Interactive Model-Centric Systems Engineering (IMCSE)

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www.sercuarc.org
We live in a world with big data...

Big data is being leveraged in many ways to gain insights into phenomena and to create predictive models...

The impact of big data is felt across many fields, and will only increase...

Application Areas
- transportation, consumer products, entertainment, banking, life sciences, physical sciences, ...
- communications, education, sports, insurance, manufacturing, retail, healthcare, utilities, dating ...

Big data provides a foundation for large scale analytics to predict the future.
Making Sense of the Data: Visual Analytics

What is Visual Analytics?

Visual analytics provides the last 12 inches between the masses of information and the human mind to make decisions

“Visual analytics is the science of analytical reasoning facilitated by interactive visual interfaces”

People use visual analytics tools and techniques to
- Synthesize information and derive insight from massive, dynamic, ambiguous, and often conflicting data
- Detect the expected and discover the unexpected
- Provide timely, defensible, and understandable assessments
- Communicate assessment effectively for action.

Enabling Software Tools

www.visual-analytics.eu/faq/

...It is a collaboration between human and computer

www.graphinsight.com


Application Areas
- homeland security, intelligence community, law enforcement, financial markets, anti-fraud
- banking, communications, education, insurance, life sciences, manufacturing, retail, utilities, ...

Visual analytics is resulting in a transformative capability, bridging human and computer analysis for natural* data

*observable “ground truth” possible

Our Domain: Complex Systems

Our application domain is the development of (artificial) systems that serve the purpose of delivering value to stakeholders...

The complexity of our systems has been growing over time, not only due to scale and interconnectedness, but also due to increased scope in our ability to describe the system.

Five aspects of system complexity

Developing complex systems necessitates an approach to generate, manage, and analyze artificial data across these five aspects.
Model-based Systems 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.”

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

NDIA SE Division: Model-Based Engineering (MBE) Subcommittee Report (2011)

- Reduce acquisition time of first article systems and solutions
- Reduce time to implement planned and foreseen changes
- Enhance reliability
- Enhance interoperability

...each of these benefits enhance affordability

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
Merging the Four: Interactive Model-Centric Systems Engineering

- 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

- 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
What is IMCSE?

More than just visual analytics...

Our data is generated by models (e.g. “M” of MBSE)...

In SE, our job is to make decisions that result in systems that deliver value to our stakeholders...

**Two critical gaps in current approaches:**
1. Visual analytics of artificial (model-generated) data
2. Active tradeoffs of the models themselves

**Key questions:**
- How can techniques from VA result in better model-enabled SE decisions?
- How can we determine proper trust and truthfulness for various types of models?
- Ultimately, how can this approach help to manage complexity in modern SE and deliver more affordable and valuable systems?

**IMCSE Goal:** leveraging visual analytics applied to model-generated “big data,” develop a rigorous framework, with associated MPTs, that results in transformative new capabilities for SE decision making
Interaction between Humans and Models Enables Anticipatory Capacity

Anticipatory Capacity

Key Enablers

- Mindset – systems thinking
- Methods – model-based
- Environment – hw/sw enhanced

**Anticipatory Capacity** 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.

Rhodes and Ross 2008

- Anticipation (ability to look forward in order to take a future decision or action)
- Pattern recognition skills
- Subject to cognitive limits, preferences, and biases...

Interactive Model-Centric Systems Engineering
Decision Science – Visual Analytics – MBSE

- Complex, integrated models
- Varied levels of fidelity
- Large artificial data sets
IMCSE Role in Decisions

- Make portfolio decisions using discovered capability gaps and synergies
- Select resilient concepts by anticipating and evaluating future uncertainties
- Determine proactive resourcing adjustments to accelerate development schedule
- Select optimal prior program models for reuse with trade-off of alternative models
- Reach agreement on change impact assessments through interactive model-based sessions

**Discoverer II**
- 1998
- 24 satellites, IOC: ??, cost: $10B
- Cancelled in 2000
  - High costs, lack of stated reqts or CONOPs, trade-off analyses
  - Would overtax existing systems

**Space-Based Radar (SBR)**
- 2001
- 9 satellites, IOC: 2008, cost: $34B
- Effectively cancelled in 2005
  - Lack of agreement among stakeholders, no approved CONOPs
  - No plan for downstream acquisition issues

**Space Radar (SR)**
- 2005
- 2 satellites, IOC: 2015, cost: $??B
- Cancelled in 2008
  - Failed to meet reqts oversight
  - Lacked long-term funding plan

