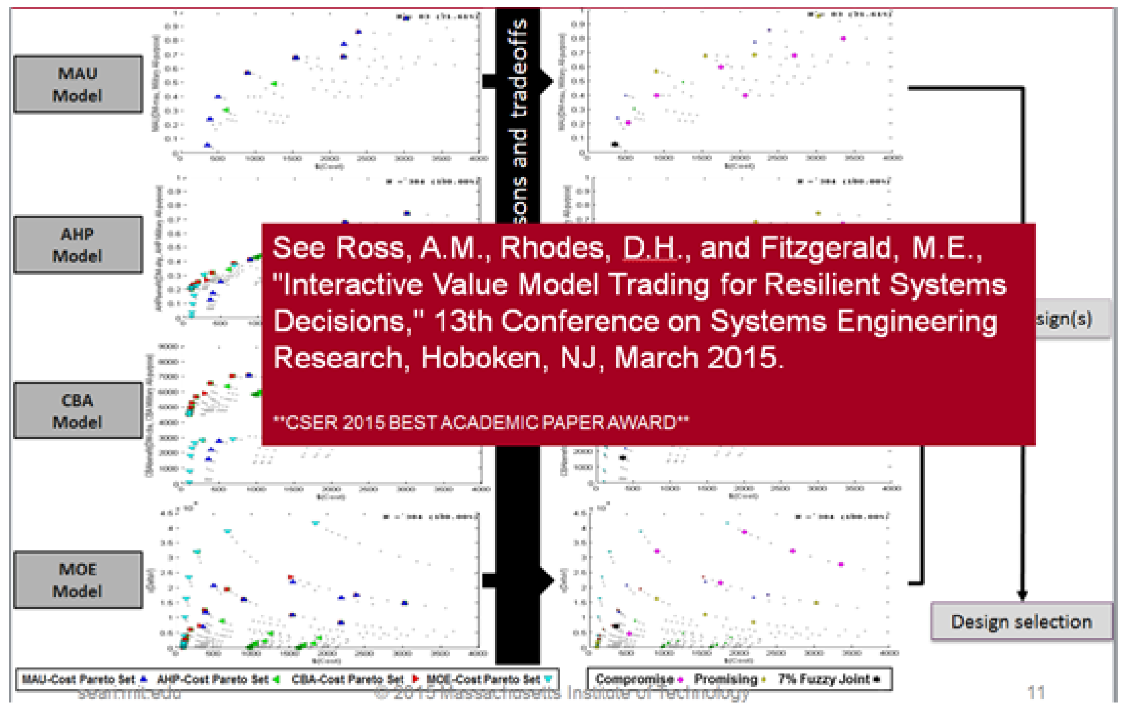
$MOE(X_i) = X_i$

Value Model Tradeoffs -- Discussion

Using same performance and cost models, different "best" solutions arise as a consequence of value model choice

Explicit consideration of value model choice and tradeoffs, including identification of solutions robust to variation in value model can result in more resilient decisions in the long run

- Choice of value model determines the attractiveness of each solution
- Each value model will likely highlight different systems
- Can identify systems that do well across multiple value models
- Analysis useful if value model choice is uncertain or likely to change



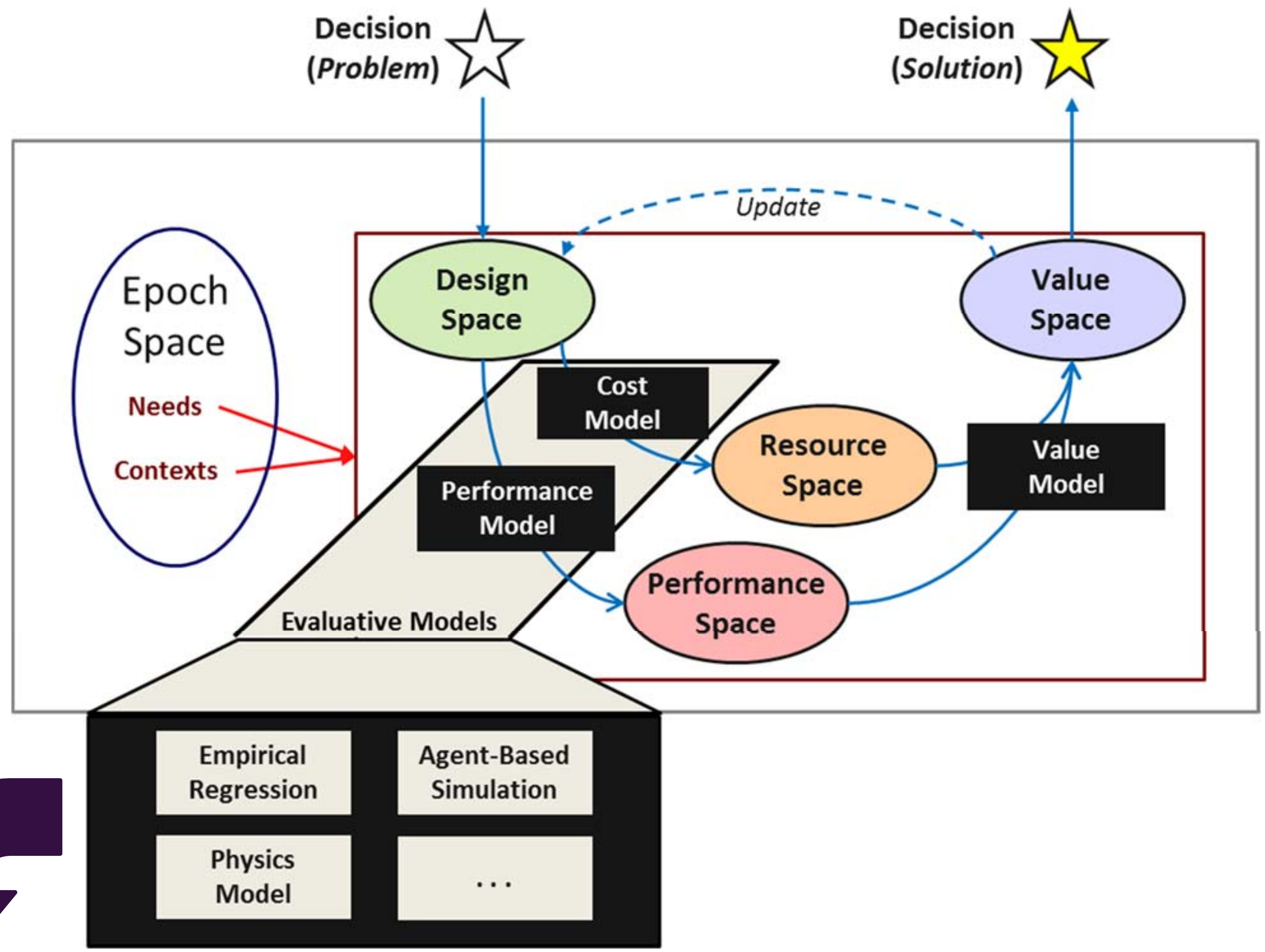
See Ross, A.M., Rhodes, D.H., and Fitzgerald, M.E., "Interactive Value Model Trading for Resilient Systems Decisions," 13th Conference on Systems Engineering Research, Hoboken, NJ, March 2015.

