Design for Affordability in Complex Systems and Programs Using Tradespace-based Affordability Analysis*

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Systems Engineering Advancement Research Initiative

SEArI is positioned within the MIT Engineering Systems Division and the MIT SSRC

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

Current/Past Sponsors:

Past Performance
• More than decade of research in value-driven design and tradespace exploration
• Successful research across multi-year projects
• Numerous publications and courses

Leadership
• Dr. Donna Rhodes
  • Director, Principal Investigator
• Dr. Adam Ross
  • Lead Research Scientist
• Prof. Daniel Hastings
  • Faculty Strategic Advisor

Technical Team
• 8 Graduate Research Assistants
• 4 Affiliated Graduate Students
• 6 Undergraduate Students
• 3 Affiliated Researchers
SEArri Research Seeks to “Change the Picture”

ESSENTIAL ELEMENTS

- Appropriate **competencies** in workforce
- Advanced **methods** for anticipatory analysis, decision making, and architecting
- Enabling enterprise strategies and model-based **environments**
## Building Anticipatory Capacity

<table>
<thead>
<tr>
<th>COMPETENCIES</th>
<th>METHODS</th>
<th>ENVIRONMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ability to think deeply about ‘systems in context’</td>
<td>Perform dynamic tradespace exploration</td>
<td>Computing power/toolsets to enact methods</td>
</tr>
<tr>
<td>Enhance ability to think about ‘systems in time’</td>
<td>Model-based approach to derive alternative futures</td>
<td>Support multi-stakeholder negotiations in tradespace exploration</td>
</tr>
<tr>
<td>Use situational leadership to make decisions at multiple system levels</td>
<td>Apply methods at varying levels of fidelity</td>
<td>Enable comprehension of complex data sets</td>
</tr>
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</table>

Agenda

- Motivation
- Defining Affordability as an Ability
- Affordability Analysis using Tradespace-based Methods
- Space Tug Case Study
- Results of Single Epoch, Multi-Epoch and Single Era Analysis
- Conclusion & Future Work
Motivation

• The architecting of complex systems and programs faces much uncertainty
  – Massive cost overruns, schedule delays, failures to anticipate future requirements and ultimately unrealized capabilities (Cordesman and Frederiksen, 2006)
  – Weaknesses in initial program definition and costing (IDA, 2009)

• Leads to rising costs and schedule slippages

F-35 Joint Strike Fighter and Ballistic Missile Defense System
Motivation

- **DESIGN FOR AFFORDABILITY**
  - Account for performance, cost and schedule parameters

- **Affordability mandated as a requirement** at all milestone decision points of program development (Carter, 2010a, 2010b)

- Affordability has emerged as a high priority concept in systems engineering (SE) that directs early stage design process towards greater cost effectiveness and schedule effectiveness

(Tuttle and Bobinis, 2012)
The Affordability Paradigm

- Carter 2010 Memorandum and Better Buying Power Initiative – “Mandate Affordability as a Requirement” for defense acquisition
- Many tools and frameworks have been proposed to integrate affordability analysis with existing SE methods
The Affordability Paradigm

- Current processes have been limited to static tradeoffs of systems with performance and costs in current operating environments, or in single point futures
- Lack of consensual definition and guiding principles for affordability analysis in the SE community
- Failure to explicitly capture dynamic aspects of system or program and its changing environment over its lifecycle
- Need to have a complementary set of constructs and methods for enabling the affordability paradigm
Affordability as an Ility

• Consider **affordability as an ility**, which is a system property that manifests and determines values after a system is put into initial use (de Weck, Ross and Rhodes 2012)

• Affordability can be treated as an ility that drives the design of more affordable yet technically sound architectures

• It emerges at the nexus of decisions within changing contexts (i.e. what is “right” decision over time?)

