Systems Engineering Advancement Research Initiative

# Addressing Systems Engineering Challenges Through Collaborative Research

September 11, 2007

Dr. Donna H. Rhodes
Massachusetts Institute of Technology

rhodes@mit.edu

# Field of Systems Engineering

# What is Systems Engineering?

SYSTEMS ENGINEERING (Traditional)

Systems engineering is the **process** of selecting and synthesizing the application of the appropriate scientific and technical knowledge in order to **translate system requirements into system design.** (Chase)

# What is Systems Engineering?

SYSTEMS ENGINEERING (Advanced)

Systems engineering is **a branch of engineering** that concentrates on **design and application of the whole** as distinct from the parts… looking at the problem in its entirety, taking into account all the facets and variables and **relating the social to the technical** aspects. (Ramo)

# Changing Face of Systems Engineering

| TRADITIONAL SE | ADVANCED SE |
| --- | --- |
| Transformation of customer requirements to design | Effective transformation of stakeholder needs to fielded (and sustainable) solution |
| Requirements clearly specified, frozen early | Focus on product families and systems-of-systems |
| Emphasis on minimizing changes | Complex interdependencies of system and enterprise |
| Design to meet well specified set of requirements | Growing importance of systems architecting |
| Performance objectives specified at project start | Designing to accommodate change |
| Focus on reliability, maintainability, and availability | Emphasis on expanded set of "ilities" and designing in *robustness, flexibility, adaptability* in concept phase |

# What is Systems Engineering?

*Systems Engineering is an interdisciplinary approach and means to enable the realization of successful systems.*

*Systems Engineering integrates all the disciplines and specialty groups into a team effort forming a structured development process that proceeds from concept to production to operation.*

*Systems Engineering considers both the business and the technical needs of all customers with the goal of providing a quality product that meets the user needs.*

*International Council on Systems Engineering*

# Motivations for Research in Advanced Systems Engineering

# DSB/AFSAB Report on Acquisition of National Security Space Programs

May 2003

## Findings:

Cost has replaced mission success as the primary driver in managing space development programs

Unrealistic estimates lead to unrealistic budgets and unexecutable programs

Undisciplined definition and uncontrolled growth in system requirements increase cost and schedule delays

Government capabilities to lead and manage the acquisition process have seriously eroded

Industry has failed to implement proven practices on some programs

# Critical Need for Systems Engineering for "Robustness"

***In a 2004 workshop, Dr. Marvin Sambur, (then) Assistant Secretary of the AF for Acquisition, noted that average program is 36% overrun according to recent studies -- which disrupts the overall portfolio of programs.***

***The primary reason cited in studies of problem programs state the number one reason for programs going off track is systems engineering.***

Systems Engineering for robustness means developing systems/system-of-systems that are:

- Capable of adapting to changes in mission and requirements
- Expandable/scalable
- Designed to accommodate growth in capability
- Able to reliably function given changes in threats and environment
- Effectively/affordably sustainable over their lifecycle
- Easily modified to leverage new technologies

Reference: Rhodes, D., *Workshop Report – Air Force/LAI Workshop on Systems Engineering for Robustness, July 2004*, http://lean.mit.edu

# Today's Failures Exhibit Global Engineering Complexities

## October 8 2005

## CryoSat Mission lost due to launch failure

*Mr Yuri Bakhvalov, First Deputy Director General of the Khrunichev Space Centre on behalf of the Russian State Commission officially confirmed that the launch of CryoSat ended in a* ***failure due to an anomaly in the launch sequence …. missing command from the onboard flight control system…***

.

*This loss means that Europe and the worldwide scientific community will not be able to rely on such data from the CryoSat mission and will not be able to improve their knowledge of ice, especially sea ice and its impact on climate change.*

**Will this event have an impact on ESA's relationship with Russia?**

*Space has always been a risky business. Failures can happen on each side. From this end I do not expect any impact on relations with Russia. I wish to underline that in this particular case we, ESA, were customers to Eurockot, the launch service provider, which is a joint venture between EADS Space Transportation (Germany) and Krunichev (Russia).*

# Systems Engineering Continues to Be Cited as a Source of Problems

**DOD IG: Lack of systems engineering imperils missile system**

**Published on Mar. 20, 2006**

A lack of systems engineering plans could derail a $30 billion effort to field an integrated Ballistic Missile Defense System (BMDS), the Defense Department's inspector general said in a report released earlier this month.

The Missile Defense Agency (MDA) has not completed a systems engineering plan or developed a sustainment plan for BMDS, jeopardizing the development of an integrated BMDS, the DOD IG said.

The report emphasizes that DOD must practice strong systems engineering to effectively sustain weapons systems. That begins with design and development.

# Evolution of Practice of Systems Engineering

*Over the past five or six decades, the discipline known as "Systems Engineering" has evolved. At one time, many years ago, development of a capability was relatively simple to orchestrate.*

*The design and development of parts, engineering calculations, assembly, and testing was conducted by a small number of people. Those days are long gone.*

*Teams of people, sometimes numbering in the thousands are involved in the development of systems; and, what was previously only a development practice has evolved to become a science and engineering discipline.*

***Saunders, T., et al, System-of-Systems Engineering for Air Force Capability Development: Executive Summary and Annotated Brief, AF SAB TR -05-04, 2005***

# Contemporary Systems Engineering

- Systems of systems
- Extended enterprises
- Network-centric paradigm
- Delivering value to society
- Sustainability of systems
- Design for flexibility
- Managing uncertainty
- Predictability of systems
- Spiral capable processes
- Model-based engineering
- … and more

*This requires a broader field of study for future systems leaders and enabling changes in education and research …*

# MIT Venue for Systems Education and Research

# MIT Engineering Systems Division as Intellectual Home for Systems Research

*MIT is tackling the large-scale engineering challenges of the 21st century through a new organization….*

The Engineering Systems Division (ESD) creates and shares interdisciplinary knowledge about complex engineering systems through initiatives in education, research, and industry partnerships.

- Cross-cutting academic unit including engineering, management, social sciences
- Broadens engineering practice to include context of challenges as well as consequences of technological advancement
- Dual mission: (1) evolve engineering systems as new field of study and (2) transform engineering education and practice

Council of 40+ universities is collaborating on this goal (http://www.cesun.org)

Systems Engineering Advancement Research Initiative

# ES versus SE
# What Is the Difference?

**SYSTEMS ENGINEERING (Traditional)**

Systems engineering is the process of selecting and synthesizing the application of the appropriate scientific and technical knowledge in order to translate system requirements into system design. (Chase)

