The Role of MDO in the Design for Complex Engineered Systems (DCES)

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Complex Engineered Systems
Role of MDO

- MDO has potential to play a pivotal role
- An enabler for DCES
- Need to understand issues associated with DCES
- Need to understand the opportunities on the horizon to adequately respond as a community
- Need to fully appreciate the origins and evolution of MDO
- How did we get here and what can we do in the future?
MDO Evolution

• 1960s:
  • Lucien Schmit – Introduces Structural Optimization

• 1970s:
  • Structural Optimization becomes more accepted (increase in computer power)
  • Motivation to address multidisciplinary issues

• 1980s:
  • MDO conceived – 1st MAO Symposium early 1980s
MDO Evolution

• 1988:
  • 2nd NASA/AF Symposium on MAO

• 1990:
  • 3rd NASA/AF Symposium on MAO, San Francisco, CA

• Foundational Question for MDO:
  • How do you know what to change when everything affects everything else?

• Growth in computational infrastructure facilitated emergence of MDO
Computer Revolution (Intel)
Computer Timeline

1980:
- HP-85 introduced
- IBM hires Bill Gates and Paul Allen to develop operating system – DOS
- IBM hires Microsoft to develop computer language versions for PC
- FORTRAN 77 created
- Star Wars: Empire Strikes Back released

1981:
- IBM released IBM PC with MS-DOS
- HP – first 32 bit chip
- Commodore VIC-20, world’s most popular PC
- Logitech launched
Computer Timeline

1982:
- Tron released – first movie to use computer generated special effects
- Autodesk released
- Commodore 64, with 64 kilobytes of memory
- First CD released by Phillips
- Apple – first company to hit $1B in PC sales
- AutoCAD released

1983:
- TIME nominates computer as ‘machine of the year’ – first non-human ever nominated
- ARPANET standardizes TCP/IP
- President Reagan orders GPS for civilian use
Computer Timeline

• 1984:
  • Apple commercial airs during Super Bowl XVIII
  • Macintosh introduced by Apple
  • 3.5 inch floppy introduced
  • Dell founded
  • IBM introduces EGA video card
  • Fred Cohen introduces concept of computer viruses for first time
  • Term cyberspace coined

• 1985:
  • First internet domain name registered – Symbolics
  • First Gamepad by Nintendo
  • Quantum Computer Services founded – later becomes AOL
  • First C++ reference guide released
Computer Timeline

- **1986:**
  - Microsoft listed on NYSE – Bill Gates becomes one of youngest billionaires in world
  - ibm.com comes online
  - Unisys founded

- **1987:**
  - Apple.com comes online
  - IBM introduces VGA

- **1990:**
  - Hypertext system created
  - ARPANET replaced by NSFNET
  - Internet Movie Database launched - IMDb
Concurrent Advances

- **1960s-1980s**: CAD tools released

- **1960s-1970s**: FEM codes developed

- **1970s-1980s**: CFD codes (2D and 3D)
A Perfect Storm

- Emergence of computers fostered innovation in structures, aerodynamics and other disciplines
- MDO evolved as computer capabilities evolved
- Goal of MDO in 1980s-1990s: Perform integrated system analysis and optimization
- Underlying presumptions
  - 1: Little need for humans – automation desired
  - 2: Results obtained under certainty
  - 3: If we knew all inputs and outputs of disciplinary subsystems we could optimize system
  - 4: A system optimization could be implemented
Evolution of Systems Engineering

- 1940s – Bell Telephone Laboratories used term
- 1960s – Apollo program successful example
- Growing complexity demanded systems approach
- 1990 – NCOSE founded
  - 1989 GD hosts meeting at UCSD to discuss lack of qualified engineers who appreciated systems thinking
  - 1990 Boeing hosts second meeting – adopt charter
  - 1991 Aerospace Corporation hosts meeting
NCOSE Issues

• General
  • How do you define systems engineering?
  • What is a systems engineer?
  • Who is a good systems engineer?
  • Is it system or systems engineering?
  • Difference between systems engineering, design, integration and management
  • Systems engineering lacks society, journals, and stature.
NCOSE Issues

• **Process Related**
  • Dealing with complexity is a difficult task.
  • Products need more optimization.
  • Is systems engineering a philosophy or a discipline?
  • What is the role of systems engineering in a product life cycle?
  • Benefits of systems engineering need to be documented.
  • How do you measure the health of the systems engineering process?
  • Process may be application-specific.
NCOSE Issues

- **Product Related**
  - Need to optimize requirements, designs, and products.
  - How to manage and trace requirements.
  - Operational concepts lacking.
  - Lack of tools and automation to support requirements development.
NCOSE Issues

• Program Related
  • Systems engineering is a people problem.
  • Systems engineering not used to manage the program, only the product.
  • Administrators and managers do not realize need for systems engineering.
  • Organizations and customers inhibit proper use of systems engineering.
  • Too much specialization; specialty integration poor.
  • Interface definition poor.
  • Relationship between systems engineering, concurrent engineering, and TQM.
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MDO and SE

