Integrating Design and Verification Decisions

Alejandro Salado, PhD
Assistant Professor of Systems Science and Systems Engineering
Grado Department of Industrial & Systems Engineering
Virginia Tech
Email: asalado@vt.edu
Do you consider VERIFICATION when designing a system?
Beyond DESIGNING features for verification
TRADITIONALLY...

**DESIGN A SYSTEM**

**DEFINE ITS VERIFICATION STRATEGY**
WITH NEW APPROACHES…

TRADESPACE EXPLORATION
WITH NEW APPROACHES…

Value-Driven Design

Value = Cost + Benefit + Consequences
Preferred Strategy = Highest E(V)

E(V) = \sum (Probability \cdot VALUE)

E(V_{min}) \leq E(V_{test}) \leq E(V_{max})

PRODUCT Prob. (Good) Prob. (Bad)

1st Req. PASS 

2nd Req. PASS 

OUTCOMES

PRODUCT Prob. (Good) Prob. (Bad)

FAIL

PROBABILITY

Good product Bad Product

REWORK

3X

FAIL 3X

Value-Driven Design
But what is VERIFICATION, really?
Validation left out in this paper…

VERIFICATION is knowledge discovery

System CHARACTERIZATION with a given level of confidence
\[ E \left[ S_{\text{VALUE}} \right] = f \left( S_c, P(S_c), SN \right) \]

\[ \text{max}_{P(S_c)} f \left( \text{arg max}_{S_c} f \left( S_c, 1, SN \right), P(S_c), SN \right) \] 

\[ \land \] 

\[ \text{max}_{S_c, P(S_c)} f \left( S_c, P(S_c), SN \right) \]
TWO design alternatives: A and B
THREE verification alternative strategies: 1, 2, & 3
SEQUENTIAL DECISIONS

Design benchmark

Design decision

Alternative A
FALSE
-350

Value 1
25.0%
650
0.0%
300

Value 2
50.0%
400
0.0%
50

Value 3
25.0%
200
0.0%
-150

Alternative B
TRUE
-100

Value 3
95.0%
200
95.0%
100

Value 4
5.0%
180
5.0%
80

Alternatives:

Alternative A
Value 1
Value 2
Value 3

Alternative B
Value 3
Value 4
## SEQUENTIAL DECISIONS

<table>
<thead>
<tr>
<th>Decision</th>
<th>Value 1 (%)</th>
<th>Value 2 (%)</th>
<th>Value 3 (%)</th>
<th>Value 4 (%)</th>
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<tbody>
<tr>
<td>Verification decision</td>
<td>99</td>
<td>99</td>
<td>99</td>
<td>99</td>
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<tr>
<td>Verif Strategy 1</td>
<td>97</td>
<td>97</td>
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<td>97</td>
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<td>Verif Strategy 2</td>
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<td>95</td>
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<tr>
<td>No verification</td>
<td>99</td>
<td>99</td>
<td>99</td>
<td>99</td>
</tr>
</tbody>
</table>

### DESIGN B + VERIFICATION 3

- **Verif Strategy 1**
  - **Value 1**: 99%
  - **Value 2**: 99%
  - **Value 3**: 99%
  - **Value 4**: 99%

- **Verif Strategy 2**
  - **Value 1**: 97%
  - **Value 2**: 97%
  - **Value 3**: 97%
  - **Value 4**: 97%

- **No verification**
  - **Value 1**: 99%
  - **Value 2**: 99%
  - **Value 3**: 99%
  - **Value 4**: 99%
CONCURRENT DECISIONS

