



Systems Engineering Advancement Research Initiative

Addressing Systems Engineering Challenges Through Collaborative Research

September 2007

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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

Transformation of customer requirements to design

Requirements clearly specified, frozen early

Emphasis on minimizing changes

Design to meet well specified set of requirements

Performance objectives specified at project start

Focus on reliability, maintainability, and availability

ADVANCED SE

Effective transformation of stakeholder needs to fielded (and sustainable) solution

Focus on product families and systems-of-systems

Complex interdependencies of system and enterprise

Growing importance of systems architecting

Designing to accommodate change

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

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

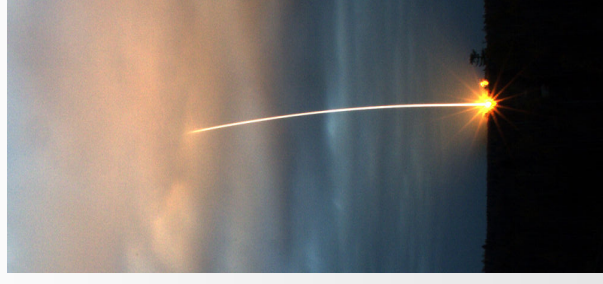
Reference: Rhodes, D., *Workshop Report – Air Force/LAI Workshop on Systems Engineering for Robustness, July 2004*, <http://lean.mit.edu>

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 Khrunichev (Russia).

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 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>)

ES versus SE

What Is the Difference?

SYSTEMS ENGINEERING (Traditional)

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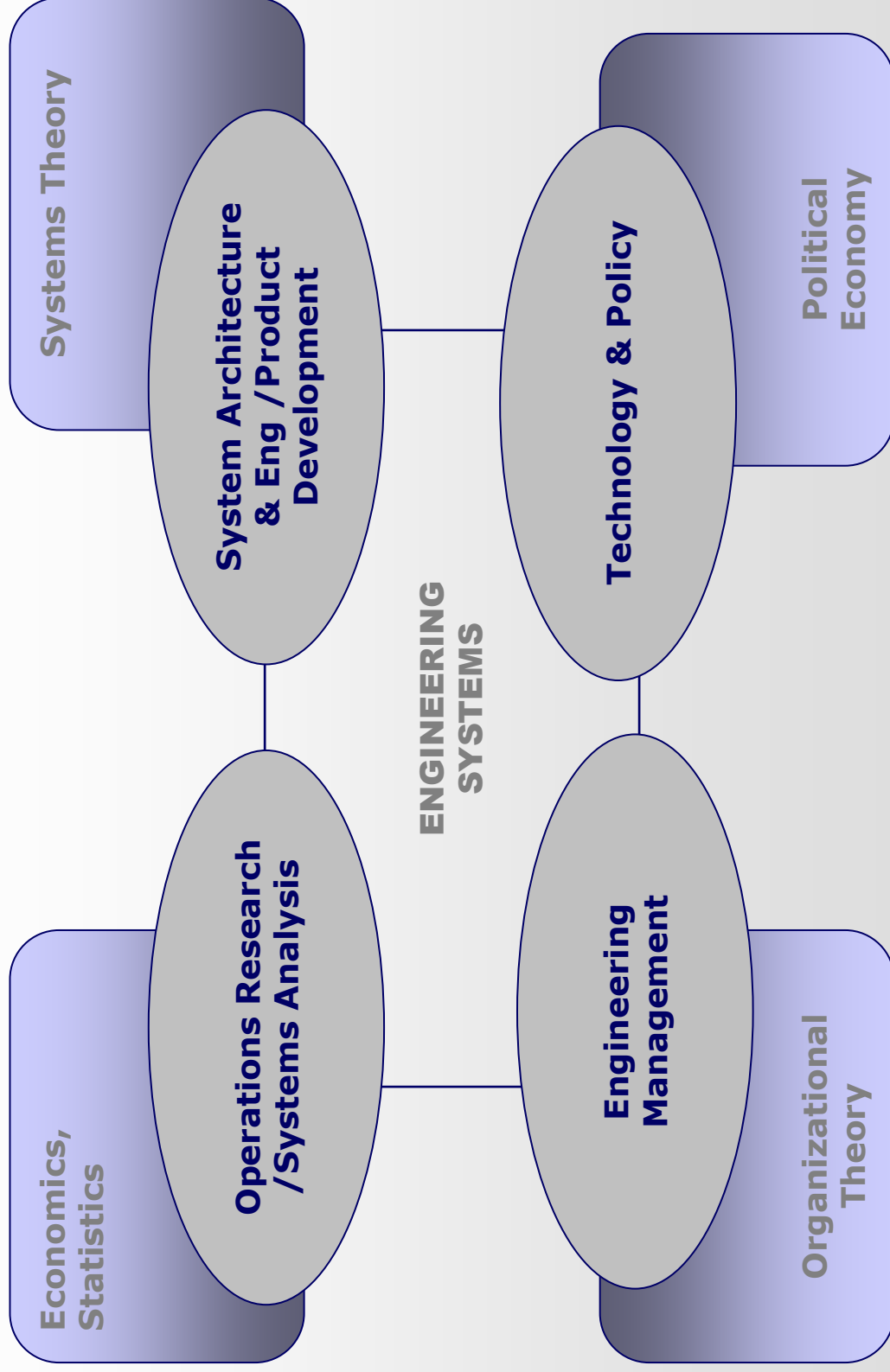
SYSTEMS ENGINEERING (Advanced)