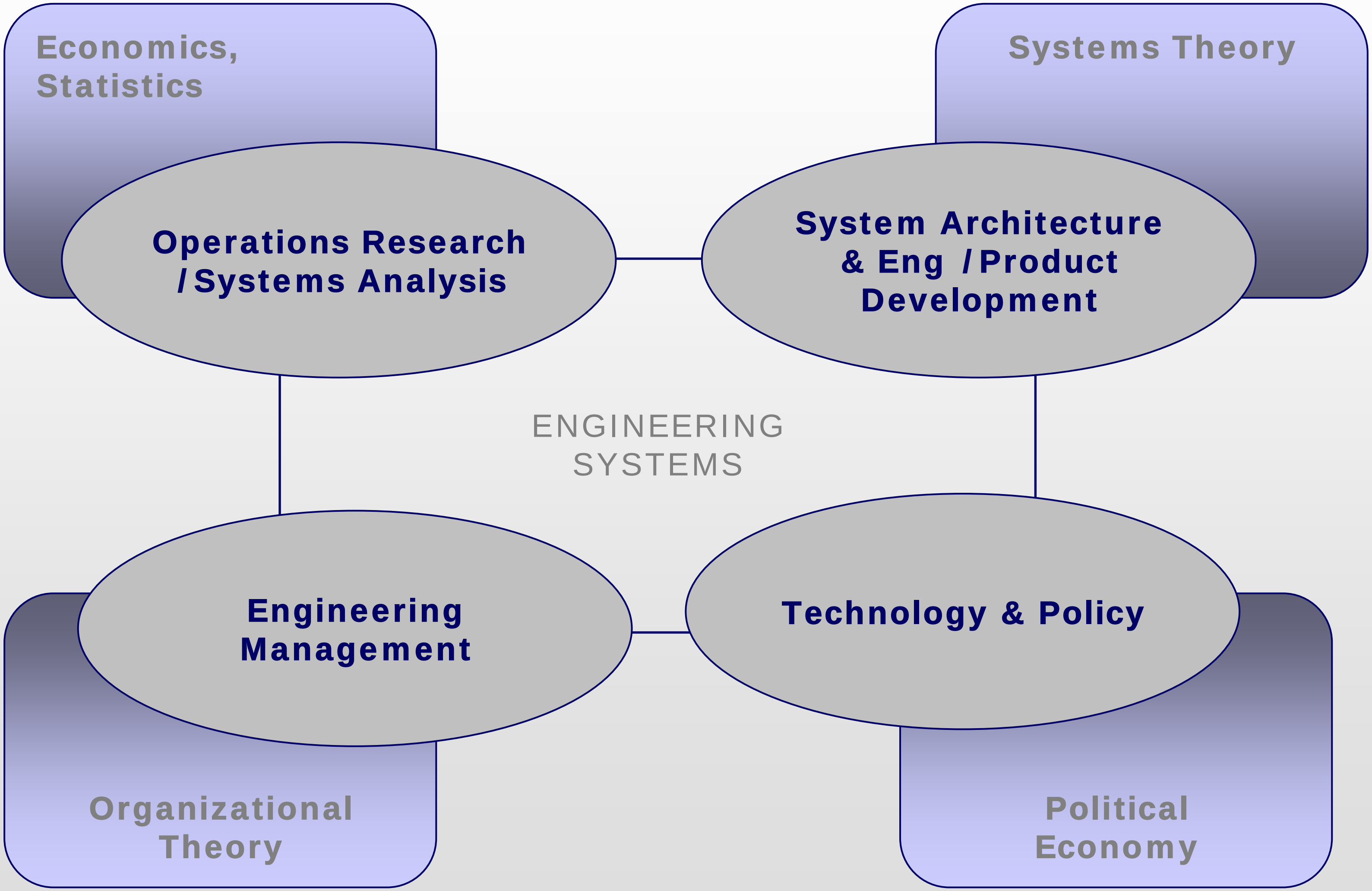
**SYSTEMS ENGINEERING (Advanced)**

Systems engineering is a branch of engineering that concentrates on design and application of the whole as distinct from the parts… looking at the problem in its entirety, taking into account all the facets and variables and relating the social to the technical aspects. (Ramo)

**ENGINEERING SYSTEMS**

A field of study taking an integrative holistic view of large-scale, complex, technologically-enabled systems with significant enterprise level interactions and socio-technical interfaces.

# Engineering Systems as a Field of Study



# Engineering Systems Requires Four Perspectives

1. A very **broad interdisciplinary perspective**, embracing technology, policy, management science, and social science.

2. An **intensified incorporation of system properties** (such as sustainability, safety and flexibility) in the design process.
   - Note that these are lifecycle properties rather than first use properties.
   - These properties, often called "ilities" emphasize important intellectual considerations associated with long term use of engineering systems.

3. **Enterprise perspective**, acknowledging interconnectedness of product system with enterprise system that develops and sustains it.
   - This involves understanding, architecting and developing organizational structures, policy system, processes, knowledgebase, and enabling technologies as part of the overall engineering system.

4. A **complex synthesis of stakeholder perspectives**, of which there may be conflicting and competing needs which must be resolved to serve the highest order system (system-of-system) need.

# Impact of Engineering Systems on Systems Engineering

ES can provide a broader landscape (context field) for SE

ES brings together a more diverse set of researchers and scholars

ES establishes a larger footprint in the university, driving a strong research focus and investment

*The Engineering Systems Division provides the research venue for a new initiative on advanced systems engineering…*

# MIT Research Initiative in Advanced Systems Engineering

# Systems Engineering Advancement Research Initiative (SEAri)

## Mission

***Advance the theories, methods, and effective practice of systems engineering applied to complex socio-technical systems through collaborative research***

Current Sponsors: US Air Force Office of Scientific Research, Singapore Defense Sciences Office, US Air Force, Aerospace Corporation, MITRE Corporation, NASA , MIT Portugal Program, Draper Laboratory, Lean Aerospace Initiative

**3 Cambridge Center**

**NE20 – 388/343**

| | *Traditional Systems Engineering* | *Advanced Systems Engineering* |
|---|---|---|
| Purpose | Development of single system to meet stakeholder requirements and defined performance | Evolving new system of systems capability by leveraging synergies of legacy systems |
| System Architecture | System architecture established early in lifecycle; remains relatively stable | Dynamic adaptation of architecture as needs change |
| System Interoperability | Defines and implements specific interface requirements to integrate components in system | Component systems can operate independently of SoS in a useful manner Protocols and standards essential to enable interoperable systems |
| System "ilities" | Reliability, Maintainability, Availability are typical ilities | Enhanced emphasis on "ilities" such as Flexibility, Adaptability, Composeability |
| Acquisition and Management | Centralized acquisition and management of the system | SoS component systems separately acquired, and continue to be managed and operated as independent systems |
| Anticipation of Needs | Concept phase activity to determine system needs | Intense concept phase analysis followed by continuous anticipation, aided by ongoing experimentation |
| Cost | Single or homogenous stakeholder group with stable cost/funding profile and similar measures of success | Multiple heterogeneous stakeholder groups with divergent cost goals and measures of success |

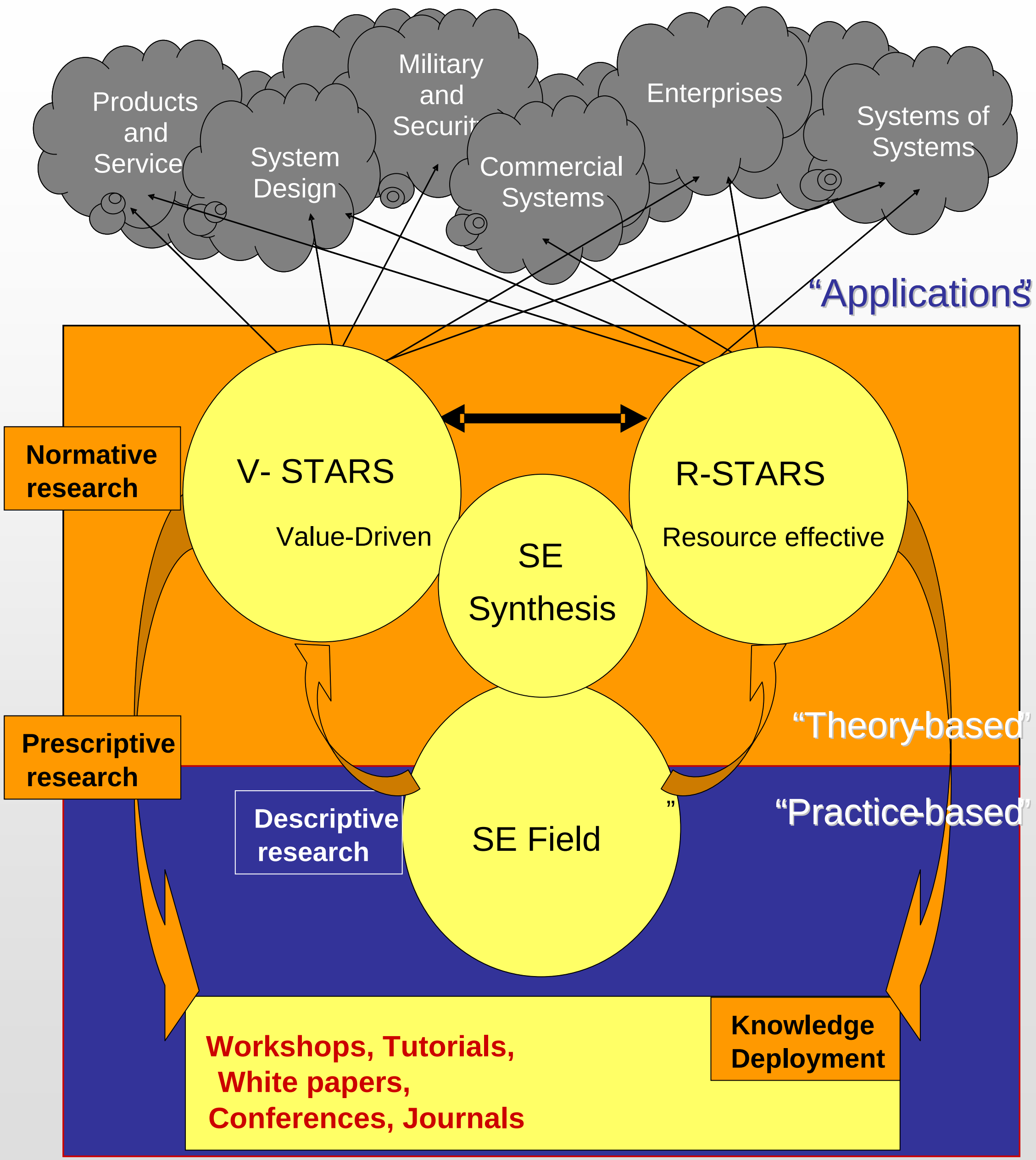
Structured with four interacting "clusters" that undertake research in a portfolio of four topics:

1. Socio-Technical Decision Making

2. Designing for Value Robustness

3. Systems Engineering Economics

4. Systems Engineering in the Enterprise



# Research Portfolio (1)

## SOCIO-TECHNICAL DECISION MAKING

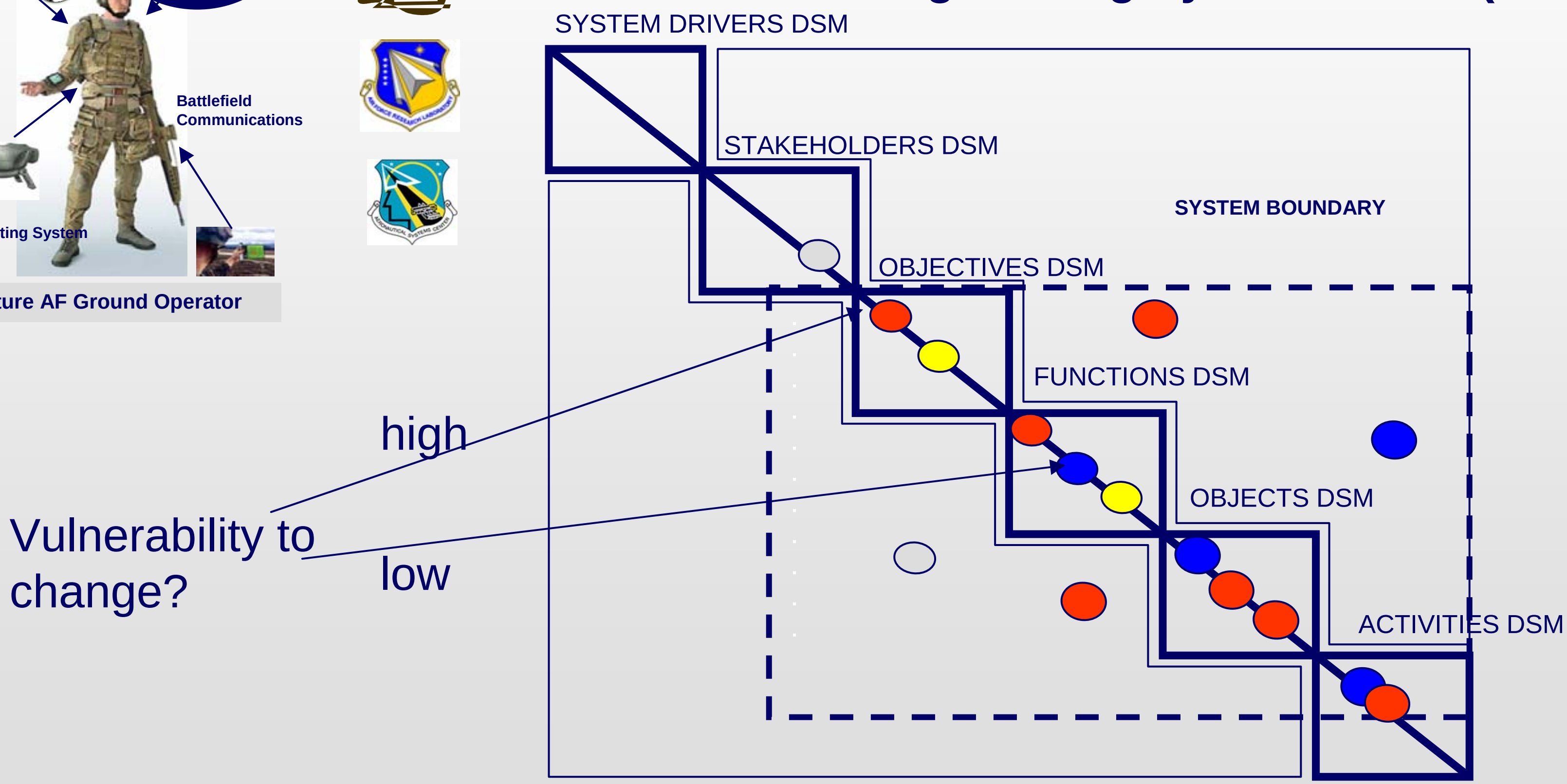
*This area of research is concerned with the context of socio-technical systems. Based on a multi-disciplinary approach, decision making techniques are developed through the exploration of:*

- Studies of decision processes and effectiveness of techniques
- Constructs for representing socio-technical systems to perform impact analysis
- Decision strategies for coupling in system of systems
- Visualization of complex trade spaces and saliency of information
- Understanding and mitigating cognitive biases in decision processes

# How Can Socio-technical Systems be Represented for Analysis and Screening for Real Options ?

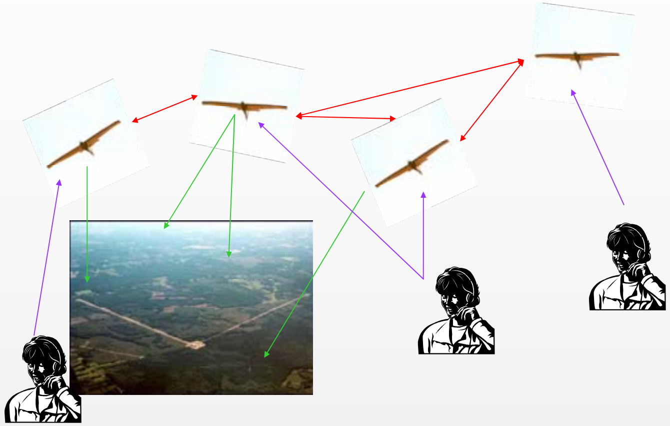

Future AF Ground Operator

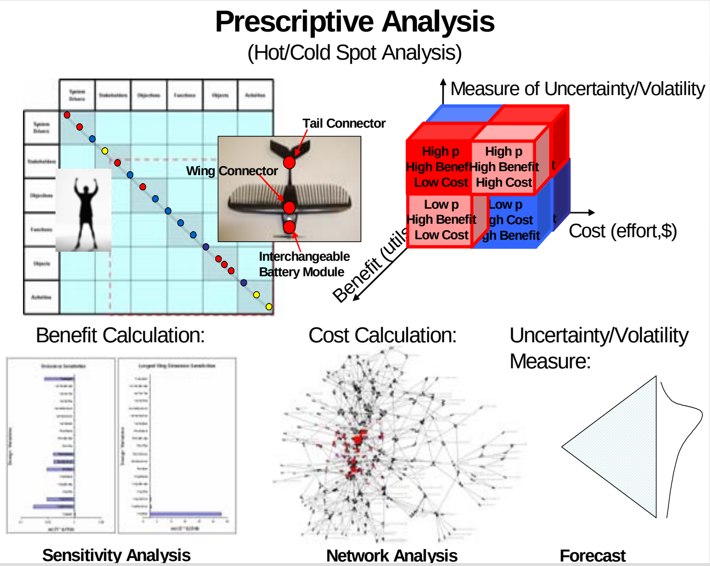
## Engineering System Matrix (ESM)




Dr. Jason Bartolomei, PhD 2007

# Uncertainty Management






## Real Options in Enterprise Architecture

Tsoline Mikaelian, Aero/Astro PhD 2009

What enterprise representation/models can be used to identify potential real option investment opportunities?