- MDO and SE took divergent paths to attack the same problem
- MDO largely looked at research issues and treated MDO as an emerging research discipline
- SE pursued largely looked at practical issues in application and process – guiding practice
- Today, neither SE nor MDO is able to solve the very problem they were developed to solve
  - What are the research challenges in DCES?
Complex Aerospace Systems

Historical schedule trends with complexity

Design for eXtreme Systems–DXS
Designing for the edge ... and beyond
Motivation for Changing Status Quo

• Three simultaneous wars, resulting in staggering costs per day

1) Iraq** $180 Million per day

2) Afghanistan** $110 Million per day

3) Stupid Design* >$150 Million per day

* Losses due to cost overruns, delays, and system cancellations (mostly due to cost overruns and delays), as of three years ago

** Averaged over multiple years, as of three years ago
• *The Collapse of Complex Societies*: Joseph Tainter (1988) – collapse of Mayan civilization and Roman Empire
• Used complexity theory, network theory, energy economics to conclude they ‘out-complexed’ themselves into extinction
Some Characteristics of LSCES

- High Costs and Risks
  - One system may cost tens of millions or billions of dollars
  - Failures typically have significant local, national or often international impacts
  - Mistakes are extremely costly (often $M & years delay)
- One complex system typically must *precisely* interact with another
  - Fighter aircraft on an aircraft carrier
  - Need adaptable interoperability -- interfacing systems will change (systems in use for decades)
- National governments and defense often involved, even with private ventures
Typical Organizations

- Size: 100s to 1000s teams involved
- Dispersed: Rarely “under one roof” or in one location
- Multiple Entities: Multiple companies, bosses, incentive systems
- Multiple Interfaces: Can be over 500,000 and largely uncontrollable
- Bureaucracy: Most common structure
How Can We Design LSCES?

- Complexity of the systems seriously challenge the design enterprise
- No one person can understand the system – requires collective understanding
- SE decomposes and recomposes – but there are inherent interactions that are compromised
- There is no system objective function or risk preferences
NSF* - Background

- Workshop Series on DCES
  - META (DARPA/NSF) – December 2009
  - Workshop on Engineering Systems Design (Collopy/Deshmukh) – Feb 2010
  - Design of Large-scale Complex Systems (Collopy) – Sept 2010
  - The Future of Multidisciplinary Design Optimization – Advancing the Design of Complex Systems (Simpson/Martins) – Sept 2010
- Special Session MAO Conference – Sept 2012
- Engineering and Systems Design/System Science at NSF

*The views and opinions expressed are mine and in no way reflect those of the National Science Foundation*
Systems Engineering: Two Views

Fielding an elegant design

- Produces the intended result
- Both robust and efficient
- Generates the minimum of unintended consequences

Michael Griffin

There is no way MDO can be implemented as originally conceived in the traditional SE view
A “Design” View of Systems Engineering

Fielding an elegant design
• Works as intended
• Both robust and efficient
• Generates the minimum of unintended consequences

• Link research, design, systems engineering, operations, manufacturing, disposal?
• Address uncertainties? Address ambiguities?
• Hunt down and mitigate problematic interdependencies?
Complex Engineered Systems

- Some methods, processes and tools used daily are demonstrably flawed (violate established/accepted theory)
- With requirements, we don’t know when/if we have a ‘best’ system or product
- We can’t verify that our methods, processes and tools are dependable and sound, and can be used for the system we need to design
- We need an underlying theory and framework that enables this
Science of Design for LSCES

- What are the hallmarks of such a science*?
  - Use correlative thinking (e.g. A regularly follows B in controlled experiments)
  - Seeks empirical confirmations and disconfirmations
  - Practitioners care about evaluating theories in relation to other theories
  - Uses highly consilient (i.e. explains many facts) and simple theories
  - Progresses over time, developing new theories that explain new facts

*Thagard, Computational Philosophy of Science, 1993
Foundations that Exist

- Physics and Math-based
  - Multidisciplinary Design Optimization (MDO)
  - Modeling and Simulation
  - Uncertainty Representation and Propagation
  - Complexity Science

- Social Theory
  - Decision Analysis
  - Game Theory
  - Social Psychology
  - Cognitive Science
  - Organization Theory
Four Key Opportunities

• 1 - Defining the System Objective – What do you really want it to do?
• 2 - Understanding the Implications of the Inherent Interactions – from physics, components, people, organizations, tasks – not just multidisciplinary but interdisciplinary
• 3 - Communicating the System Objective
• 4 - Decision-making and Sense-making with Ambiguity and Uncertainty
1 - Defining the System Objective

- One of the most critical and challenging aspects of problem formulation for LSCES (tend to assume objective already identified)
- Need to spend time up front on understanding the need (problem formulation)
- What happens when this isn’t captured correctly or when the scope is unrealistically large?
  - Possible project cancellation
  - Lack of customers
  - Loss of significant $ and time
  - Mission failure
  - ...