Key mission for the US government, but programs repeatedly cancelled mostly due to inability to effectively characterize cost and benefits of program under uncertainty

**IMCSE will leverage many of the benefits of MBSE and Visual Analytics**

*Congressional Budget Office, Alternatives for Military Space Radar, January 2007.*
Vision for IMCSE Research Program

• IMCSE will pursue a balanced basic and applied research approach
  — leveraging strengths of academic environment (e.g. fundamentals, rigor, neutral party view of problem), and
  — keeping the research relevant to the sponsor community, and
  — enabling opportunities for knowledge and MPT transfer to sponsors

• As the program matures, collaborations inside and outside of SERC

Knowledge Transfer Opportunities

Workshops, teleconferences and meetings, reports, papers, collaboration with other SERC activities, prototypes, MPTs, government partner applications, potential student internships

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.
To have most impact, IMCSE uses three complimentary thrusts with different timescales for impact:

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

Following year one, we anticipate additional projects within applications and fundamentals, plus updates to foundations.
Thrust 1: Foundations
IMCSE Research Pathfinder

Enabling Software Tools

- Starlight Visual Information System, www.futurepointsystems.com
- GI 1.3, www.graphinsight.com

The Pathfinder project will focus on identification of past and present related state of art and practice, and will begin to build a community of interest around IMCSE

- **Lead**: Dr. Donna H. Rhodes, Dr. Adam M. Ross
- **Summary**: Investigation of state of art and practice, conduct of an invited workshop including SERC and selected outside entities
- **Example Anticipated Outcomes**: Workshop summary report, literature review, research agenda report
Thrust 2: Applications
Interactive Schedule Reduction Model

Complex Systems Design and Analysis – META Approach

**Lead:** Professor Olivier de Weck

**Summary:** Exploratory extension of system dynamics-based Schedule Reduction Model, w/prototype model for pilot application

**Example Anticipated Outcomes:** Report, Demo, Prototype, Potential Deployment Partner


Leveraging prior work from DARPA META, the Schedule Reduction Model will be extended with interactivity as a central aspect, promoting sensitivity analyses and benchmarking to be the central use case.
Thrust 3: Fundamentals
Interactive Epoch-Era Analysis

Epoch-Era Analysis (EEA)
Considering the impact of short run and long run context and needs changes on the success of systems

Example Era

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

• **Lead**: Dr. Adam M. Ross, Dr. Donna H. Rhodes

• **Summary**: 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

• **Example Anticipated Outcomes**: Report, Papers, Proof of concept demo via mission planning support

IED attacks in Iraq: (Wired)
IMCSE Going Forward

• Looking forward to beginning this research program soon...

• This program is just a start with clear growth opportunities
  — E.g. Leverage MIT initiatives
  — E.g. Leverage other SERC initiatives
    o Full lifecycle MBSE, including Concept Engineering

• IMCSE has applicability across DoD and government in general
  — Looking for additional collaborators within SERC
  — Looking for additional government partners for case applications and field testing

• While starting in defense-oriented applications, IMCSE can be leveraged for use in government more generally
Future of SE Decision Making

• In the future, SE decisions must be more rapid, holistic, and better than “good enough”…
  – Q: How to manage system and program given dynamic uncertainties through the lifecycle?
  – A: IMCSE will enable more rapid and transparent decision making that will result in more affordable and valuable system solutions

• How could IMCSE turn out in 5-10 years?
  – Current visual analytics research shows how interaction reveals domain knowledge, which could then be used for learning systems (e.g. intelligent systems that further augment humans by anticipating queries and pre-fetching large data sets)

• Future IMCSE will show its value by enabling systems and programs to be more anticipatory and empowered to discover superior dynamic strategies, resulting in transformative capabilities

This type of capability could be used to address a host of questions, such as:

**Programmatic**
• How to write source selection criteria in RFP?
• How to implement changes to save the program today without killing the program in five years?
• How to trade changing requirements for building a "better" yet delayed system with building a less-capable system on schedule?

**Infrastructure**
• How to assess the impact of infrastructure improvements on program performance and cost?

**Systems-of-Systems**
• How to assess the impact of other asset availability to augment primary system performance during operations?

**Dynamic Acquisition Strategies**
• What are the implications of a staged deployment strategy vs. single deployment?
“Artificial things are synthesized (though not always and usually with full forethought) by human beings”


“Essentially, all models are wrong, but some are useful.”


“How can we enable more deliberate forethought in our systems throughout their lifecycle using interactive models?”