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

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

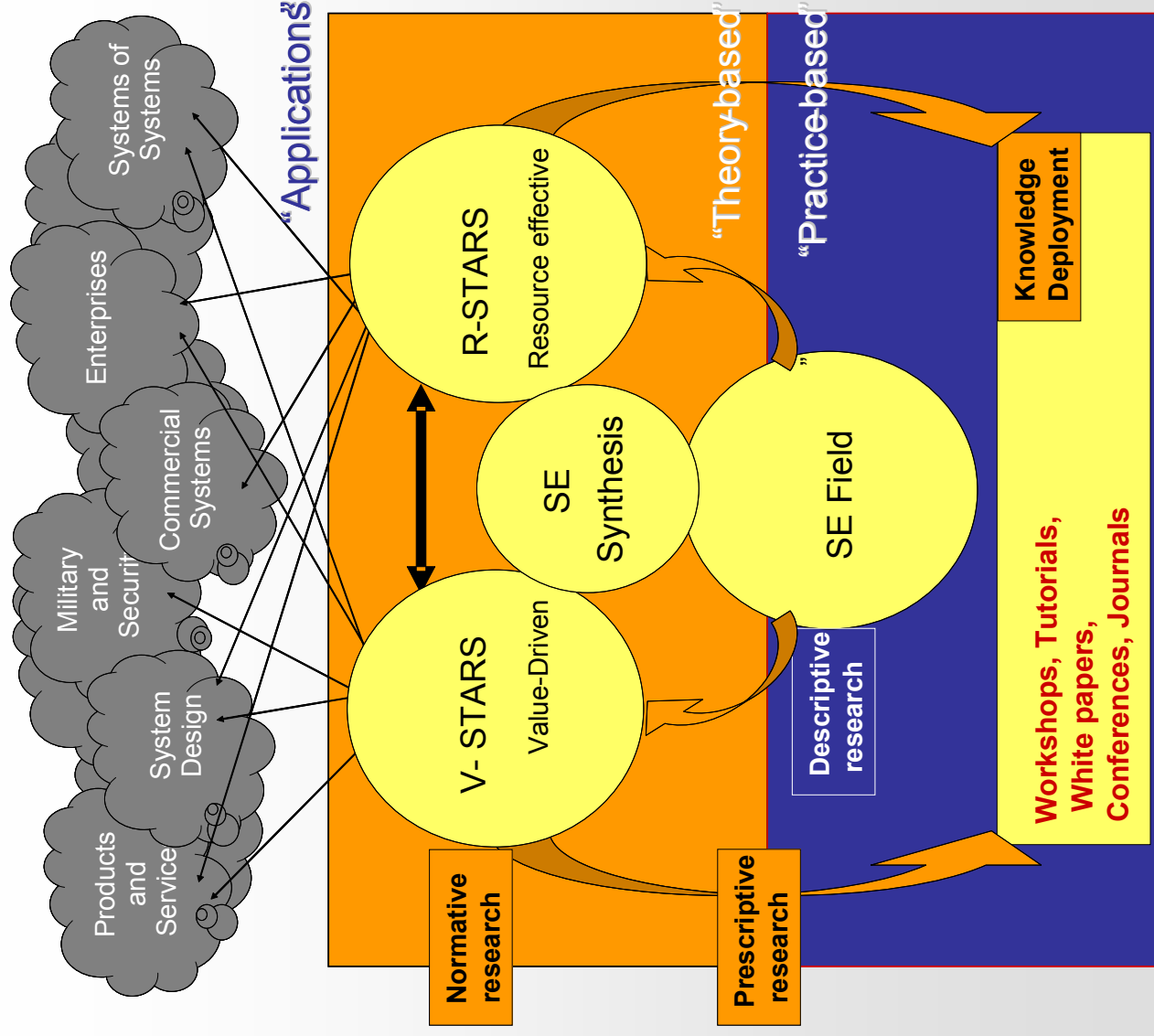


**3 Cambridge Center
NE20 – 388/343**

	<i>Traditional Systems Engineering</i>	<i>Advanced Systems Engineering</i>
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

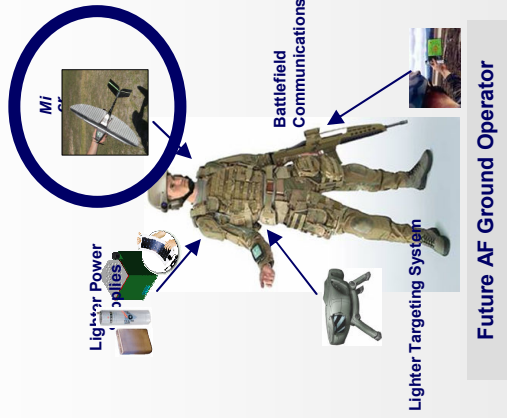


Research Portfolio (1)