CSER 2015 BEST ACADEMIC PAPER AWARD

Evaluative Model Trading

Expand scope beyond value model trades

- Build confidence in model results in low-validation domains
- Makes physical logic of models apparent to decision makers
- Can help identify "true" insights vs. modeling artifacts

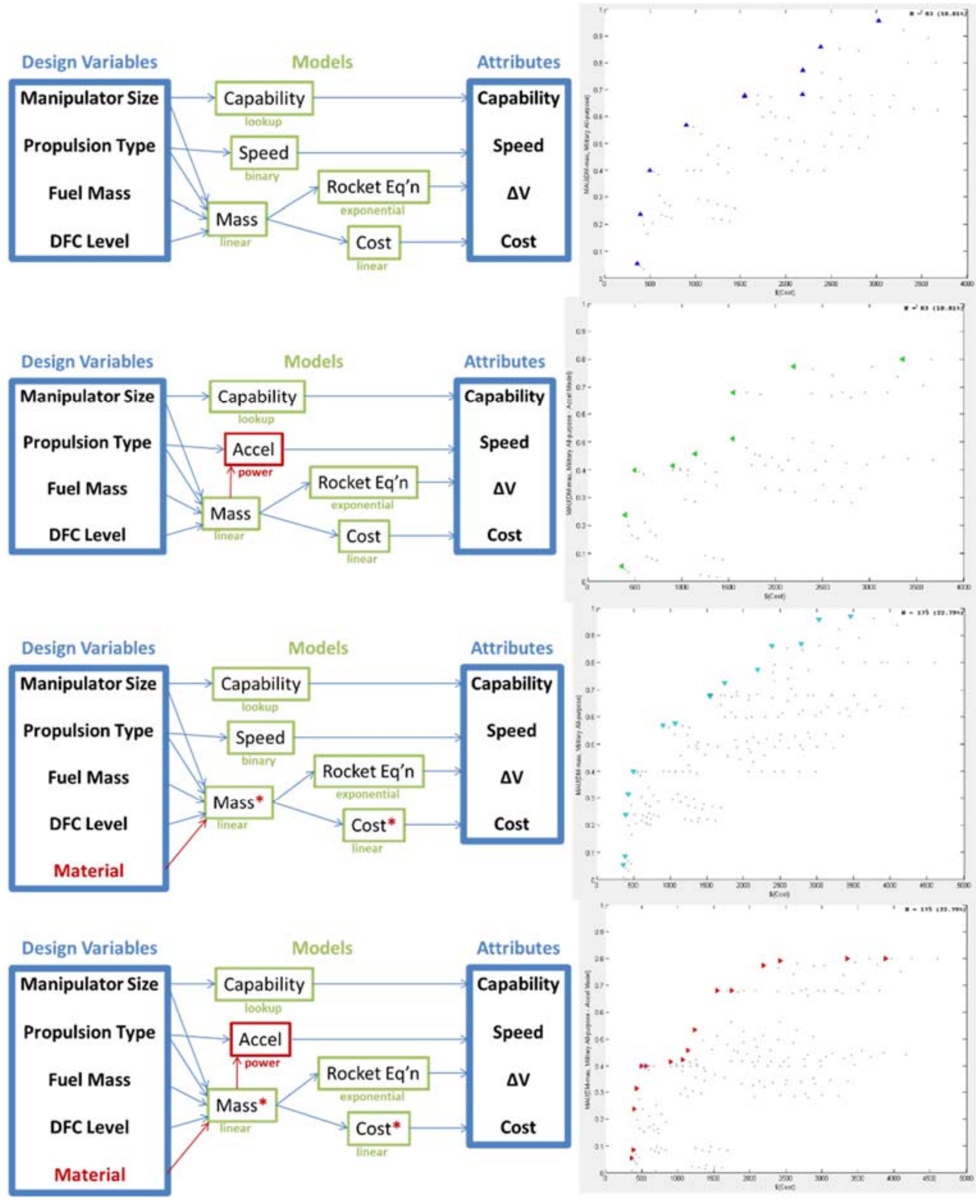


Just as with value models, there are many different ways to calculate performance