**Design A**

**Verification Strategy 1**

Value 1: 80.0% Value 3: 80.0%

Value 2: 650
Value 3: 200

**Verification decision**

Value 1: 140
Value 2: 15.0%
Value 3: 400
Value 4: -50

**Alternative A**

Value 1: 15.0%
Value 3: 400
Value 4: -50

**Verification Strategy 2**

Value 1: 140
Value 2: 15.0%
Value 3: 400
Value 4: -50

**No Verification**

Value 1: 5.0%
Value 2: 5.0%
Value 3: 200
Value 4: -250

**Verification decision**

Value 1: -350
Value 2: 140
Value 3: 650
Value 4: 200

**Design decision**

Value 1: 99.0%
Value 3: 99.0%

**Alternative B**

Value 1: 140
Value 2: 99

**Verification Strategy 2**

Value 1: 99.0%
Value 3: 99.0%

**No Verification**

Value 1: 5.0%
Value 2: 5.0%
Value 3: 200
Value 4: -100

Huntsville, AL 3/29/2016

Dr. Alejandro Salado – Grado Department of Industrial and Systems Engineering
<table>
<thead>
<tr>
<th>DECISION</th>
<th>SEQUENTIAL</th>
<th>CONCURRENT</th>
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</thead>
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<tr>
<td>DESIGN</td>
<td>B</td>
<td>A</td>
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<td>VERIFICATION</td>
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<td>1</td>
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<tr>
<td>EXPECTED VALUE</td>
<td>99</td>
<td>140</td>
</tr>
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</table>

Verification NOT ONLY informs the design of an alternative, it ALSO informs the selection of the design alternative.
NEXT

Decomposition and composition

Scalability

Beyond design and verification
IMAGE SOURCES


Slide 5 notional verification tradespace: Salado A. Applying tradespace exploration to verification engineering: From practice to theory and back again. 2016 Conference on Systems Engineering Research (CSER), Huntsville, AL (USA)

Slide 6 VDD process image: http://www.aere.iastate.edu/bloebaum/

Impact of Organization Structure on the Value of a Commercial Communication Satellite

Benjamin Kwasa
Dr. Hanumanthrao Kannan
Dr. Christina L. Bloebaum
Introduction

• What are large-scale complex engineered systems (LSCES)?
  • Entities that are an aggregate of multiple parts
    • Tightly coupled yielding a collective behavior
    • Simple summation of parts does not produce intended result
  • Associated with high cost and risk
  • Require large organizations to develop
  • Often need to interact with other complex systems and therefore organizations
Introduction

• Systems Engineering (INCOSE)
  • Requirements formulation and propagation
  • Hierarchical decomposition of system to subsystems
  • Requirements Documents
    • Stakeholders' Requirements Document (StkhldrsRD)
    • System Requirements Document (SRD)
    • Systems Requirement Validation Document (SRVD)
  • Sequential Design implementation
Introduction

• Potential drawbacks of requirements-driven design
  • Limits the design space
    • Requirements remove unwanted areas
  • Feasibility is the end goal of the design process
    • Does not offer preferences on alternatives in the feasible region
  • Use of Interface Control Documents (ICD) to keep track of couplings
  • Does not address organization structure design
Introduction
Introduction

• Need for a different approach to systems design
  • Achieve Michael Griffin’s definition of an elegant design
    • Effective
    • Efficient
    • Robust
    • Minimize Unintended consequences
  • Foundations for design of elegant systems
    • Multidisciplinary Design Optimization
    • Value-Driven Design
    • Decision Analysis
    • Organization Design
Background

- Multidisciplinary Design Optimization (MDO)
  - Evolved from structural optimization in 1980s
  - Utilizes objective function, equality and inequality constraints to find optimum
  - Allows for optimization of complex systems vis-à-vis coupled analyses
Background

• MDO
  • Mathematical quantification of couplings has been previously addressed in research work (Bloebaum, C.L, English, K.)

GSE Method: Uses local sensitivities to obtain system derivatives to capture system behavior

\[
\begin{bmatrix}
I & -\frac{\partial Y_A}{\partial Y_B} \\
-\frac{\partial Y_B}{\partial Y_A} & I
\end{bmatrix}
\begin{bmatrix}
\frac{dY_A}{dX_A} & \frac{dY_A}{dX_B} \\
\frac{dY_B}{dX_A} & \frac{dY_B}{dX_B}
\end{bmatrix} =
\begin{bmatrix}
\frac{\partial Y_A}{\partial X_A} & 0 \\
0 & \frac{\partial Y_B}{\partial X_B}
\end{bmatrix}
\]
Background