SOCIO-TECHNICAL DECISION MAKING

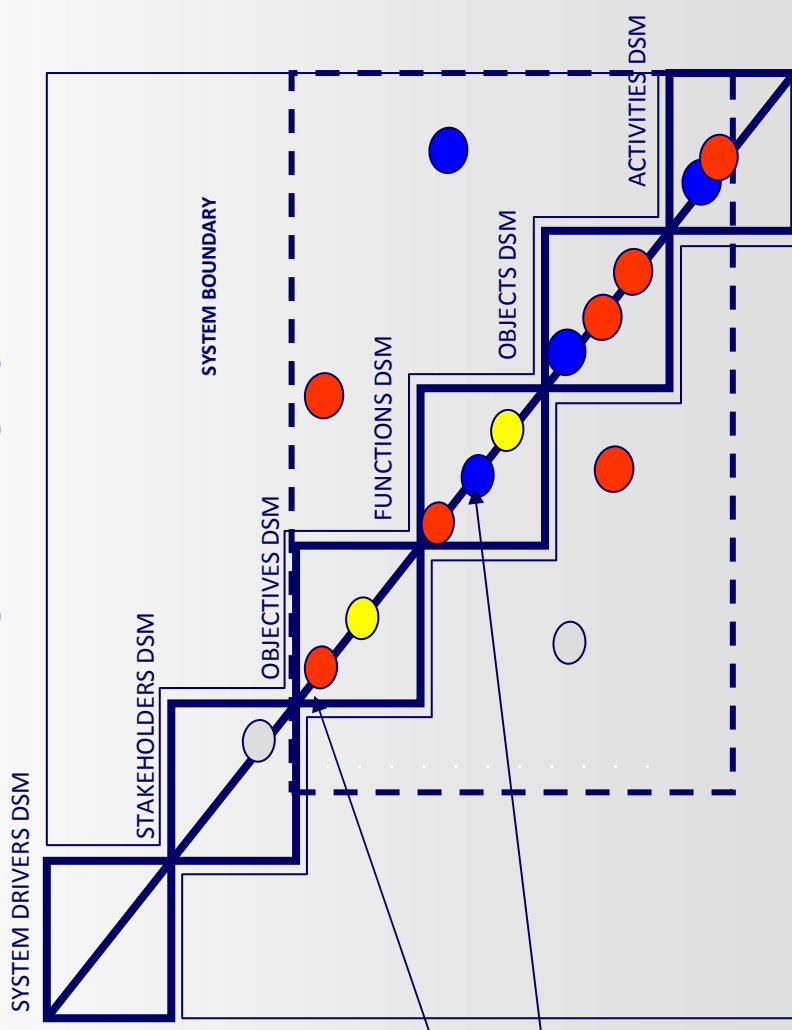
This area of research is concerned with the context of socio-technical systems. Based on a multi-disciplinary approach, decision making techniques are developed through the exploration of:

- 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 ?

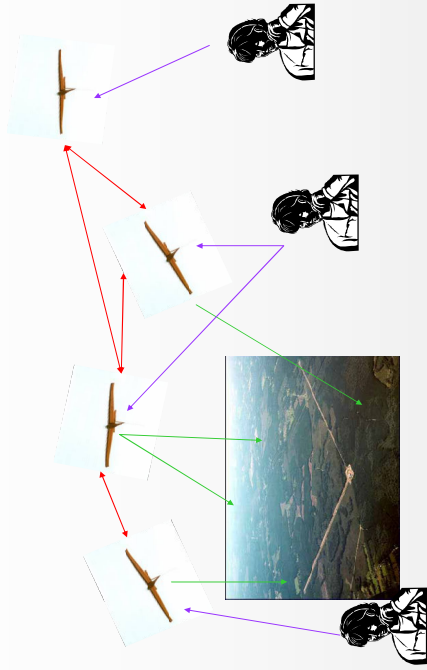
Engineering System Matrix (ESM)



high
low
Vulnerability to change?

Dr. Jason Bartolomei, PhD 2007

Uncertainty Management



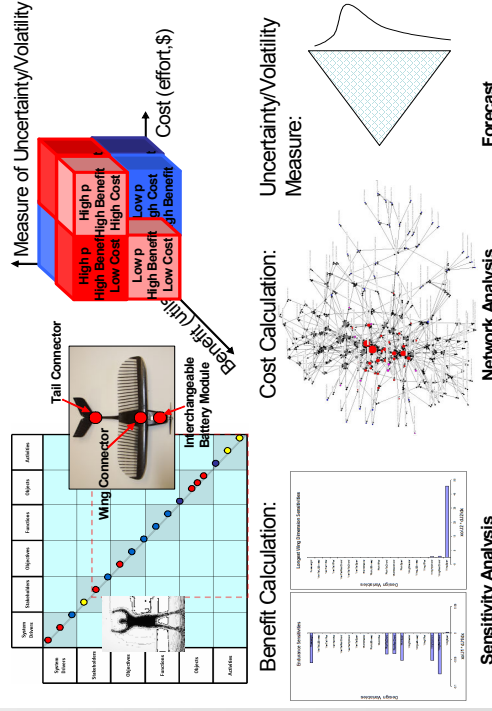
Real Options in Enterprise Architecture

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?

Prescriptive Analysis (Hot/Cold Spot Analysis)

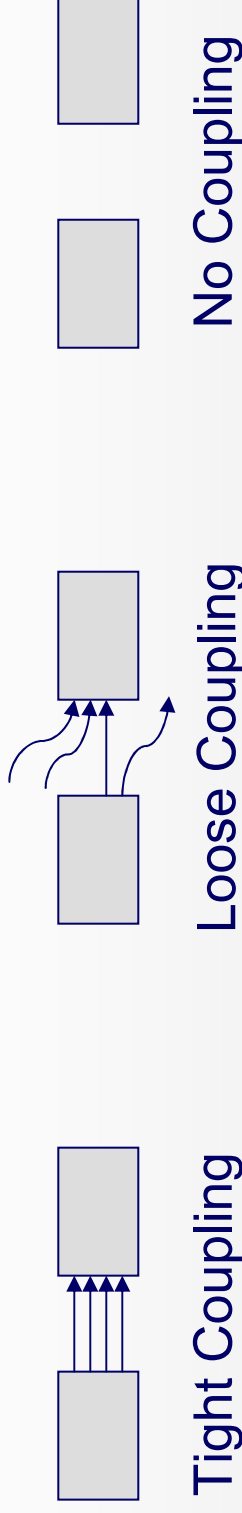


Engineering Systems Matrix for Real Options Analysis

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?