Space Tug Demonstration Case

Continuation of value-model trading "best paper" case…

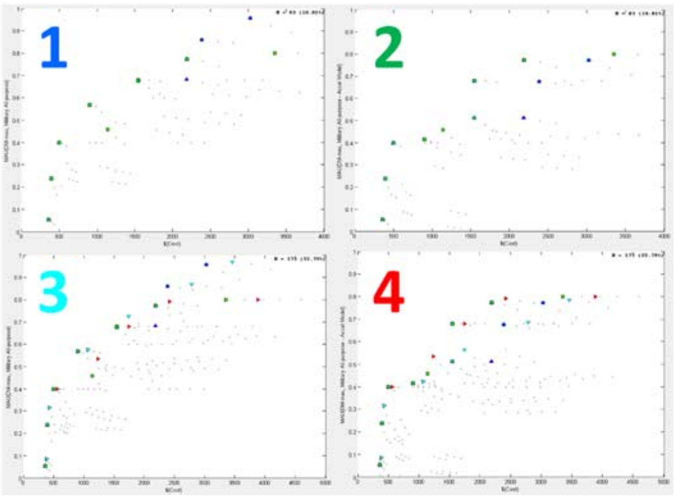
- Four different model implementations lead to four different tradespaces
- Includes fidelity improvements:
  - design representation (material type)
  - performance evaluation (speed calculations)

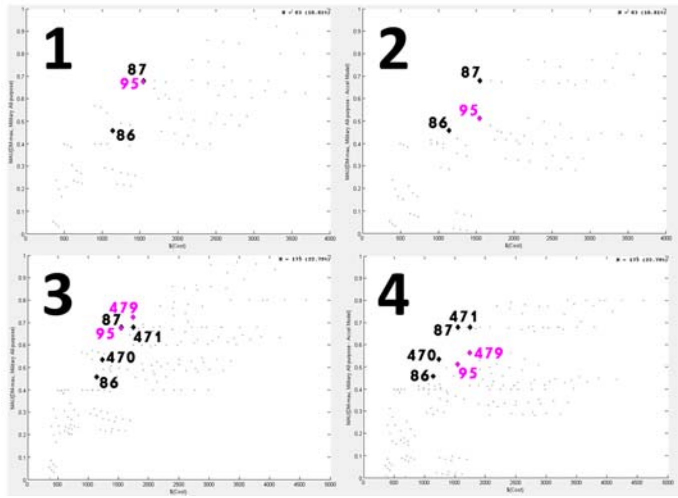


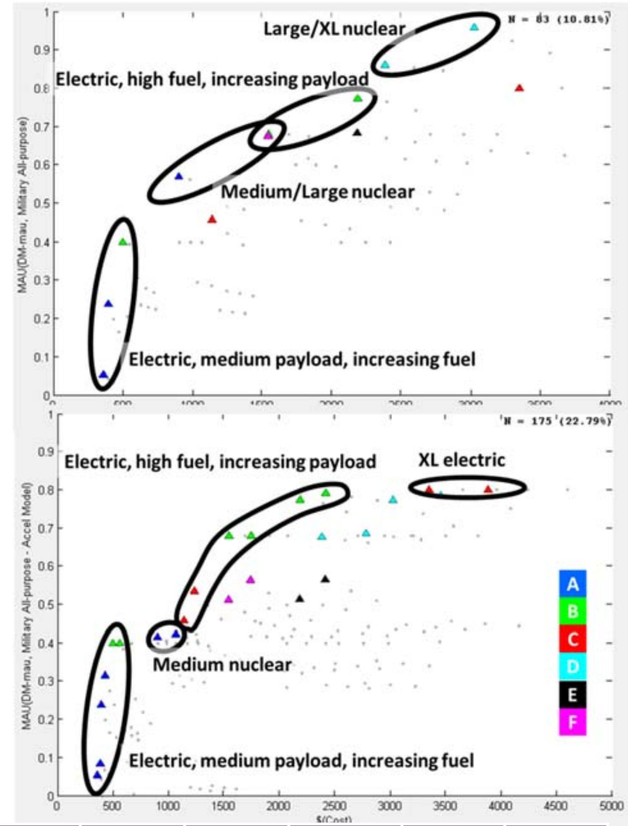
Small model changes can lead to significant changes in the tradespace (not quite as much as for value models)

"instead of expending efforts to find the "right" model, what can be determined by leveraging multiple different models in order to garner potentially novel insights, especially when "fit for purpose" may be unclear early in the system lifecycle?"