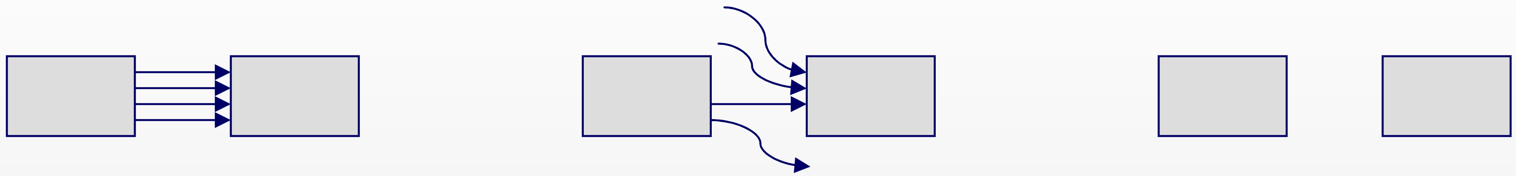
How can you quantify the value of real options in enterprises to enable the selection of an options portfolio in enterprise decision making?

## Engineering Systems Matrix for Real Options Analysis

Jennifer Wilds, SM Aero/Astro and TPP 2008

How can the Engineering Systems Matrix (ESM) be applied for understanding real options in complex systems?

# When Should Systems Use Tight or Loose Coupling?



Tight Coupling | Loose Coupling | No Coupling

Loosely coupling is **approach to designing interfaces** across constituent systems to **reduce the interdependencies** across constituent systems

Seeks to **increase flexibility** in **adding** constituent systems, **replacing** constituent systems, **changing** operations within constituent systems and **re-architecting** the SOS

A way to manage tension between global and local value in SOS design

Nirav Shah, PhD Candidate, 2007

# Research Portfolio (2)

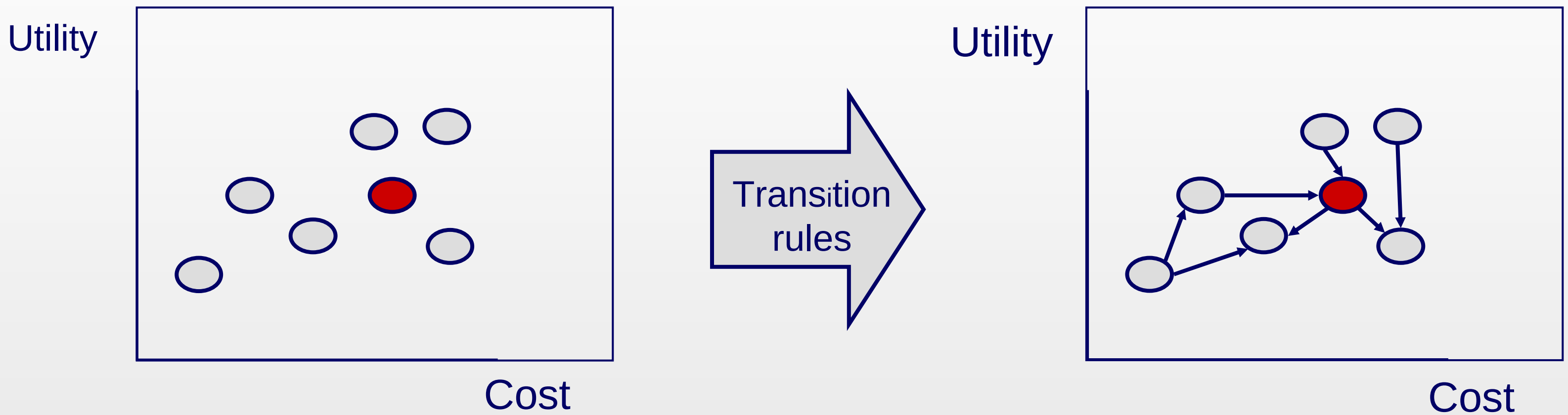
## DESIGNING for VALUE ROBUSTNESS

*This area of research seeks to develop methods for concept exploration, architecting and design using a dynamic perspective for the purpose of realizing systems, products, and services that deliver sustained value to stakeholders in a changing world.*

- Methods for dynamic multi-attribute trade space exploration
- Architecting principles and strategies for designing survivable systems
- Quantification of the changeability of a system design
- Techniques for the consideration of unarticulated and latent stakeholder value
- Taxonomy for enabling stakeholder dialogue on ‘ilities’

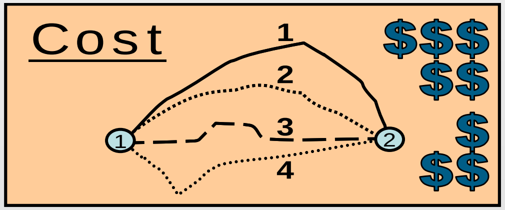
# How Can Dynamic Tradespaces be Explored ?

Tradespace Networks




Tradespace designs = nodes

Applied transition rules = arcs




**Transition rules are mechanisms to change one design into another**
**The more outgoing arcs, the more potential change mechanisms**

Dr. Adam M. Ross, PhD 2006, adamross@mit.edu

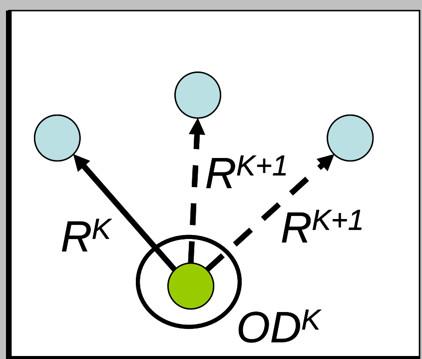
  

# How Can Changeability of a Design be Measured?

objective

## Outdegree

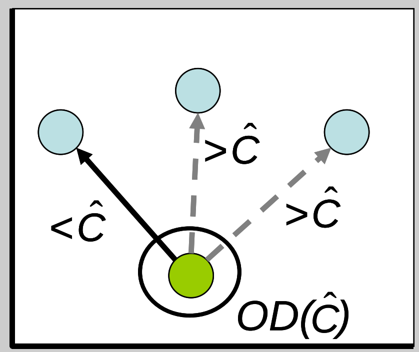
# outgoing arcs from a given node



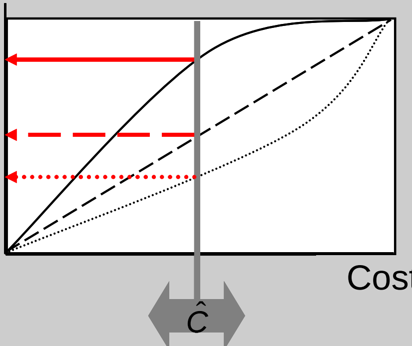

subjective

## Filtered Outdegree

# outgoing arcs from design at acceptable “cost”
(measure of changeability)




Outdegree




Subjective Filter

Filtered outdegree is a measure of the apparent changeability of a design

Dr. Adam M. Ross, PhD 2006, adamross@mit.edu

SEARI Systems Engineering Advancement Research Initiative

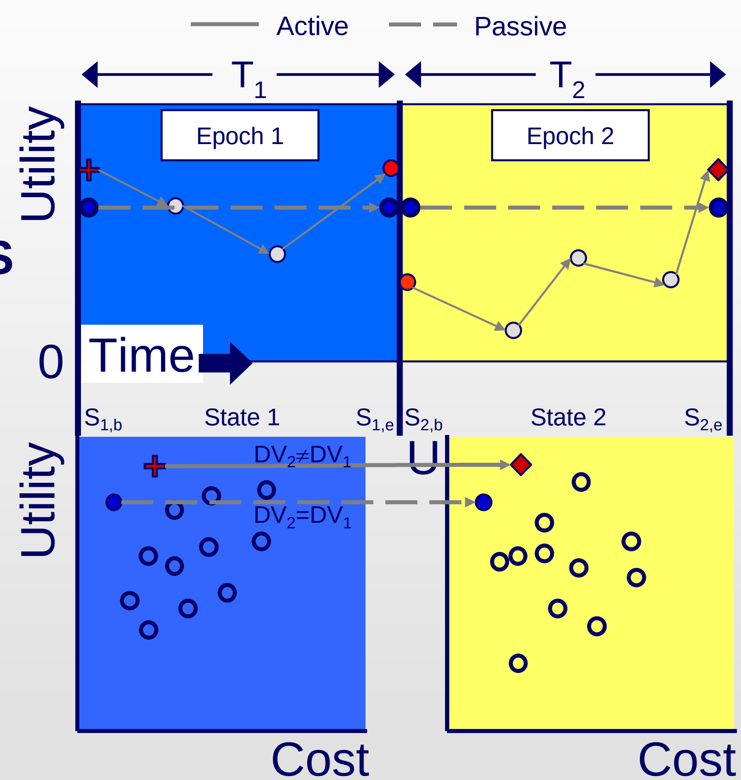
# What Strategies Can be Used to Achieve Value Robustness?