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

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.

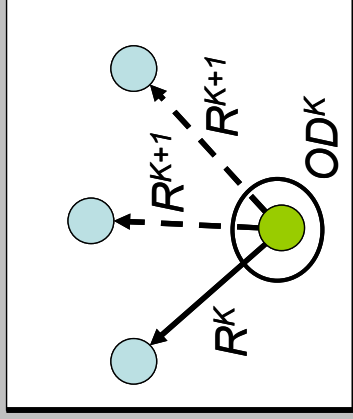
- Methods for dynamic multi-attribute trade space exploration
- Architecting principles and strategies for designing survivable systems
- Quantification of the changeability of a system design
- Techniques for the consideration of unarticulated and latent stakeholder value
- Taxonomy for enabling stakeholder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

How Can Changeability of a Design be Measured?

objective

Outdegree

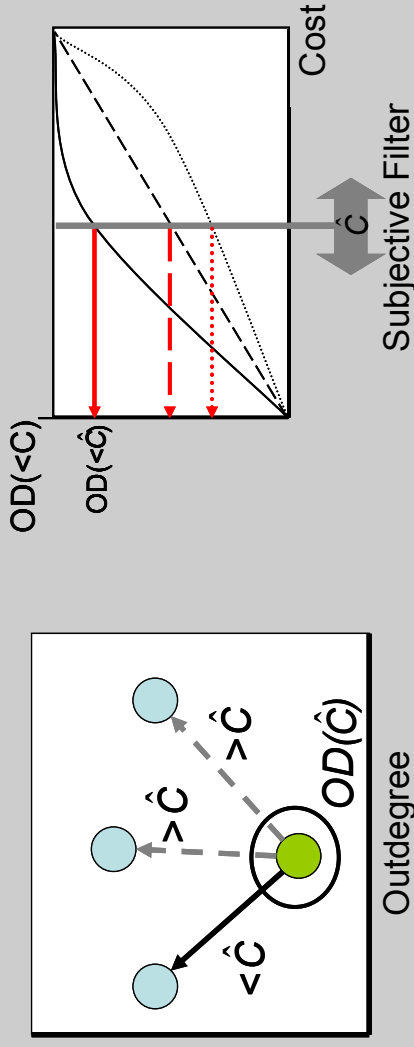
outgoing arcs from a given node



subjective

Filtered Outdegree

outgoing arcs from design at acceptable "cost" (measure of changeability)



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

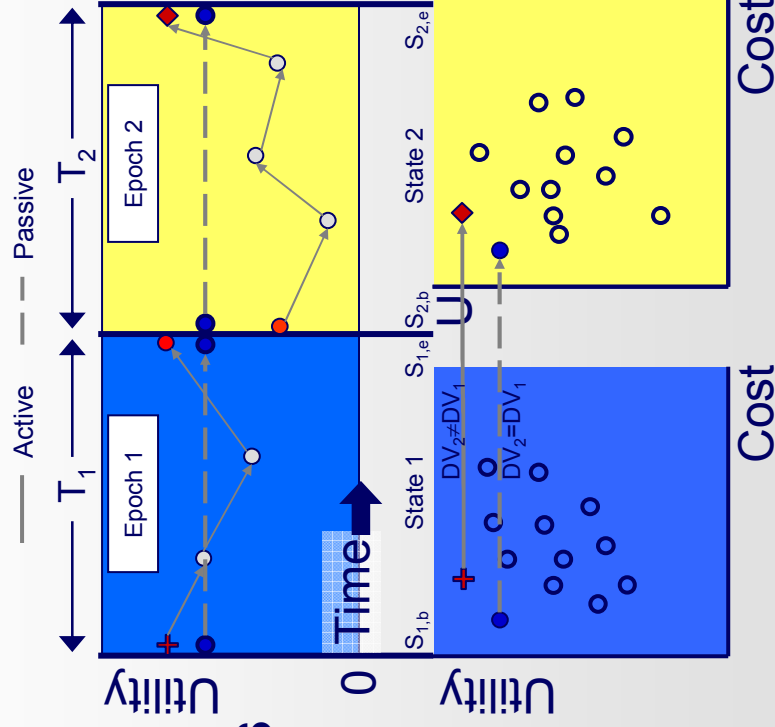
Dr. Adam M. Ross, PhD 2006, adamross@mit.edu

What Strategies Can be Used to Achieve Value Robustness?