Space Tug Analysis







- Pareto fronts are similar in low-cost domain, divergent in high-cost
- Six emergent categories of efficient solutions
  - A. Fully robust to model trading (low cost)
  - B. High-fuel electric, downgraded by switch to carbon, unless new speed model is used
  - C. Efficient only under new speed submodel
  - D. Efficient only under old speed (carry too much fuel)
  - E. Modeling artifact due to low fidelity
  - F. Emergent modeling artifact due to submodel interactions

Efficient Alternatives in each Model

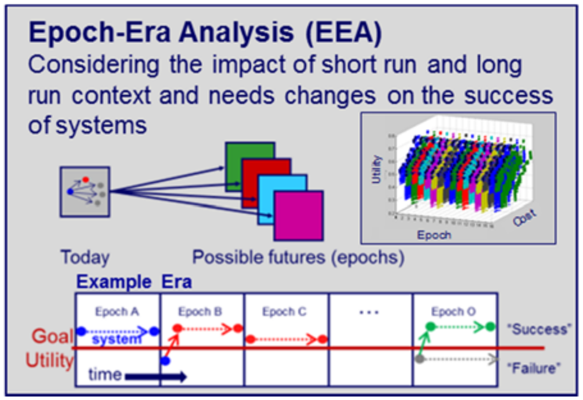
Category	Design ID (Aluminum)	Model 1	Model 2	Model 3	Model 4	Design ID (Carbon)	Model 3	Model 4
A	52	✓	✓	✓	✓	436	✓	✓
	53	✓	✓	✓	✓	437	✓	✓
	63	✓	✓	✓	✓	447	✓	✓
B	54	✓	✓	✓	✓	438		✓
	87	✓	✓	✓	✓	471		✓
	119	✓	✓	✓	✓	503		✓
C	86		✓		✓	470		✓
	120		✓		✓	504		✓
D	96	✓		✓		480	✓	
	128	✓		✓		512	✓	
E	127	✓				511		
F	95	✓	✓	✓		479	✓	

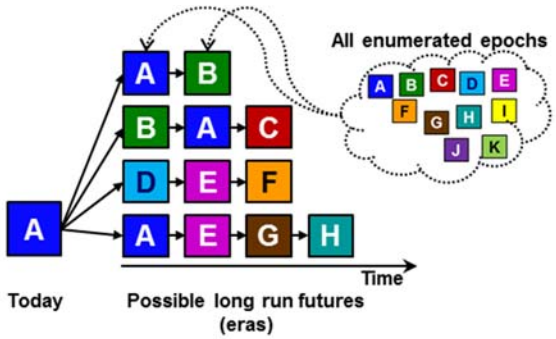
Interactive Epoch-Era Analysis

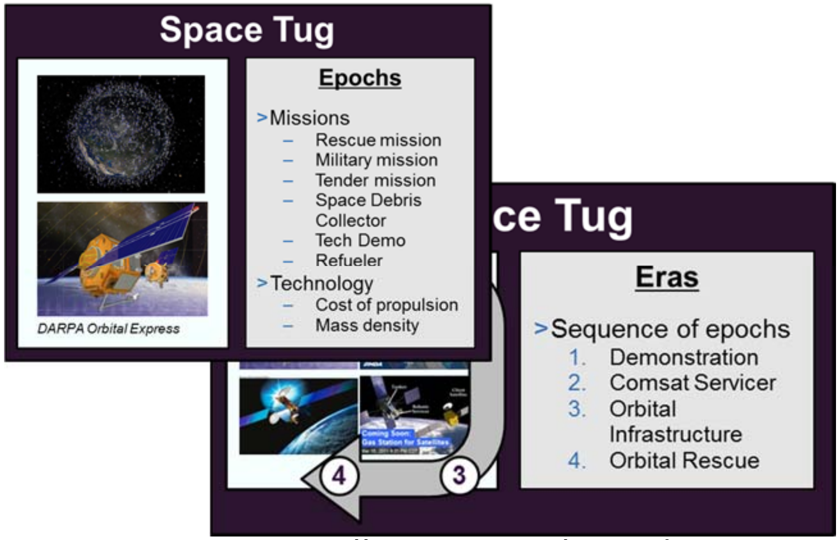
Expected Outcome: Contributing toward the development of a prescriptive framework, and associated interactive tools, for constructing and conducting large scale quantitative analyses across uncertain futures, enabling resilient system decisions

Interactive Epoch-Era Analysis as Potential Game-changer

EEA is a framework that supports narrative and computational scenario planning and analysis for both short run and long run futures







- Anticipating, analyzing, and making sense of a system's possible futures is a computationally, cognitively, and perceptually challenging task
- IEEA leverages the strengths of humans, models, and computers to enable development of vastly more resilient system outcomes
- Anticipated contributions of IEEA:
  - enable the elicitation of broader and more complete set of possible epochs and eras
  - through a human-in-the-loop implementation, help to intelligently limit potentially unbounded growth in epoch and era spaces
  - enable the development of superior intuition, buy-in, and insight generation for decision-making across dynamic uncertainties
  - enable the discovery of heretofore unseen dynamic strategies for system value sustainment (resilience) across uncertain futures

Every system has billions of possible futures, across which the system may or may not be useful/affordable/survivable/robust/sustainable… How many of these futures should you consider and plan for?