**New Context Drivers**
- External Constraints
- Design Technologies
- Value expectations

## RESEARCH SUGGESTS TWO STRATEGIES FOR VALUE ROBUSTNESS

1. **Passive**
   - Choose "clever" designs that remain high value
   - Quantifiable: Pareto Trace number

2. **Active**
   - Choose changeable designs that can deliver high value when needed
   - Quantifiable: Filtered Outdegree



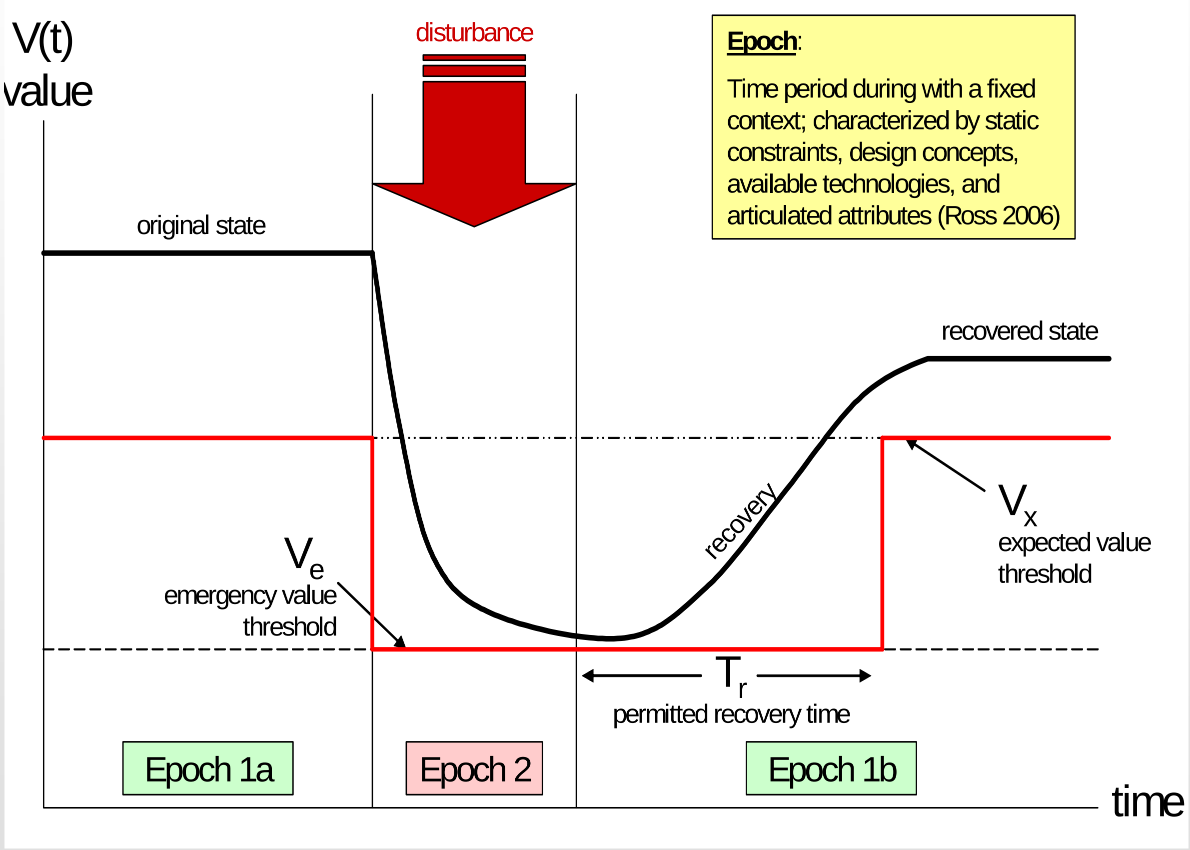

Value robust designs can deliver value in spite of inevitable context change


Dr. Adam M. Ross, PhD 2006, adamross@mit.edu

# What are the Principles for Architecting for Survivability?

**The interdependence of large-scale, distributed systems has grown since the advent of modern telecommunications**

**Engineering systems are increasingly at risk from disturbances that rapidly propagate through networks, damage critical infrastructure, and undermine system-of-systems**




Matt Richards, PhD Student, 2009

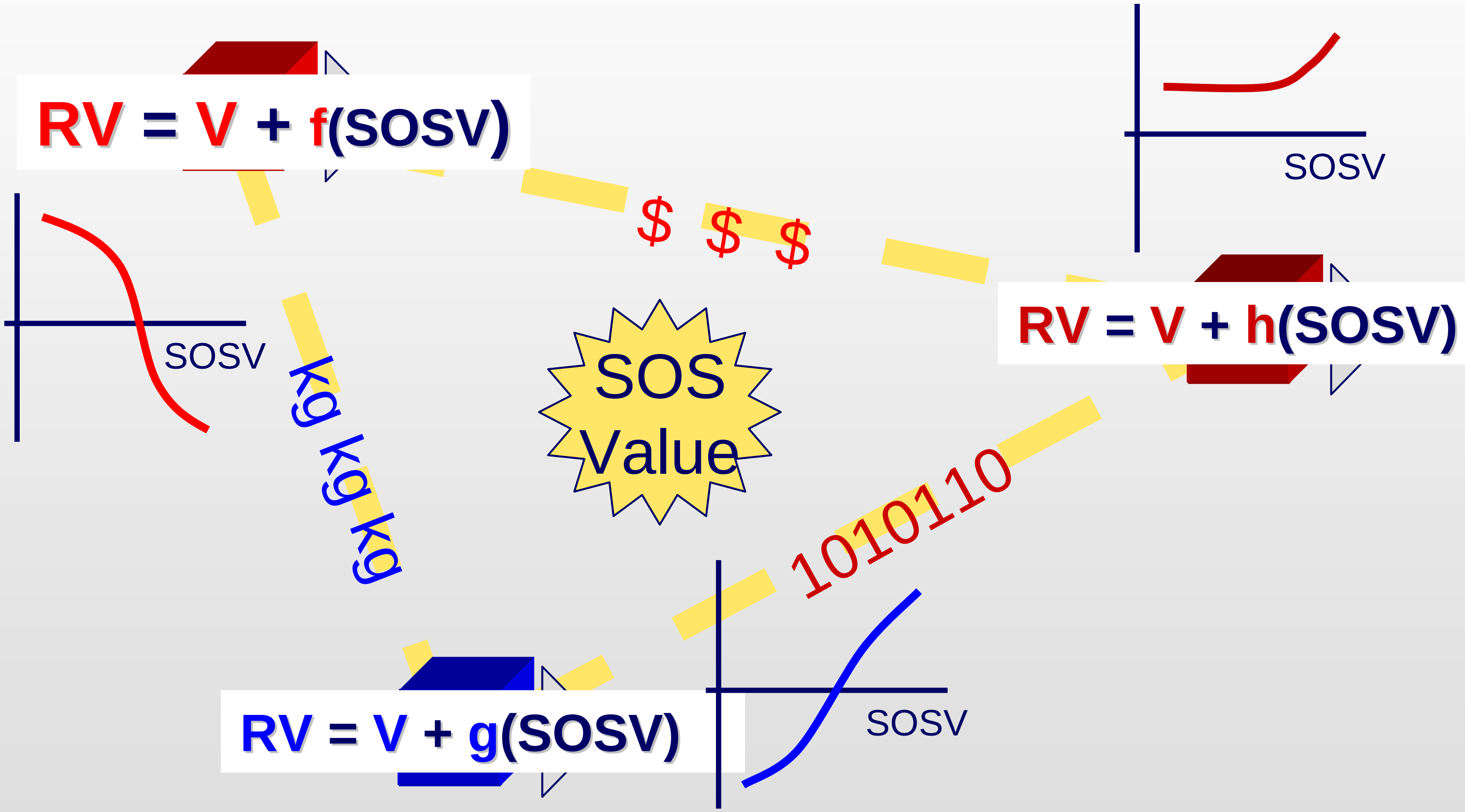
# Research Portfolio (3)