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



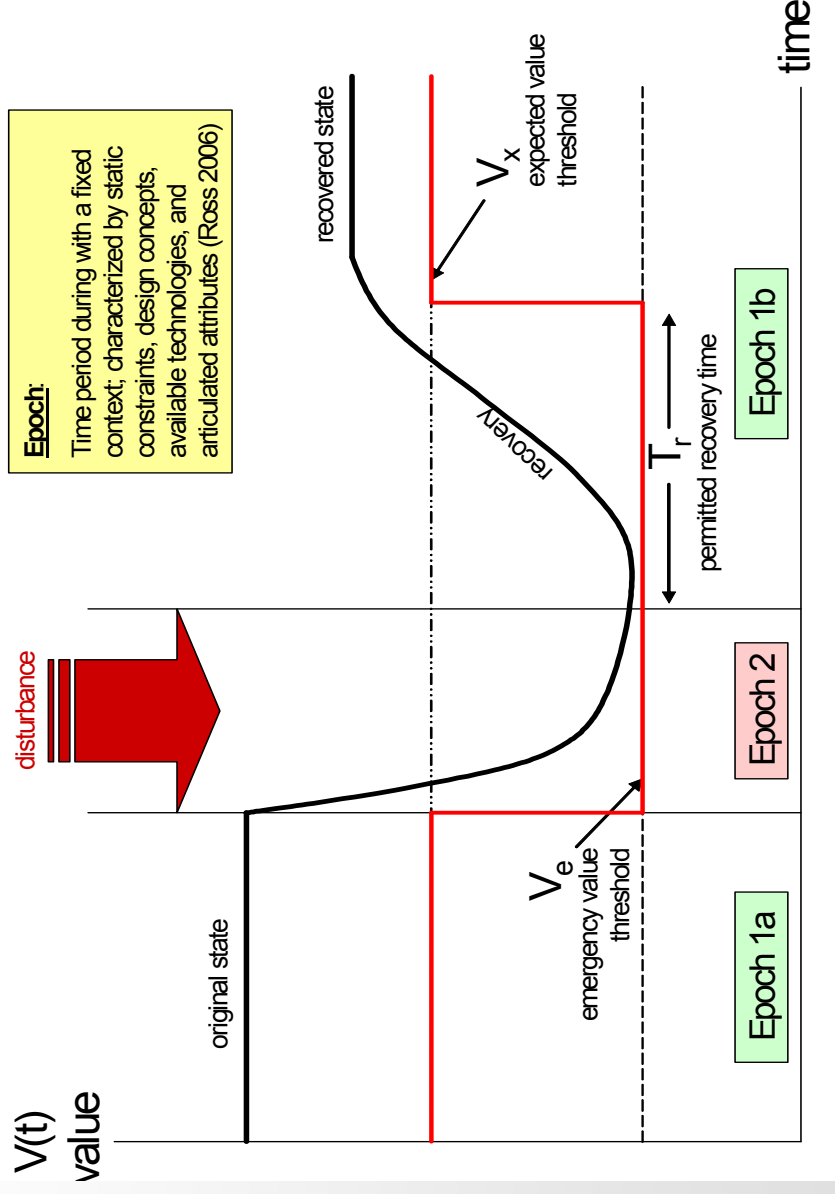
Value robust designs can deliver value in spite of inevitable context change

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

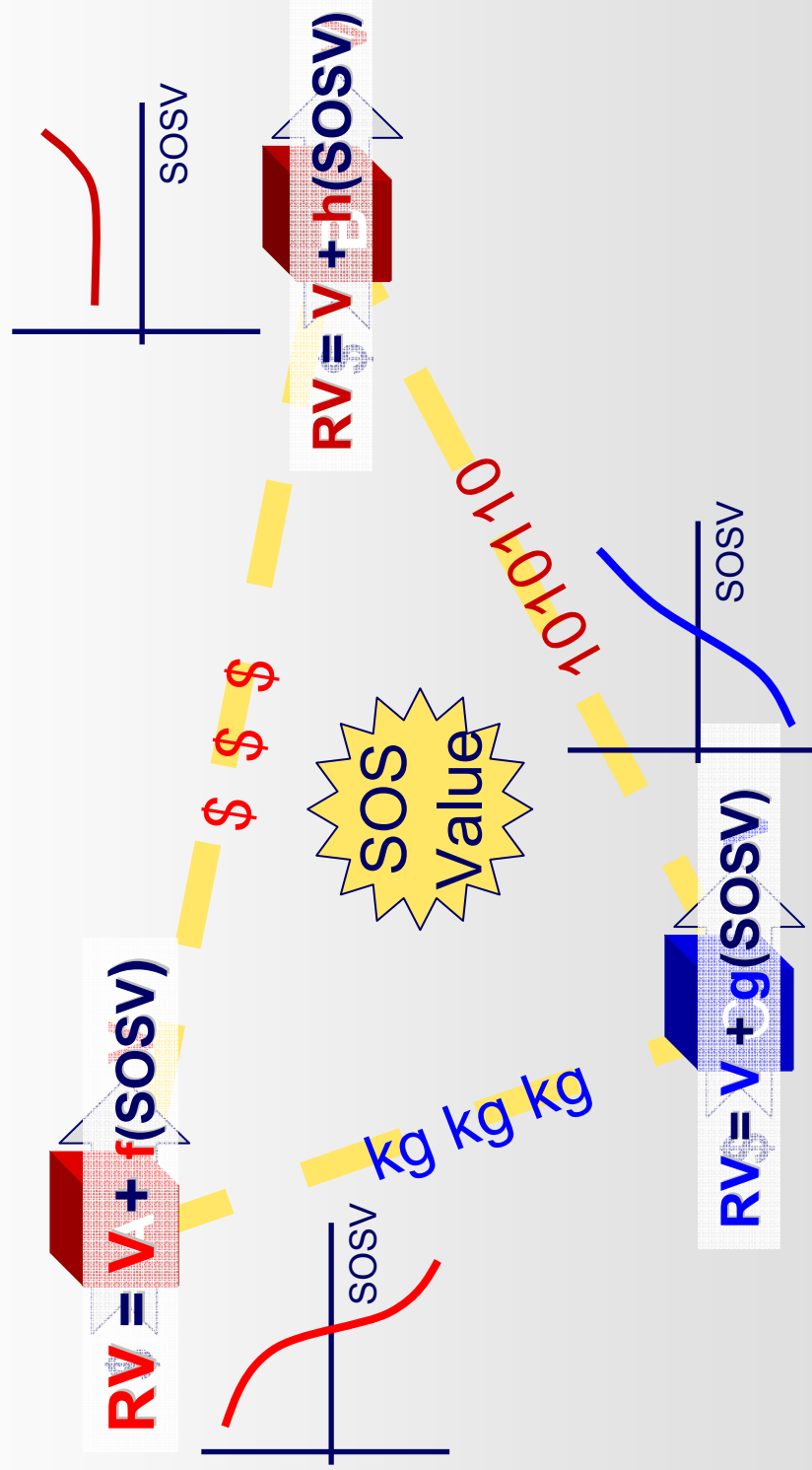


SYSTEMS ENGINEERING ECONOMICS

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 ?