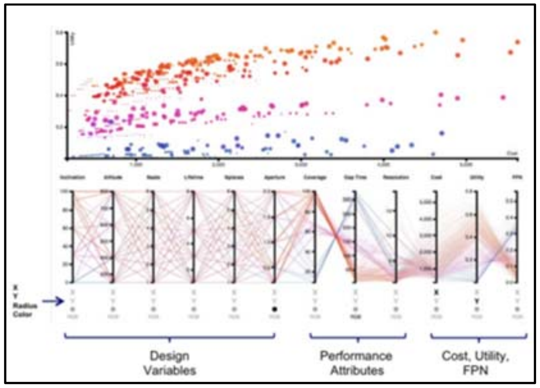
Visual Analytics and Interactive Visualization

- Integrating data interaction and advanced engineering methods is seen as key to the current research effort on IEEA

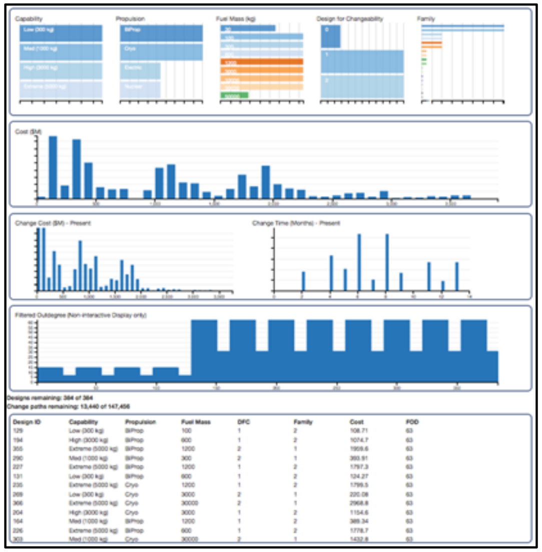
- Interactive visualization provides an analyst with immediate feedback how impacts from decisions and dimensional constraints propagate to system value
  - — Multiple coordinated visualization
  - — Dynamic sorting/filtering
  - — Animated transitions
  - — Interactive highlighting
  - — Online Analytical Processing (OLAP)

- Benefits of interaction with data through visual interfaces of this type is an area of active research in the visual analytics community

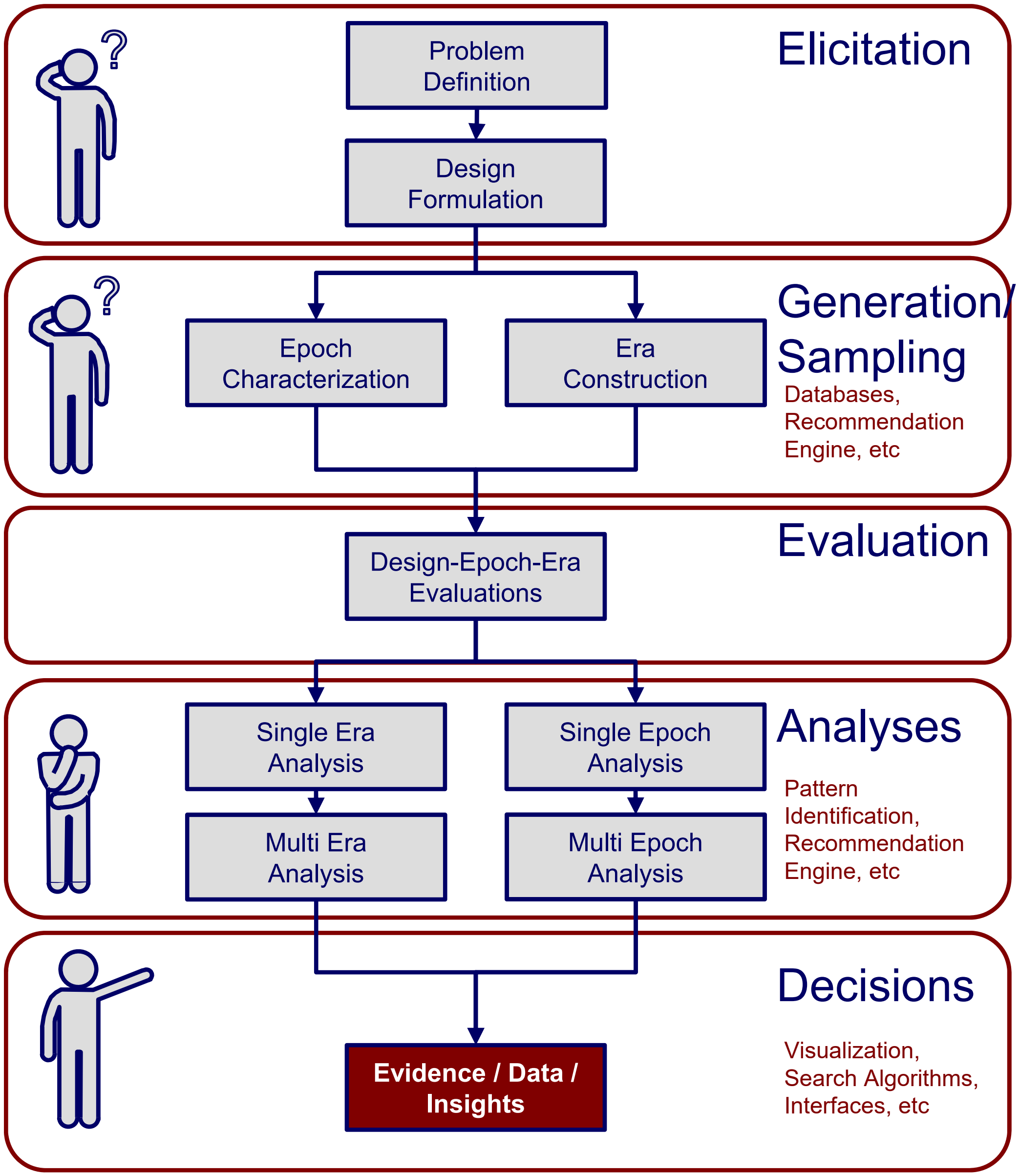
Single-Epoch Coordinated Views



Interactive Filtering (OLAP)