There are many specific techniques that modellers use, which enable us to discover aspects of reality that may not be obvious to everyone... but they are not as important as the ability to understand the underlying dynamics of a complex system well enough to assess whether the assumptions of a model are correct and complete. ...whether a model reflects reality, and to identify and deal with divergences between theory and data“


“Models can easily become so complex that they are impenetrable, unexaminable, and virtually unalterable.”

Back up slides
Using an “Epoch”-based Framework is Not New…

**Era**

**Variable:**
- Environment
- “Systems”
- Value

**Epoch Shift**

**Change in:**
- Environment
- “Systems”
- Value

**Epoch**

**Fixed:**
- Environment
- “Systems”
- Value

(EEA example slide courtesy of Andrew Long, 2010)
Various Epochs Define the World for our Systems...

(EEA example slide courtesy of Andrew Long, 2010)
... and Can be Assembled into Possible Eras (Futures)

Our Path Today

Cold War → War on Terror

Alternative Eras

(EEA example slide courtesy of Andrew Long, 2010)
Example: Modern HMMWV

(EEA example slide courtesy of Andrew Long, 2010)
Many possible contexts and needs may unfold in the future, impacting actual and perceived system utility and cost. “Epoch-based thinking” can be used to structure anticipatory scenario analysis.

Example triggers for epoch shifts impacting a system
- Change in political environment
- Entrance of new competitor in market
- Emergence of significant new or changed stakeholder need(s)
- Policy mandate impacting product line, services or operations

Categories of epoch variables can aid in thinking about key changing factors:

E.g., Resources, Policy, Infrastructure, Technology, End Uses (“Markets”), Competition, etc.
Storyboarding with Epochs

Two aspects to an **Epoch**:

1. Needs (expectations)
2. Context (constraints including resources, technology, etc.)

**Example system: Serviceable satellite**

System BOL \( \rightarrow \) \( T_1 \) \( \rightarrow \) Major failure \( \rightarrow \) Service to “upgrade” \( \rightarrow \) \( T_2 \) \( \rightarrow \) Major failure \( \rightarrow \) System EOL

Value degradation

New Context: new value function (objective fcn)

Service to “restore”

Value outage: Servicing time

Same system, but perceived value decrease

Service to “restore”

...
Epochs and Eras to Consider Long Run Uncertainties

- System Development Lifecycle (SDLC) is a crucial organizing construct for managing system design activities, but does not facilitate management of uncertain contexts and mission needs

- **Epoch**
  - A period of time during which the context and mission needs are static
  - Duration is determined by underlying dynamics of contextual factors considered

- **Era**
  - Spans the total lifecycle of a system
  - Constitutes an integrated set of epochs
  - Allows analysis of system evolution strategies

Epoch-Era Analysis provides a structured way to consider the impact of context changes and mission needs over the SDLC (Ross and Rhodes 2008)
Using Epochs for Proposing Time-Based Strategies across Eras

Discretization of change timeline into short run and long run enables analysis

**Epoch:**
Time period with a fixed context; characterized by static constraints, design concepts, available technologies, and articulated needs.

**Era:**
Time-ordered sequence of epochs

In order to pursue dynamic strategies, a system must have temporal properties, i.e., “-ilities” such as flexibility, evolvability, or survivability.
**Summary:** Catalyze human-model interaction capabilities and MPTs to rapidly conceive of systems, and to accelerate rapid trades for deciding on what is most effective, given present knowledge and future uncertainties, and what is practical, given resources and constraints.

- **Project 1: IMCSE Pathfinder**
  - Investigation of state of art and practice
  - Invited research workshop with report
  - Pathfinder project report

- **Project 2: Interactive Schedule Reduction Model**
  - Exploratory extension w/prototype model for pilot application, and project report

- **Project 3: Interactive Epoch-Era Analysis**
  - Exploratory development of interaction capability w/ demo case via mission planning support, and project report

- **Build community and publish several papers**
Prior Related Work

• Prior SERC research: RT-30: Graphical CONOPS

• Prior/ongoing MIT research under other sponsors:
  — Research lab with interactive tradespace exploration capability (prior-NRO, foreign gov’ts)
  — Prototype schedule reduction model (prior-DARPA)
  — Epoch-Era Analysis (EEA)
    o Method development for considering alternative futures (prior-NRO)
    o Method refinement (prior-AFOSR, NPS, foreign gov’ts)
    o Method application cases within multiple domains (prior-NRO, AFOSR, NPS, USCG, Army, foreign gov’ts)
  — Development and transition of MPTs embodying research outcomes (prior-foreign gov’ts)