SYSTEMS ENGINEERING ECONOMICS

*This research area aims at developing a new paradigm that encompasses an economics view of systems engineering to achieve measurable and predictable outcomes while delivering value to stakeholders.*

- Measurement of productivity and quantifying SE ROI
- Advanced methods for reuse, cost modeling, and risk modeling
- Application of real options in systems and enterprises
- Leading indicators for systems engineering effectiveness

# What Influences Local and Global Value in a SoS ?



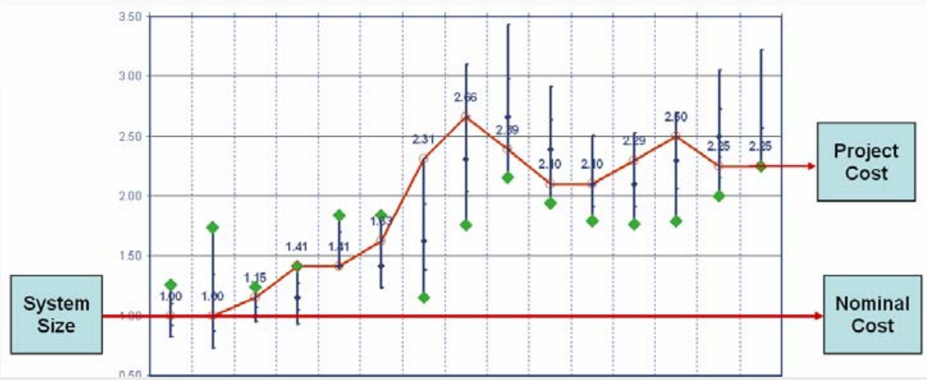

Nirav Shah, PhD Candidate, 2007

Systems Engineering Advancement Research Initiative

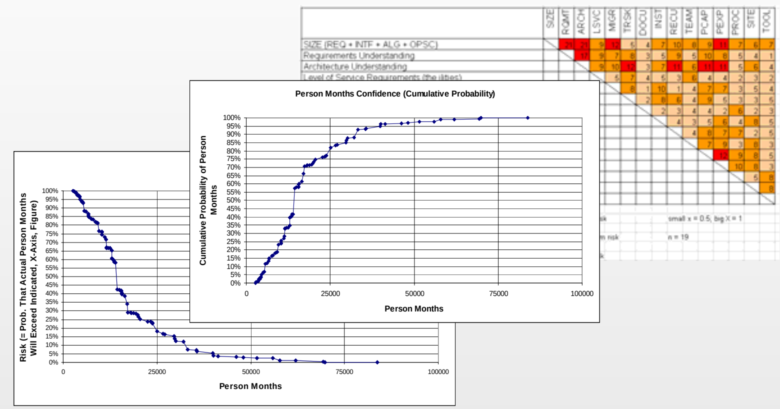
# Models, Measures, and Leading Indicators for Project Success

## Through Better Execution of Systems Engineering

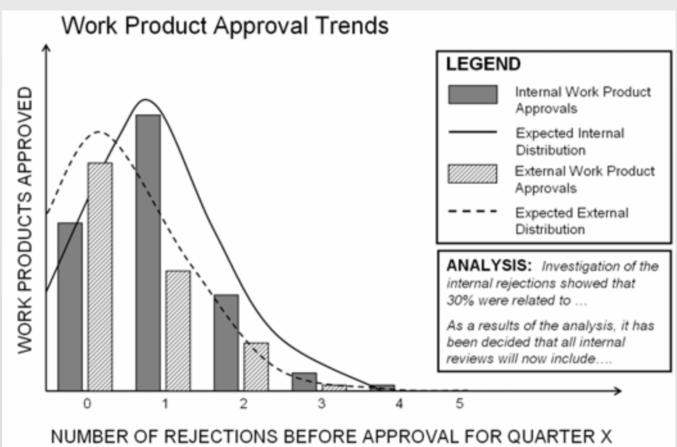
### Cost and schedule modeling



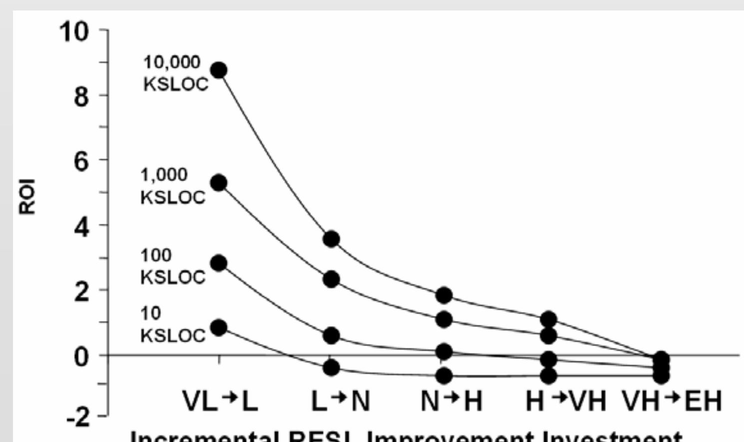

### Project Risk Assessment




### Leading Indicators for Performance




### Systems Engineering ROI



# Research Portfolio (4)

SYSTEMS ENGINEERING in the ENTERPRISE

*This research area involves empirical studies and case based research for the purpose of understanding how to achieve more effective systems engineering practice in context of the nature of the system being developed, external context, and the characteristics of the associated enterprise.*

- Engineering systems thinking in individuals and teams
- Collaborative, distributed systems engineering practices
- Social contexts of enterprise systems engineering
- Alignment of enterprise culture and processes
- Socio-technical systems studies and models

*The understanding of the organizational and technical interactions in our systems, emphatically including the human beings who are a part of them, is the present-day frontier of both engineering education and practice.*

Dr. Michael D. Griffin, Administrator, NASA
Boeing Lecture, Purdue University
28 March 2007

# Enabling Systems Thinking to Accelerate the Development of Senior Systems Engineers

SEARI Systems Engineering Advancement Research Initiative

**Even though systems thinking definitions diverge, there is consensus on primary mechanisms that enable or obstruct systems thinking development in engineers**

**Dr. Heidi Davidz, PhD 2006**

**Consensus on primary mechanisms that enable or obstruct systems thinking development in engineers**

1. **Experiential learning**
2. **Individual characteristics**
3. **Supportive environment**

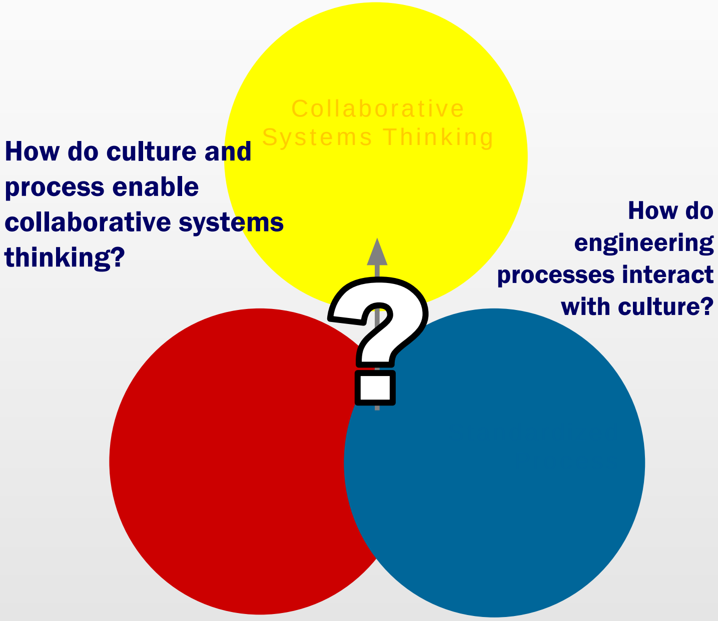
# Collaborative Systems Thinking
## *Aligning Culture and Standardized Process*

Examines the development of systems thinking within teams of engineers.