IEEA Framework

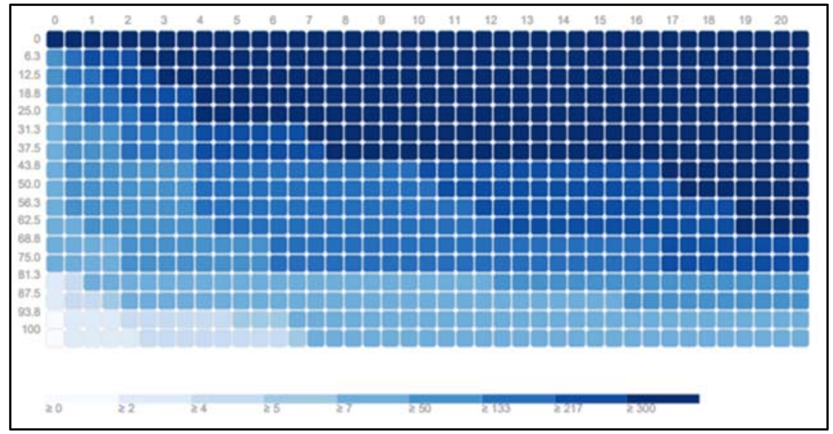


- 10 processes of IEEA aim to address the need for methods and metrics for early-stage conceptual design of systems with sustainable value
- Modifying RCS/RMACS to explicitly include iterative and interactive considerations enables better visibility into how top-level decisions impact value sustainment

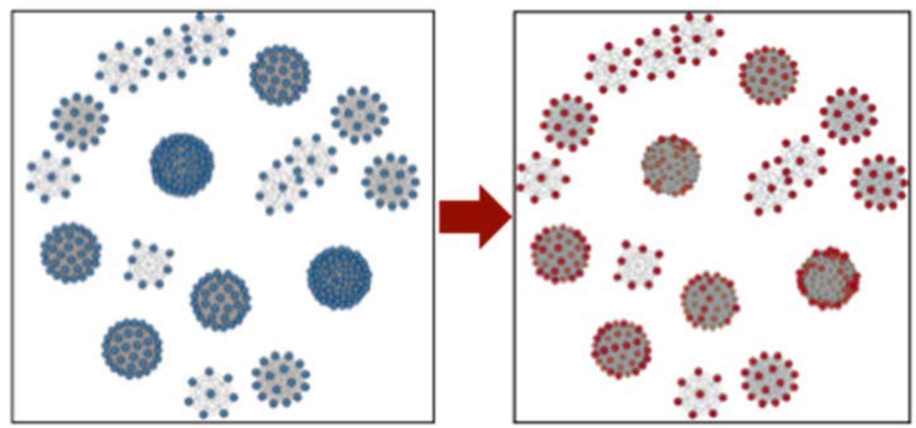
Multi-Epoch Analysis

- Several new interactive visual representations introduced
- Interactive heatmap visualization of compromise between Pareto efficiency across epochs
- Changeability analysis through force-directed graph visualization
  - —Quickly identify design families/communities
  - —Evaluate performance using traditional metrics (FOD) and network centrality metrics not previously applied to multi-epoch changeability analysis

Multi-Epoch Robustness (Heatmap)



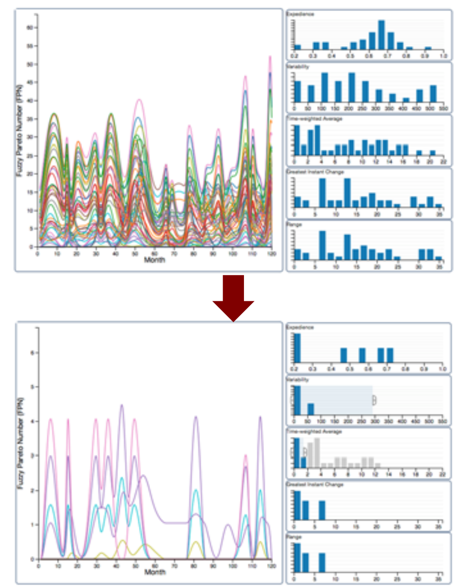
Multi-Epoch Changeability (Force-directed graph)



Single/Multi-Era Analysis

- Coordinated visualization for interactive filtering during single-era analysis based on 5 new era-level metrics that evaluate temporal aspects of value delivery
- Complete exploration of the uncertainty space intractable for most problems
- Goal for MERA is to identify relevant path dependencies that stem from:
  - Perturbations, disturbances and epoch shifts
  - Changes to a design as it progresses through lifecycle