• This suggests *tradespace exploration* methods would provide insights in the search for affordable designs

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**Affordability is the property of becoming or remaining feasible relative to resource needs and resource constraints**

(Wu, Ross and Rhodes 2013)
Affordability as an Ility

Affordability is the property of becoming or remaining feasible relative to resource needs and resource constraints

- **Resource needs**: Set of resource requirements elicited from stakeholders (tend toward zero, but some preferences w.r.t. more)
- **Resource constraints**: Statements of restrictions on these requirements that limit range of feasible solutions, externally imposed
- **Goal of Affordability Analysis**: Identify solutions that remain feasible throughout or for a large part of the system lifecycle

(Wu, Ross and Rhodes 2013)
Tradespace-based Methods

- Affordability analysis can be conducted using *tradespace exploration* (TSE)

  - TSE (Ross and Hastings 2005):
    - Model-based investigation of many design alternatives
    - Avoiding premature fixation on point designs and narrow requirements


- EEA (Ross and Rhodes 2008):
  - Model-based investigation of many alternative futures
  - Promotes exploration of impact of short run and long run uncertainties on system/program success
Methodology for Affordability Analysis

1. Use Multi-Attribute Tradespace Exploration (MATE)

2. Use Multi-Attribute Expense (MAE) function instead of “cost”

3. Use constraint levels to determine affordable solution region

4. Select preferred designs from region

5. Use Epoch-Era Analysis (EEA) to account for the evolution of preferred design(s) over time
Multi-Attribute Tradespace Exploration data flow for affordability analysis
(Wu, Ross and Rhodes 2013)
MAE for Affordability

- **Use Multi-Attribute Expense (MAE) instead of “cost” in TSE**
- Break down “cost” into “different colors of money”
- MAE is similar to MAU function by (Keeney and Raiffa 1993)
- A dimensionless, non-ratio scale metric

\[ KE(X) + 1 = \prod_{i=1}^{N} [Kk_iE_i(X_i) + 1] \]  \hspace{1cm} (Diller 2002)

- Quantified on a 0 to 1 scale:
  - 0: Minimal dissatisfaction
  - 1: Complete dissatisfaction
- **Modify MATE to compare MAE against MAU for affordability analysis**
Constraint Levels

- Constraint levels reflect external constraints that are imposed on stakeholders
- Establish constraint levels for minimum utility and maximum expense
- Find derived minimum expected expense
- Area bounded by three constraint levels is the affordable solution region

Defining the affordable solution space using external constraint levels for a fixed context (Wu, Ross and Rhodes 2013)
Methods are scalable to various layers of application
EEA for Affordability

- EEA discretizes system lifecycle into **epochs** (time periods with fixed context and needs) and **eras** (ordered sequence of epochs)
- Consists of single epoch, multi-epoch, and single era analyses
- Permits **resource-centric approach** for evaluating system design concepts

(a) Original Epoch-Era Analysis Diagram by Ross and Rhodes 2008; (b) Modified Epoch-Era Analysis diagram for Affordability Analysis (Wu, Ross and Rhodes 2013)
Summary of Method

- Use **MATE**
- Use **MAE** instead of cost
- Construct tradespaces bounded by MAU and MAE
- Establish **constraint levels** in tradespaces
- Determine **affordable solution region**
- Select preferred designs from region
- Apply **EEA** to allow for structured evaluation of design alternatives across many alternative futures
- Complete affordability analysis by ensuring that a potential design’s cost, schedule and performance parameters are feasible across the entire lifecycle
Application to Space Tug

- **Space Tug**: a single general-purpose space transportation vehicle designed to transfer space systems between orbits
- **Why Space Tug?** A simple case study that has been validated and used for concept evaluations in many MIT SEAriri theses and publications
- **Conduct a** **System and Program** level analysis
System Level Analysis

- System design variables

<table>
<thead>
<tr>
<th>Manipulator Capability</th>
<th>Propulsion Type</th>
<th>Propellant Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>Storable Bipropellant</td>
<td>30</td>
</tr>
<tr>
<td>Medium</td>
<td>Cryogenic</td>
<td>100</td>
</tr>
<tr>
<td>High</td>
<td>Electric</td>
<td>300</td>
</tr>
<tr>
<td>Extreme</td>
<td>Nuclear</td>
<td>600</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1200</td>
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<tr>
<td></td>
<td></td>
<td>3000</td>
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<td></td>
<td></td>
<td>10000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>30000</td>
</tr>
</tbody>
</table>