Emphasis placed on the role of standard process and its interactions with organizational culture.

Research motivated by desire to better understand systems thinking at the team level within engineering.

Focuses on the role of standardized process, its artifacts and associated tools, in enabling or promoting team level systems thinking —termed collaborative systems thinking.




**Caroline Twomey Lamb, PhD Student, 2009**

# Collaborative Distributed Systems Engineering in the Aerospace Industry

**Develop heuristics for successful CDSE resulting from case studies**

**Recommendations to overcome barriers to successful CDSE**

**Recommendations for future work in this area**

**Social Factors:**
- Local/Company Culture Differences
- Career Development Advancement
- Distributed Teamwork
- Communications
- Working w/ IT and tools
- Project Management

**CDSE**

**Technical Factors:**
- SE Process/Architecture
- Distributed Decision Making
- Tools/Information Technology
- Knowledge Management
- Cost & Schedule
- Product Impact

**Darlene Utter, S.M. 2007**

# Collaborative Research Imperatives and Example Projects

# Imperative

## Engineering research while still dependent upon individual contributors must evolve to be more synergistic

Our society is faced with large scale problems demanding a multi-faceted and interdisciplinary systems approach

Requires researchers from diverse disciplines to collaboratively work on problems using shared data sets and aligning around harmonized research threads

Need to understand how to synthesize individual research efforts, with good mechanisms for research succession planning and transition of research to practice

We strive for research leading to sustainable engineering systems meeting broad societal needs … we are challenged by current policies, funding approach, and traditional university/research stovepipes

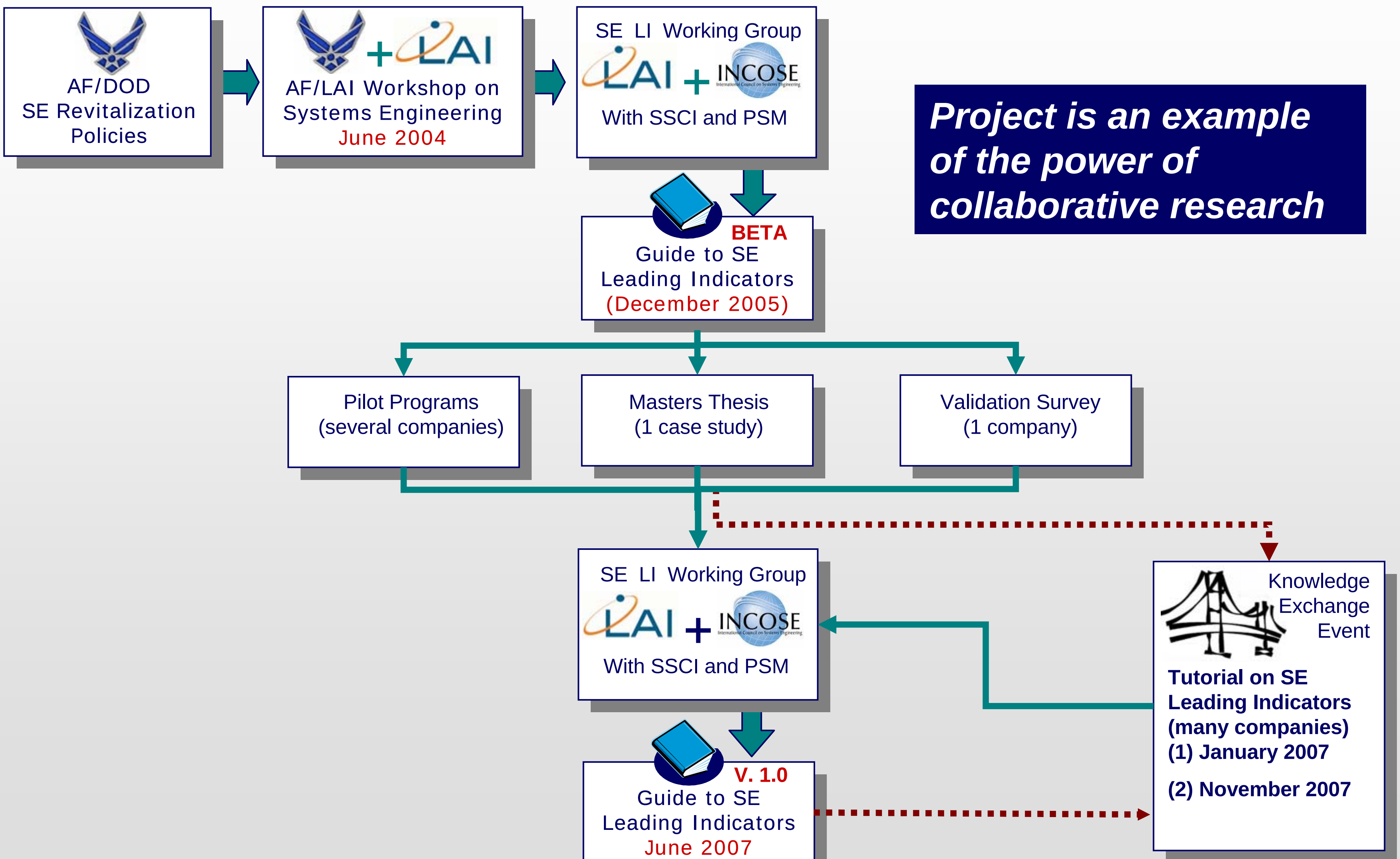
# Imperative

## Engineering education and research must be a collaborative endeavor of government, industry, and academia

- Complex engineering research can not take place solely in a laboratory within university walls but rather real world enterprises must be our "learning laboratories"
- Expanded view of who an "educator" is -- faculty, researchers, practitioners, policy makers, peers
- Additionally, we need more cross cutting experiences for educators and practitioners alike
- Faculty have a very urgent need for case studies for use in the classroom … without practitioner involvement these will lack depth to have educational impact
- Engineering education and research can not be just a cooperation; must be a true collaboration

# SE Leading Indicators Project

## *Creating New Knowledge*



# MITRE/MIT Research on Social Contexts of Systems Engineering

## *Leverage Diversity of Research Team*

Develop social science capabilities and products complementing MITRE's technical capabilities in order to meet the challenges of Systems Engineering at the Enterprise level

- Transform practical field experience of MITRE site staff into social-scientific understanding that is usefully transferable
- Leverage experience and approaches from MIT partners

Technical Approach

- ❖ Case Studies
- ❖ Workshops
- ❖ 2nd Round of Case Studies
- ❖ Communicate Lessons Learned

# Draper /MIT Research Dynamic Tradespace Exploration Applied to System of Systems

*Extending Research to Enhance Practice*

New research launched in July 2007 (first Draper project with MIT ESD) to extend work of Ross (2006)

University research project coupled to related in-house IR&D project

Leverage geographic co-location for highly interactive research engagement

Mutual benefit

- Enhance Draper capabilities and processes
- Further validate and extend MIT methodology
- Collaborative learning