1 - Defining the System Objective

- Examples of Projects Gone Astray
  - Death Star (fiction, but a great example)
  - U.S. Army SLAMRAAM
    - > 10 years, >$3 B, 0 Orders = Cancellation
    - What they really needed was a shorter range system for enemy helicopters
1 - Defining the System Objective

- Science of Design for LSCES should enable assurance that the system is an accurate reflection of the objective and that it work as intended
- Research opportunities (combining social and technical areas):
  - Relationship between desired objective and procurement
  - Policy impacts on objective choice
  - Relationship of organizational risk, technological readiness, mission success, profit, etc. on objective choice
2 - Inherent Interactions

- Interactions exist not only for the physics, but for organizations, teams, people, components, tasks, etc.
- How can we understand the impacts associated with these interactions?
- What are the existing theories and disciplines from which we can draw for our Science of LSCES?
  - Many rich opportunities in physics-based and social-based disciplines
2 - Inherent Interactions

• Physics-based Approaches
  • Modeling and Simulation
    • Challenges: Seamless fidelity across scales, interoperability, how much fidelity required?
  • MDO
    • Challenges: Limitations of SE framework, incorporation of uncertainty, human-in-the-loop, organizational impacts
2 - Inherent Interactions

- Complexity Science
  - Challenges: relevance of natural/biologically inspired methods to engineered systems, emergent behavior as a result of humans in the process, what does emergence mean for LSCES, will simulations be meaningful?
2 - Inherent Interactions

- Social/Organizational Approaches
  - Organization Theory, Cognitive Science, Behavioral Psychology, Sociology, Social Network Science
  - Challenges: Creation of High Reliability Organizations (HROs), Impact of organizational structure on outcome, impact of incentive structures on outcome, team construction and communication, etc.
3 - Communication of System Objective

- There is a need to enable all participants – at all levels and stages – to understand the impact of their decisions on the system objective(s)
  - How can this happen with requirements flow-down?
  - Would a value-driven approach be a feasible alternative?
Value-Driven Design (VDD)

- Requirements are often arbitrary and limit the design space without identifying the ‘objective’
- Requirements are propagated down without meaning
- VDD offers a value-based alternative for decomposition
- A value statement is created that captures critical design preferences for entire system
- The value statement can be propagated to all levels to enable trades across groups

*Embracing VDD will enable MDO to be implemented at a system level*
3 - Communication of System Objective

• Example of program challenged by over-requirements and inability to perform trades
  • Marine’s Expeditionary Fighting Vehicle
    • Needed to storm beaches from as far away as 25 nautical miles at high speed (29 mph)
    • Cost and time issues
    • Experts questioned validity of req’s
    • No system objective –
      • Low-level trades extremely difficult
3 - Communication of System Objective

- Value-Driven Design (VDD) as an Alternative
  - VDD would enable trade-space analysis across layers and stages
  - VDD could facilitate easier adoption of system level MDO strategies
  - Challenges: would require change to existing acquisition system, would change the design environment, question as to whether value statements can be constructed for LSCES (scale), value statements for mission agencies vs. industry, risk tolerance across levels, …
3 - Communication of System Objective

• Social Science fields such as Social Network Analysis and Positive Organizational Scholarship (POS) can contribute to:
  • Quality and architecture of communication pathways
  • Enabling employees to understand their role in the company’s mission and success
• Challenges are to be able to identify how organizational practices can impact design – and avoid this
4 – Decision-making and Sense-making with Uncertainty/Ambiguity

- A key need is the ability to fully understand the situation and then make effective decisions, in the face of ambiguity and uncertainty
  - Ambiguity: a confusion issue requiring substantial communication
  - Uncertainty: ignorance issue when outcome can’t be precisely predicted
- Sense-making is resolving ambiguity
- Decision-making is making a decision in the face of uncertainty
4 – Decision-making and Sense-making with Uncertainty/Ambiguity

- Challenges for Sense-making: Social sciences have much to offer (e.g. cognitive science, social psychology, etc.) but in what ways can the theories/methods/tools be transitioned for use in LSCES
- Decision Analysis – provides a structure that models an individual’s decision under uncertainty
  - Game Theory
  - Mechanism Design
- Challenges and research opportunities: Can DA be scaled for LSCES, how easy would it be to implement, relationship to emergent behavior of CS, role for VDD/MDO
Systems Renaissance

- We are on cusp of a Renaissance in Systems Engineering
- The MDO community is well-posed to help guide future development
- The MDO community should look at this as an opportunity and be willing to embrace the larger challenges
- Where will we go from here?
Thank you!
Please contact me with any questions

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