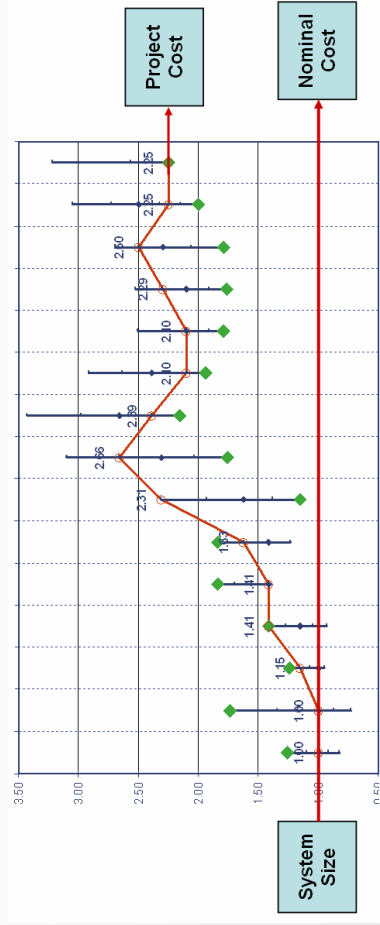


Nirav Shah, PhD Candidate, 2007

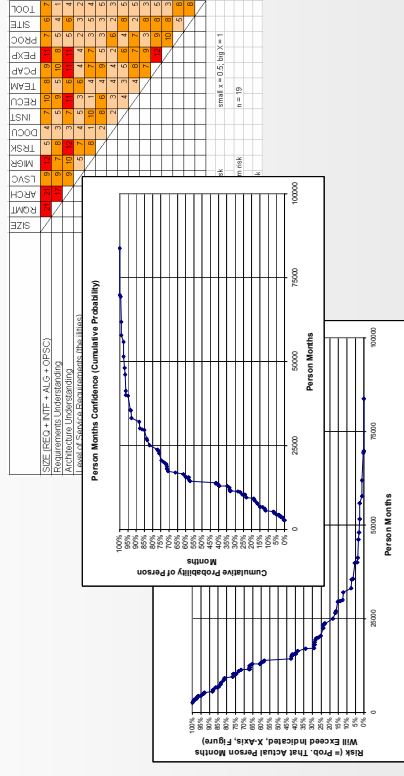
Models, Measures, and Leading Indicators for Project Success