# Summary

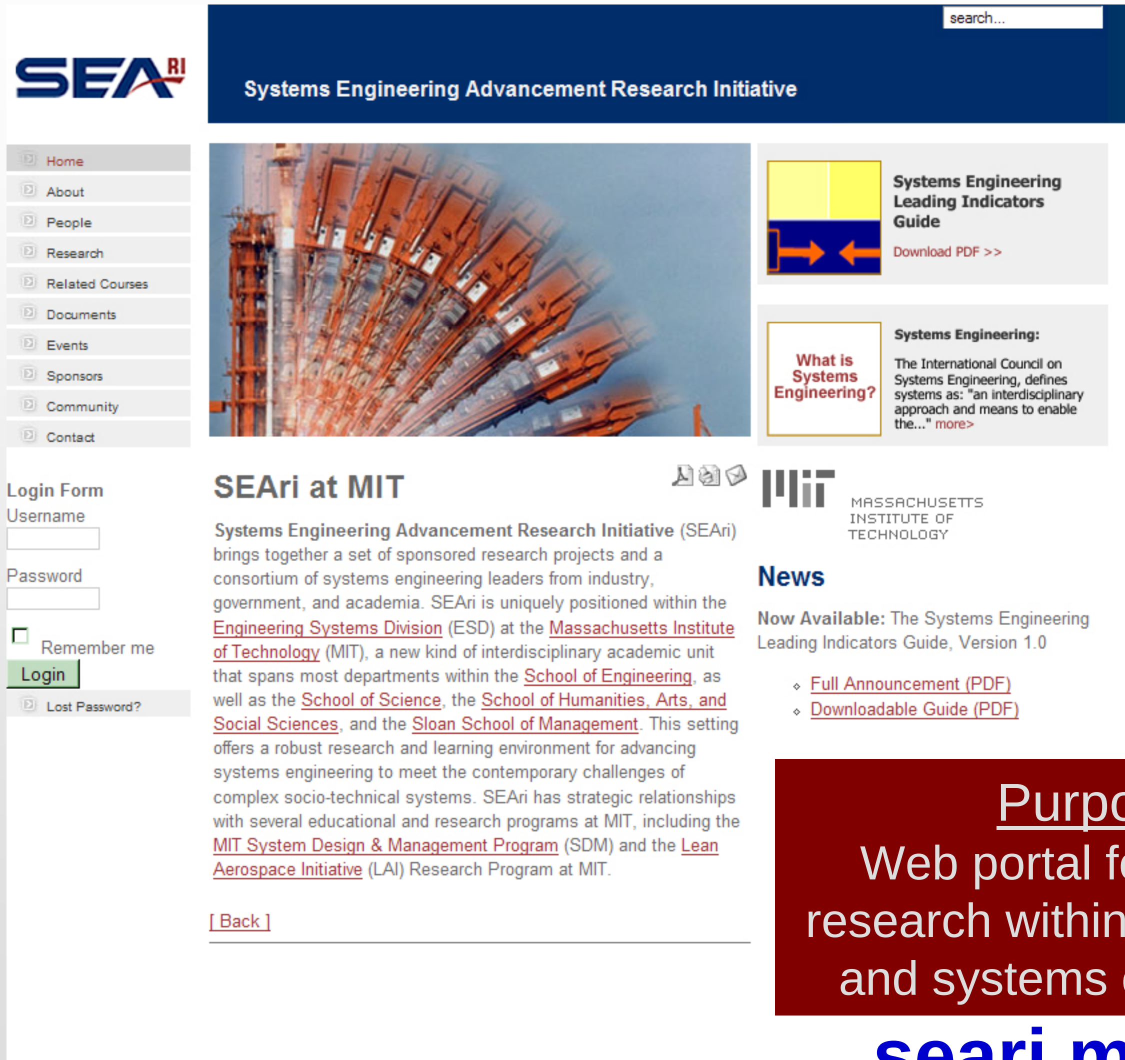
# SEAri Seeks To Impact Theory, Methods, And Practice

- MIT Engineering Systems Division (ESD) provides an interdisciplinary research venue
- Strategic collaboration with other MIT education and research centers (e.g., LAI, SDM)
- Hybrid research model for collaboration
  - Single sponsor research projects
  - Consortium research
- Realization of research goals is predicated on deep collaboration with industry and government

# Access to Research

<u>Navigation</u>

- Home
- About
- People
- Research
- Related Courses
- Documents
- Events
- Sponsors
- Community
- Contact
- *Internal*




**<u>Purpose</u>**

Web portal for sharing research within SEAri, MIT, and systems community

**[seari.mit.edu](http://seari.mit.edu)**

# Sharing Research Outcomes

*2007*
*SEAri Research Summit*
*October 16*
*MIT Faculty Club*

**Dynamic**

**SEARI Research Bulletin Published at End of Each Semester**


Systems Engineering Advancement Research Initiative

RESEARCH BULLETIN DECEMBER 2006 Vol. 1, Issue 1

**SEA^RI Consortium Launched**

SEA^RI is launching a new consortium focused on the advancement of systems engineering to enhance its ongoing sponsored research program. The consortium's goals include expanding the current research, accelerating the transition of research outcomes to industry practice, and engaging members in collaborative projects.

Wh... s ...sored research projects are ...ed to suit an individual sponsor's interest, the consortium research projects will address the broad

**A Message from the Director**

*In this inaugural issue of the SEA^RI Research ... is worth reflecting on what motivates o... research program, as well as our de... complement the existing sponsored research ... consortium. During recent years, systems e... has received increased focus and expanded i... on a global scale. Many new university depart... programs have been developed in response ... demand for skilled engineers who can think s... about complex systems. As a systems comm... see the enterprises in which systems engi...*

**Research Spotlight 1**

**...xploratory Research Studies Best ...ractices in Collaborative Distributed ...ystems Engineering**

*...search by: Darlene Utter, S.M., Eng. Systems*

...rlene Utter recently completed her masters research ...estigating emerging best practices in collaborative ...tributed systems engineering (CDSE), focused on ...ee major objectives. The first was to define successful ...cial and technical CDSE practices by examining how ...aerospace and defense companies are performing ...s practice, and lessons they have learned. Successful ...DSE involves many factors; eleven are addressed in ...e research: use of CDSE and collaboration tools; ...heduling and conduct of meetings; communication; ...ining of engineers; overcoming social and cultural

*necessary for contractors to perform collaborative, distributed systems engineering (CDSE) over several geographical locations. Previous research has demonstrated that the design practices of distributed design teams differ from those of traditional, co-located teams. However, many companies today are performing CDSE using processes and methods developed for traditional SE environments and are therefore encountering many issues. Successful SE practices are difficult to carry-out when performed by a traditional, collocated enterprise. The addition of geographic distribution and cross-company or intra-company collaboration in SE presents a myriad of social and technological challenges that necessitate new and different SE methods for success. Best practices for CDSE are currently unknown (or undocumented).*

**SEA^RI News**

**Prof. Hastings Awarded Research Contract by Singapore DSTA**

The purpose of this three year project, initiated September 2006, is to develop an analytical framework for representing a group of homogeneous Mini Air Vehicles. The project is entitled *An Engineering Systems Analysis of Systems Architecture Issues with a Swarm of Mini Air Vehicles (MAV)*, and involves SEA^RI doctoral student Tsoline Mikaelian. An objective of the research is to identify places in a system architecture where real options can mitigate performance risk. Hastings, a

**COSYSMO Book Coming in 2007**

In 2007, SEA^RI is anticipating the publication of the book *Systems Engineering Cost Estimation with COSYSMO* by Dr. Ricardo Valerdi. The book describes the anatomy and application of the Constructive Systems Engineering Cost Model (COSYSMO) together with lessons learned from implementation and calibration at companies such as BAE Systems, General Dynamics, Lockheed Martin, Northrop Grumman, L3 Communications, Raytheon, and SAIC. Prepublication copies of the book are available to selected individuals affiliated with SEA^RI by contacting Dr. Valerdi (rvalerdi@mit.edu). For information on COSYSMO visit www.valerdi.com/cosysmo.

**MIT/MITRE Joint Research Progress**

The third annual MIT ESD/MITRE Research Workshop was held on November 30 at MITRE Center in Bedford, MA. The workshop featured briefings from MIT ESD

**Static**

# Additional References

**ESD Website**

http://esd.mit.edu/

**ESD Research Centers**

http://esd.mit.edu/research_industry.html

**ESD Working Papers**

http://esd.mit.edu/WPS/

**ESD Symposium Monographs and Papers**

http://esd.mit.edu/symposium/monograph/

http://esd.mit.edu/symposium/agenda_day3.htm

**Lean Aerospace Initiative**

http://lean.mit.edu

**Refer to websites for additional information and working papers related to systems engineering at MIT**

# QUESTIONS

http://seari.mit.edu

rhodes@mit.edu