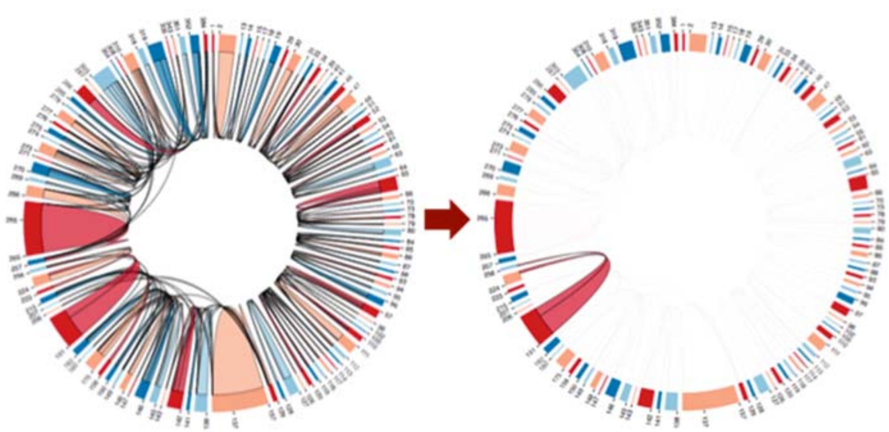
Single-Era Interactive Filtering



Era metrics:
1.Expedience
2.Variability
3.Average
4.Greatest Δ
5. Range

Filtered subset of designs based on era performance

Multi-Era Change Path Dependency Analysis



KNOWLEDGE SHARING & TRANSITION

2015 Research Transition

- 2015 IMCSE Pathfinder Workshop held January 2015
  - —Report published and paper submitted for INCOSE 2016
- Interactive Schedule Reduction Model prototype and Interactive Epoch-Era Analysis prototypes available on web
- Several technical exchange meetings with other universities, government agencies and other potential transition partners
- Four papers presented/published at 2015 Conference on Systems Engineering Research and two masters theses
- Presented research in several seminars and course lectures

IMCSE Knowledge Transfer

enabled through workshops, teleconferences and meetings, reports, conference and journal papers, collaboration with other SERC activities, online prototypes and demos, MPTs, transition partner applications

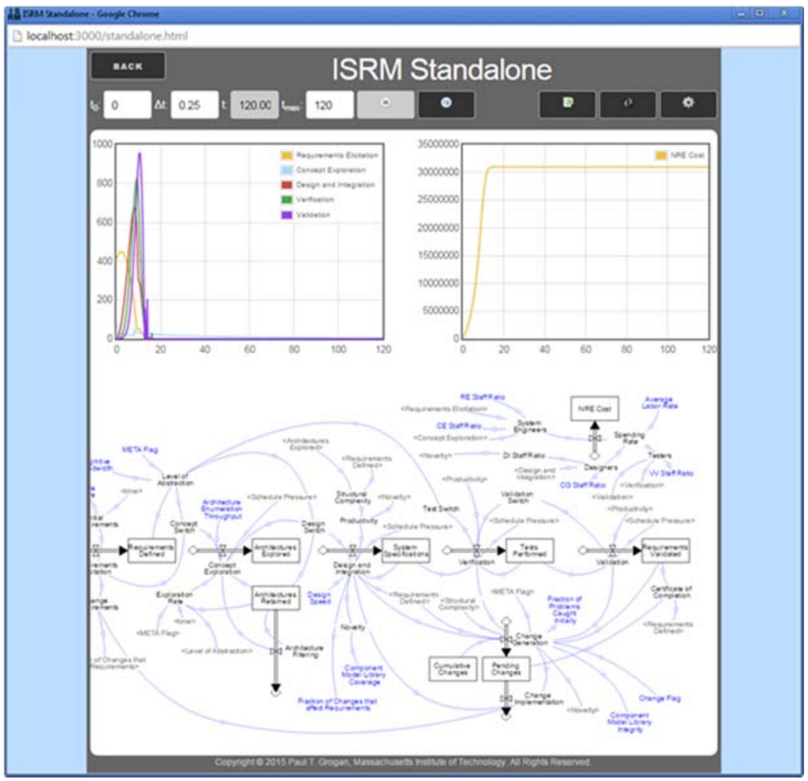
2015 RESEARCH TRANSITION
Interactive Schedule Reduction Model (ISRM)