Through Better Execution of Systems Engineering

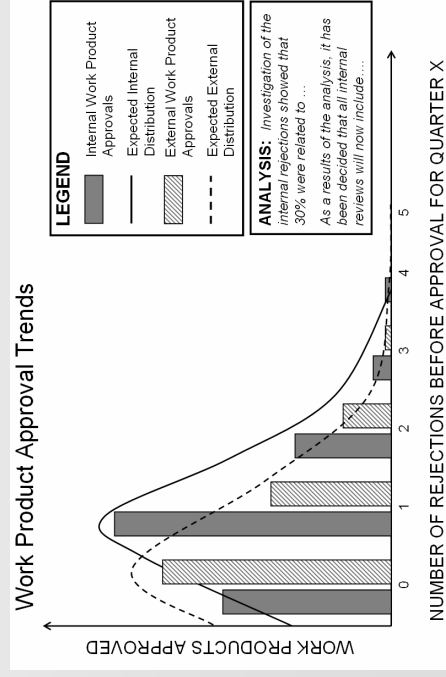
Cost and schedule modeling



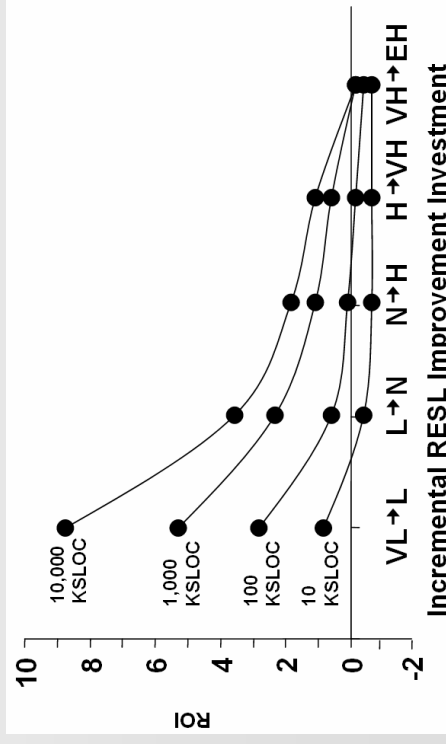
Project Risk Assessment



Leading Indicators for Performance



Systems Engineering ROI



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

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**

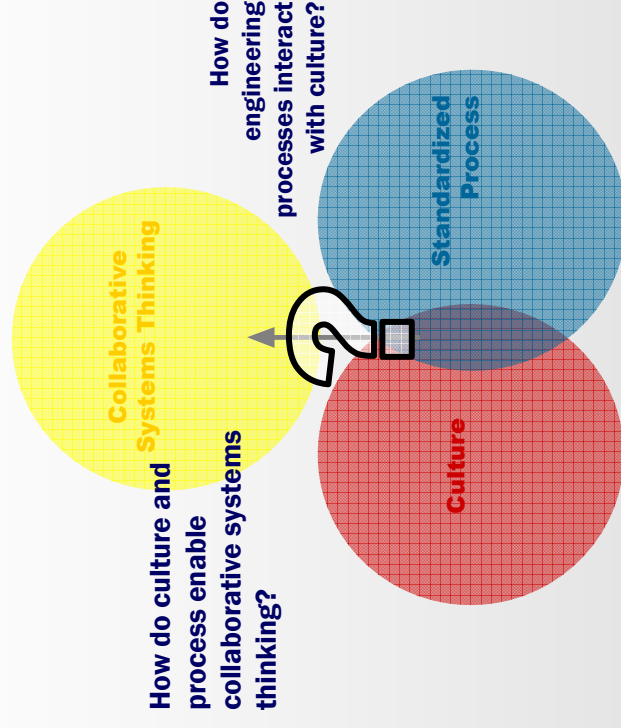
Collaborative Systems Thinking Aligning Culture and Standardized Process

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.

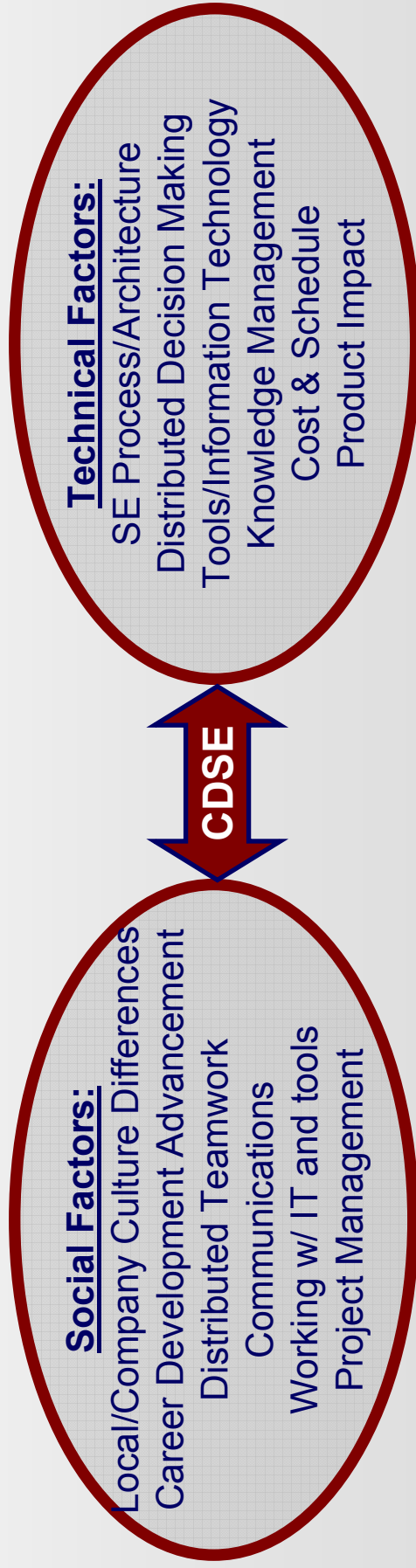


Collaborative Distributed Systems Engineering in the Aerospace Industry

Develop heuristics for successful CDSE resulting from case studies

Recommendations to overcome barriers to successful CDSE

Recommendations for future work in this area



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

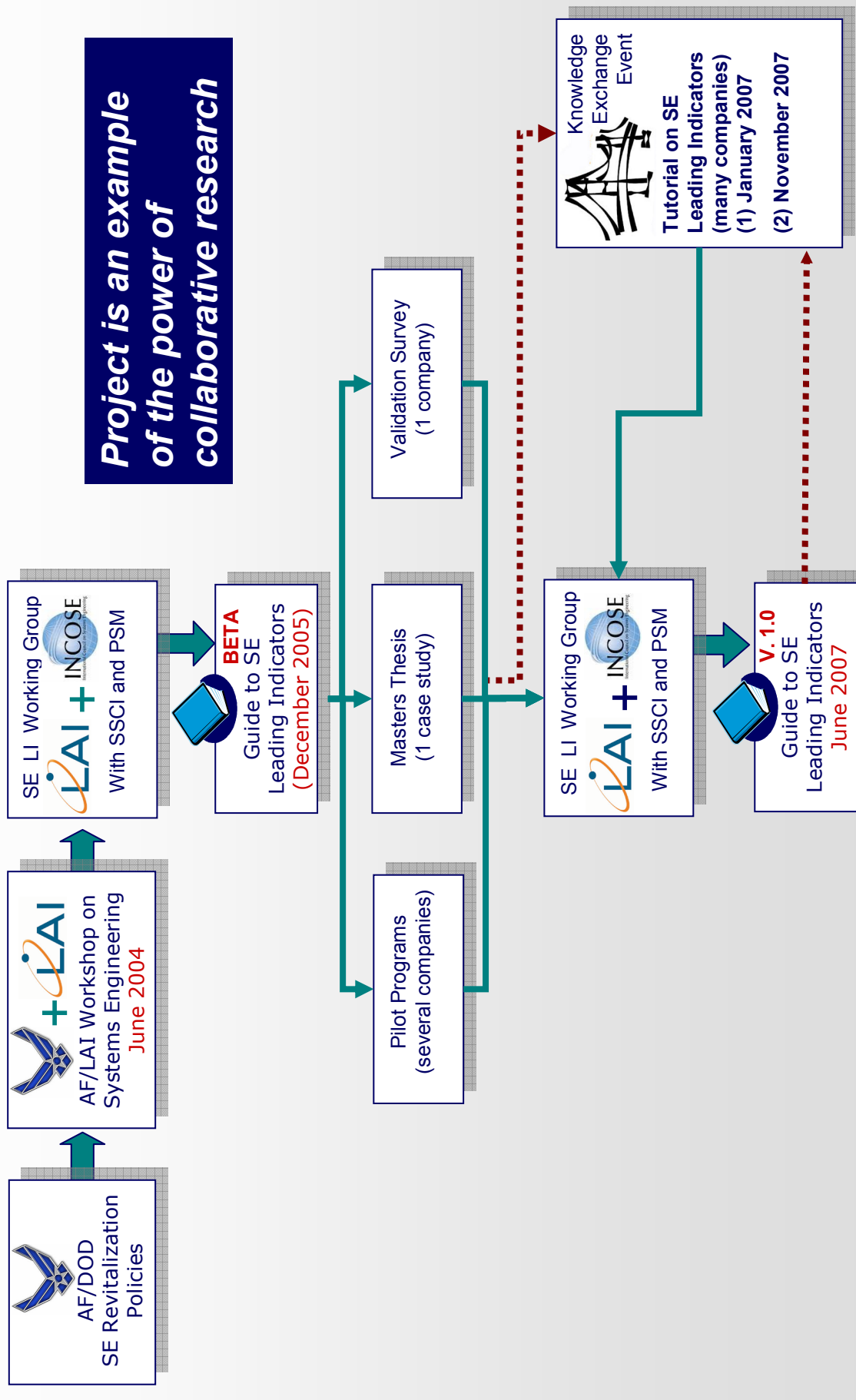
Additionally, we need more **cross cutting experiences for educators and practitioners alike**