Total of 4 x 4 x 8 = 128 possible designs
### System Level Analysis

- **System Attributes**

<table>
<thead>
<tr>
<th>Mass Capability</th>
<th>Transfer Speed</th>
<th>Delta-V</th>
</tr>
</thead>
<tbody>
<tr>
<td>A function of manipulator capability</td>
<td>A function of propulsion type</td>
<td>A function of propulsion type which affects $I_{SP}$</td>
</tr>
<tr>
<td>Contributes to overall dry mass</td>
<td>Simply defined with only 2 levels: “Slow” (Level 0) or “Fast” (Level 1)</td>
<td>A function of wet mass which is determined by the amount of propellant</td>
</tr>
</tbody>
</table>

- **MAU calculated as the weighted sum of the above 3 attributes.**
System Level Analysis

• Consider “Development Cost”, “Launch Cost” and “Development Schedule” as Expense Attributes

• Development Cost is calculated as a function of dry mass: Wertz and Larson (2011) estimates $475/kg for development cost of small satellites in FY2010 dollars.

• Baseline development schedule of 4, 8, 12, 18 months corresponding to Low, Medium, High, Extreme Capabilities

• Multiplicative factors between \(x1.5\) to \(x3.5\) used for schedule in developing Storable Bi, Cryo, Electric and Nuclear Propulsion types
Defining Epochs and Eras

• New Epoch variable of Technology Level: Present or Future

• Future technology gives higher $I_{SP}$, lower schedule, higher wet mass launch cost and higher dry mass development cost

• Space Tug to perform 8 different missions:
  – 8 different epochs with 8 different SAU functions for each of the 5 performance attributes and 8 different SAE for each of the 3 expenses

• 1st era: 8 different epochs with Present technology

• 2nd era: 8 different epochs with Future Technology
System Level Analysis

Epoch 1 “Present”

Epoch 1 “Present”

Epoch 2 “Present”

Epoch 2 “Present”

Epoch 5 “Present”

Epoch 6 “Present”

Epoch 6 “Present”
Hypothetical Problem: Due to exogenous disturbances such as solar flares and incoming asteroid debris, many American satellites in Earth orbit have been misaligned from their original orbits. More than 1 pair of misaligned satellites may collide into each other in the following 5 years even after the quickest launch time possible for a Space Tug. A single Space Tug will not be capable of realigning all satellites without incurring any risk of collisions. NASA needs to find a quick, effective but affordable solution to realign these satellites in order to prevent any collision and increase in orbital debris.

Proposed Solution:

Commence on a Space Tug program to develop 2 Space Tugs!
Program Level Analysis

Modified MATE Flow Chart

- Determine Key Decision Makers
- Scope and Bound the Mission
- Elicit Attributes and Expenses
  - Determine Utilities
- Define Design Vector Elements
  - Include Fixing Constants Vector
- Develop Model(s) to link Design, Attributes and Expenses
  - Includes Cost Modeling
- Generate the Tradespace
- Tradespace Exploration
# Program Level Analysis

The same 3 Expense Attributes (EA) Redefined, Introduced 5 New Performance Attributes (PA) to give a total of 8 program attributes

<table>
<thead>
<tr>
<th>Attributes</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(EA-1) Program Development Cost</td>
<td>Sum of development cost of individual Space Tugs</td>
</tr>
<tr>
<td>(EA-2) Program Launch Cost</td>
<td>Sum of launch costs of individual Space Tugs if in different orbits, else 2/3 of the value</td>
</tr>
<tr>
<td>(EA-3) Program Schedule</td>
<td>Maximum of the schedules of the two Space Tugs if launched to the same orbits, else the minimum</td>
</tr>
<tr>
<td>(PA-1) Program Mass Capability</td>
<td>The lower of the 2 Space Tugs in order to guarantee that the other one has higher delta-V</td>
</tr>
<tr>
<td>(PA-2) Program Delta-V</td>
<td>The lower of the 2 Space Tugs in order to guarantee that the other one has higher delta-V</td>
</tr>
<tr>
<td>(PA-3) Program Transfer Speed</td>
<td>Sum of Speed levels - “Slow-Slow” (Level 0), “Slow-Fast”/”Fast-Slow” (Level 1), “Fast-Fast” (Level 2)</td>
</tr>
<tr>
<td>(PA-4) Probability of Success</td>
<td>Probability of 2 Space Tugs being able to perform their missions at the same time</td>
</tr>
<tr>
<td>(PA-5) Mission Time</td>
<td>Duration taken to prevent the first predicted collision or multiple collisions predicted to occur at the same time</td>
</tr>
</tbody>
</table>
Program Level Analysis