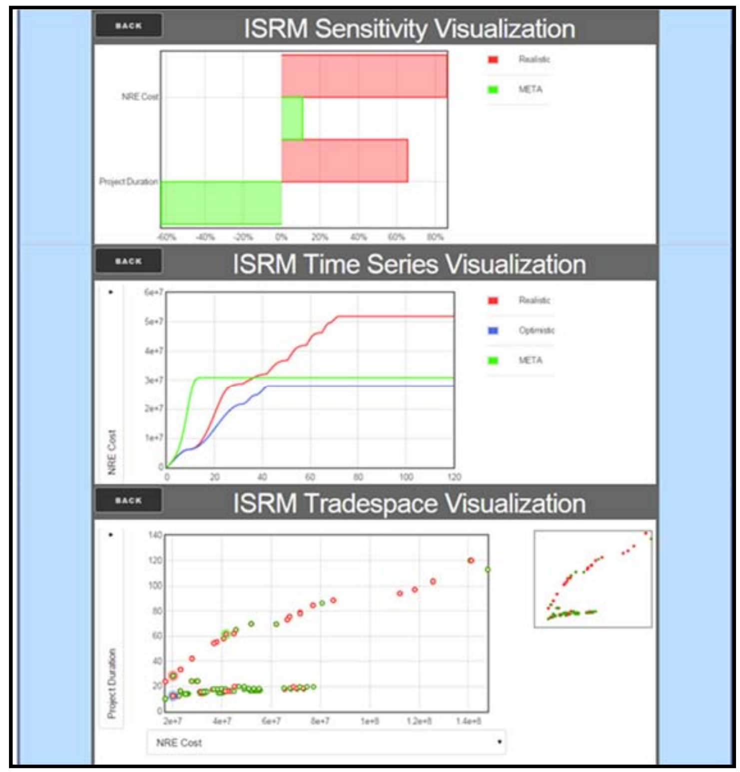
Proof of Concept Prototypes

- Transition modeling methods from proprietary tools to browser-based platforms
- Enable client-server services to compose, query, and visualize datasets across runs
- Improve ability to overcome perceptual limits (uncertainty due to incomplete knowledge)

CSER 2015 paper, source code and documentation available

- Standalone tool
  - Execute and visualize individual model runs
- Service-based tool
  - Compose, query, visualize results across model runs





Demonstrates use of new technologies to improve modeling methods/tools for open source

Source code available: https://github.com/ptgrogan/isrm

2015 CSER Publications

2015 CSER Publications

- Curry, M, and Ross, A.M., "Considerations for an Extended Framework for Interactive Epoch-Era Analysis," 13th Conference on Systems Engineering Research, Hoboken, NJ, March 2015
- Fitzgerald, M.E., and Ross, A.M., "Effects of Enhanced Multi-party Tradespace Visualization on a Two-person Negotiation," 13th Conference on Systems Engineering Research, Hoboken, NJ, March 2015
- Grogan, P.T., de Weck, O.L., Ross, A.M., and Rhodes, D.H., "Interactive Models as a System Design Tool: Applications to System Project Management," 13th Conference on Systems Engineering Research, Hoboken, NJ, March 2015
- Ross, A.M., Rhodes, D.H., and Fitzgerald, M.E., "Interactive Value Model Trading for Resilient Systems Decisions," 13th Conference on Systems Engineering Research, Hoboken, NJ, March 2015 **BEST ACADEMIC PAPER AWARD**

Access our Phase 2 report on the SERC website: http://www.sercuarc.org/research/research-program-and-projects/interactive-model-centric-systems-engineering-imcse-program-task-122/

2016 Research Leadership Summit

Event planned for 1st quarter 2016 at MIT open to leaders of IMCSE-related research and "early adopters"

Summit Goals

- Continue dialogue from Pathfinder workshop
- Exchange knowledge on emerging research relevant to IMCSE
- Gain and provide critical feedback on research
- Discuss research transition opportunities and strategies

SYSTEMS ENGINEERING
Research Center

Systems Engineering Advancement
Research Initiative

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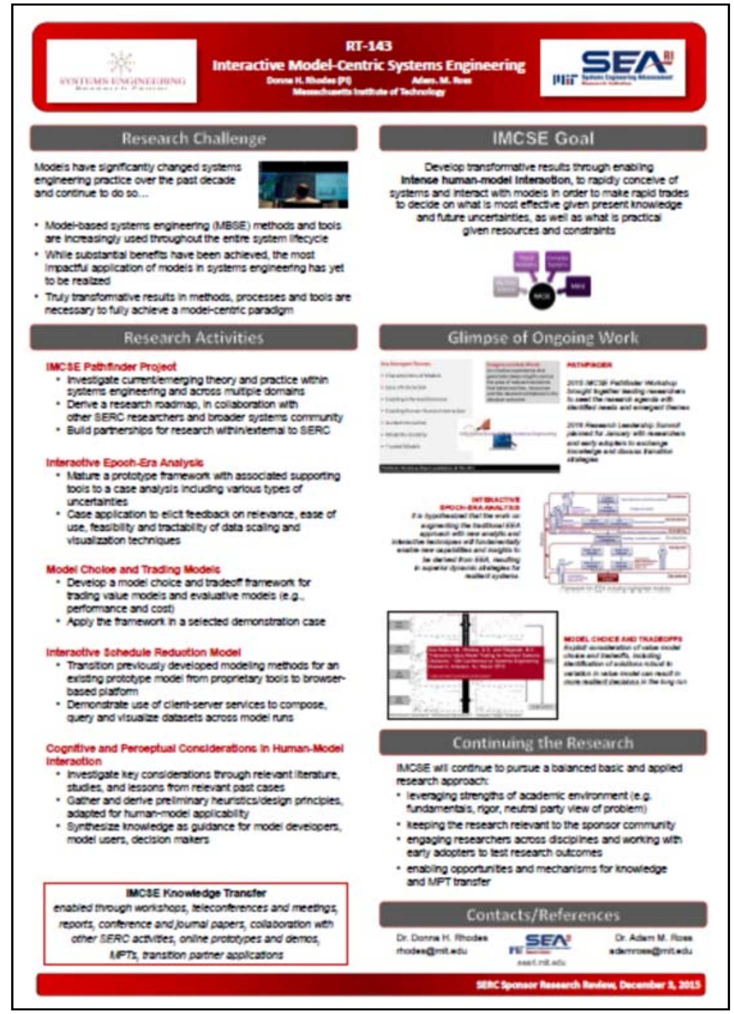

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Back up