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



Project is an example of the power of collaborative research

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

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Systems Engineering Leading Indicators Guide
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Systems Engineering:
The International Council on Systems Engineering, defines systems as: "an interdisciplinary approach and means to enable the..." [more>](#)



SEARI at MIT

Systems Engineering Advancement Research Initiative (SEARI) brings together a set of sponsored research projects and a consortium of systems engineering leaders from industry, government, and academia. SEARI is uniquely positioned within the [Engineering Systems Division \(ESD\)](#) at the [Massachusetts Institute of Technology \(MIT\)](#), a new kind of interdisciplinary academic unit that spans most departments within the [School of Engineering](#), as well as the [School of Science](#), the [School of Humanities, Arts, and Social Sciences](#), and the [Sloan School of Management](#). This setting offers a robust research and learning environment for advancing systems engineering to meet the contemporary challenges of complex socio-technical systems. SEARI has strategic relationships with several educational and research programs at MIT, including the [MIT System Design & Management Program \(SDM\)](#) and the [Lean Aerospace Initiative \(LAI\)](#) Research Program at MIT.

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY

News

Now Available: The Systems Engineering Leading Indicators Guide, Version 1.0

- ◊ [Full Announcement \(PDF\)](#)
- ◊ [Downloadable Guide \(PDF\)](#)

Purpose
Web portal for sharing research within SEARI, MIT, and systems community

seari.mit.edu

2007

SEARI Research Summit

October 16

MIT Faculty Club

Dynamic

SEARI Research Bulletin Published at End of Each Semester

Research Spotlight 1

Exploratory Research Studies: Best Practices in Collaborative Distributed Systems Engineering
research by: Doreine Iltis, S.M., Eng. Systems

Recent research has focused on collaborative engineering best practices in collaborative distributed systems engineering (CDSSE), focused on achieving major objectives. The first aim is to define successful CDSSE practices by examining how CDSSE practices and lessons they have learned. Successful CDSSE involves many factors: relevant are addressed in research: use of CDSSE and collaboration tools; leading and conduct of meetings; communication; timing of engineers; overcoming social and cultural

necessary for contractors to perform collaborative distributed systems engineering (CDSSE) over several years. The research studies have identified best practices that the design process of distributed design teams offer from those of traditional centralized design teams. However, many companies today are performing CDSSE 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 inter-company collaboration in SE presents a myriad of social and technological challenges that necessitate new and different SE methods for success. Best practices for CDSSE are currently unknown (or underdeveloped).



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.

In this inaugural issue of the SEA^{RI} Research Bulletin, it is worth reflecting on what motivates a research program, as well as our role in complementing the existing sponsored research consortium. During recent years, systems engineering has received increased focus and expanded its reach on a global scale. Many new university research programs have been developed in response to the demand for skilled engineers who can think about complex systems. As a systems consortium research program, we are interested in supporting individual sponsor's interest. The consortium research projects will address the broad

Static

SEA^{RI} News

Prof. Hastings Awarded Research Contract by Singapore DSTA

The purpose of this three-year project, initiated in September 2006, is to develop an analytical framework for representing a group of heterogeneous 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 Ismael Mousallem. An objective of the research is to identify places in a system architecture where real options can mitigate performance risk. Hastings, a



SEA^{RI} News

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 Valeri. 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. Pre-publication copies of the book are available to selected individuals affiliated with SEA^{RI} by contacting Dr. Valeri (valeri@mit.edu). For information on COSYSMO visit www.sea.mit.edu/cosysmo.

MITMITRE Joint Research Progress

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

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



Systems Engineering Advancement Research Initiative

QUESTIONS

<http://seari.mit.edu>

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