- **MAU** = \( f \{ PA-1, PA-2, PA-3, PA-4, PA-5 \} \)
- **MAE** = \( f \{ EA-1, EA-2, EA-3 \} \)
- **128 designs x 128 designs x 4 orbit location pairs x 4 reliability level pairs = 262,144 program design solutions**
- Space Tug program to perform 8 different missions:
  - 8 different epochs with 8 different SAU functions for each of the 5 attributes and 8 different SAE for each of the 3 expenses
- **1\textsuperscript{st} era:** 8 different epochs with **Present** technology
- **2\textsuperscript{nd} era:** 8 different epochs with **Future** Technology
Single-Epoch Analysis

- Generate tradespace for Epoch 1
- 6 designs along the Pareto front were chosen and labeled A to F.
- Constraint levels are set using Design A as reference.
- Maximum Expense is arbitrarily set at 1.5-2.0x above its resource expenditure and Minimum Utility is set at 1.5-2.0x below its utility
- Designs A, B, C are affordable

Tradespace for a Space Tug program in Epoch 1. (Wu, Ross and Rhodes 2013)
Single-Epoch Analysis

Characteristics of Designs A to F

<table>
<thead>
<tr>
<th>Design (Number)</th>
<th>Program Payload (kg)</th>
<th>Program Speed</th>
<th>Program Delta-V (ms⁻¹)</th>
<th>Prob. Success</th>
<th>Mission Time</th>
<th>PDC ($mil)</th>
<th>PLC ($mil)</th>
<th>PDS (mths)</th>
<th>Utility</th>
<th>Expense</th>
</tr>
</thead>
<tbody>
<tr>
<td>A (26836)</td>
<td>300</td>
<td>Fast/Fast</td>
<td>6147</td>
<td>0.96</td>
<td>Short</td>
<td>940.5</td>
<td>376.8</td>
<td>8</td>
<td>0.715</td>
<td>0.131</td>
</tr>
<tr>
<td>B (28900)</td>
<td>300</td>
<td>Fast/Fast</td>
<td>8091</td>
<td>0.96</td>
<td>Short</td>
<td>1805</td>
<td>808</td>
<td>8</td>
<td>0.774</td>
<td>0.208</td>
</tr>
<tr>
<td>C (59860)</td>
<td>300</td>
<td>Fast/Fast</td>
<td>12645</td>
<td>0.92</td>
<td>Short</td>
<td>2090</td>
<td>764</td>
<td>14</td>
<td>0.800</td>
<td>0.254</td>
</tr>
<tr>
<td>D (125908)</td>
<td>1000</td>
<td>Fast/Fast</td>
<td>8910</td>
<td>0.88</td>
<td>Short</td>
<td>3420</td>
<td>1212</td>
<td>28</td>
<td>0.823</td>
<td>0.448</td>
</tr>
<tr>
<td>E (127972)</td>
<td>1000</td>
<td>Fast/Fast</td>
<td>16150</td>
<td>0.88</td>
<td>Short</td>
<td>4750</td>
<td>1800</td>
<td>28</td>
<td>0.840</td>
<td>0.517</td>
</tr>
<tr>
<td>F (194020)</td>
<td>3000</td>
<td>Fast/Fast</td>
<td>10984</td>
<td>0.86</td>
<td>Short</td>
<td>8550</td>
<td>3080</td>
<td>42</td>
<td>0.915</td>
<td>0.763</td>
</tr>
</tbody>
</table>

Performance and Resource Attributes for Designs A to F in Epoch 1 (Wu, Ross and Rhodes 2013)
Multi-Epoch Analysis

- To find out how utility and expense of program changes across multiple epochs
- Find out how many epochs during which designs remain affordable
- Epochs 1, 5, 6, 13, 14 chosen
- Varying constraint levels were chosen for each epoch to yield different affordable solution regions

<table>
<thead>
<tr>
<th>Epoch</th>
<th>Program Payload (kg)</th>
<th>Program Speed</th>
<th>Program Delta-V (ms⁻¹)</th>
<th>Prob. Success</th>
<th>Mission Time</th>
<th>PDC ($mil)</th>
<th>PLC ($mil)</th>
<th>PDS (mths)</th>
<th>Minimum Utility</th>
<th>Derived Minimum Expense</th>
<th>Maximum Expense</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>300</td>
<td>Fast/Fast</td>
<td>5500</td>
<td>0.95</td>
<td>Short</td>
<td>2000</td>
<td>500</td>
<td>12</td>
<td>0.605</td>
<td>0.087</td>
<td>0.294</td>
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<tr>
<td>5</td>
<td>300</td>
<td>Fast/Fast</td>
<td>7000</td>
<td>0.90</td>
<td>Short</td>
<td>3000</td>
<td>900</td>
<td>12</td>
<td>0.661</td>
<td>0.178</td>
<td>0.349</td>
</tr>
<tr>
<td>6</td>
<td>1000</td>
<td>Fast/Fast</td>
<td>4000</td>
<td>0.90</td>
<td>Short</td>
<td>4000</td>
<td>1000</td>
<td>12</td>
<td>0.576</td>
<td>0.293</td>
<td>0.389</td>
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<td>300</td>
<td>Fast/Fast</td>
<td>6500</td>
<td>0.95</td>
<td>Short</td>
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<td>1200</td>
<td>24</td>
<td>0.643</td>
<td>0.079</td>
<td>0.583</td>
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<tr>
<td>14</td>
<td>1000</td>
<td>Fast/Fast</td>
<td>7000</td>
<td>0.90</td>
<td>Short</td>
<td>3000</td>
<td>1600</td>
<td>24</td>
<td>0.681</td>
<td>0.175</td>
<td>0.527</td>
</tr>
</tbody>
</table>

Performance and Resource Constraints for a Set of Epochs (sequenced as an Era) (Epochs 1,5,6,13,14) (Wu, Ross and Rhodes 2013)
Multi-Epoch Analysis

(a) Number of epochs in affordable solution region for every design
(b) Number of epochs above minimum utility level for every design

(Wu, Ross and Rhodes 2013)
Single-Era Analysis

Plot both expense and utility trajectories of designs over defined era

(a) EEA with expense considerations in a single era (b) EEA with utility considerations in a single era

(Wu, Ross and Rhodes 2013)
Single-Era Analysis

• Combining results from both utility and expense trajectories, **Design C** has the best tradeoffs among performance, cost and schedule attributes.

• Both Space Tugs have ‘Low’ mass capability, use ‘Nuclear’ propulsion, propellant mass of **3000kg**, in **LEO-LEO** orbit configuration, **high reliability**, and are carried on the **same launch vehicle**.

• The PDC is **$2.09 billion**, PLC is **$0.764 billion**, and development schedule is at least **14 months**.

<table>
<thead>
<tr>
<th>Design (Number)</th>
<th>Program Payload (kg)</th>
<th>Program Speed</th>
<th>Program Delta-V (ms(^{-1}))</th>
<th>Prob. Success</th>
<th>Mission Time</th>
<th>PDC ($mil)</th>
<th>PLC ($mil)</th>
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Conclusion & Future Work

• Defined affordability as an ability
• Introduced tradespace-based methods to conduct affordability analysis
  – Methods are scalable from systems to programs to portfolios
• Demonstrated methods on system and program levels for Space Tug
• Further examples and details can be found in:

MATE, EEA and MAE can be used in the design for affordability to avoid cost overruns and schedule slippages in the long run
THANK YOU VERY MUCH!
ANY QUESTIONS?

Contact: adamross@mit.edu or marcuswu@mit.edu

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References