• Value-Driven Design (VDD)
  • Developed in the late 1990s
  • Approach to design that places emphasis on capturing stakeholder preference in a value function “System Critical Stakeholders (SCS’s)”
  • This allows for direct comparison of alternatives through value
  • In MDO, VDD replaces the objective function and many constraints with a value function
Background

• VDD
  • Commercial application (profit, customer retention, etc.)
  • Government application (operational success e.g. survivability, effectiveness)
Background

• Organization Design
  • Science of the design and analysis of organizational structures
    • Interactions amongst entities in an organization
    • Interactions amongst entities across organizations
Background

• Organization Design
  • Evaluation of entities’ tasks: coordination (information flow), specialization, saturation, superiority
• Two main organizational structure types
  • Hierarchical
    • Hybrid hierarchical
  • Spider web
Background

- Smaller evolutionary companies e.g. software development firms begin by using spider web structures.
Background

- Larger firms with definitive products utilize hierarchical structures
Background

• Mirroring hypothesis
  • Organizations with high dependency between entities produce products whose product structure mirror the organization
  • Organizations’ use of resources is most efficient when the organization structure mirrors the product structure
  • A deviation from mirroring is explored herein
Background

• Past research:
  • Bringing MDO and VDD together to design complex systems
    • True stakeholder preferences captured (VDD)
    • Physical interactions captured (MDO)
  • Addressing uncertainties in a VDD/MDO formulation
  • Addressing coupling strengths under uncertainties

• Current work:
  • Incorporate organization design in the framework for LSCES design to improve the design process
Methodology - Commercial Communication Satellite

- Hierarchical decomposition (represents both satellite’s physical structure and organization’s structure)
Methodology—Commercial Communication Satellite

- Value function formulation
  - Objective function replaced by value function
  - True preferences are captured - Net present profit (Commercial satellite company assumed)
  - Requirements are drastically reduced

\[
\text{VDD formulation}
\]

\[
\begin{align*}
\min \ f(X,y) &= -\text{Net present profit} = -V \\
V &= f(\text{Satellite Cost}, Revenue) = -\text{Satellite Cost} + \sum_{y=1}^{OL} \frac{\text{Revenue}_y}{(1+r_d)^y} \\
r_d &: \text{discount factor} = 10\% \\
OL &: \text{Operational Lifetime} = 10 \text{ years}
\end{align*}
\]

Traditional formulation

\[
\begin{align*}
\text{find } X &= [S_{\text{long}}, G_{\text{long}}, G_{\text{lat}}, G_{\text{lat}R}, I_0, I_{\text{sup}}, P_{\text{at}}, P_{\text{gt}}, D_{\text{at}}, D_{\text{gt}}, D_{\text{gt}}.X_{\text{discrete}}]^T \\
\text{Min } f(X,y) &= \text{Total Spacecraft mass} \\
\text{s.t. } g_1: 10\text{dB} - \text{SNR_{composite}} \leq 0 \\
g_2: M_{\text{payload}} + M_{\text{propulsion}} + M_{\text{power}} + M_{\text{ADCs}} + M_{\text{thermal}} + M_{\text{structures}} - 1000 \leq 0 \\
g_3: \text{Array size} - 40m^2 \leq 0 \\
g_4: L_z - 5m \leq 0 \text{ or } h_z - 5m \leq 0 (\text{depends on bus config.}) \\
g_5: r_z - 2.5m \leq 0 \text{ or } w_z - 2.5m \leq 0 (\text{depends on bus config.}) \\
25^\circ N \leq G_{\text{lat}} \leq 50^\circ N \\
1 \text{ GHz} \leq f_a \leq 100 \text{ GHz} \\
1 \text{ GHz} \leq f_{\text{sp}} \leq 100 \text{ GHz} \\
5 \text{ W} \leq P_{\text{at}} \leq 100 \text{ W} \\
300 \text{ W} \leq P_{\text{gt}} \leq 30000 \text{ W} \\
0.5m \leq D_{\text{at}} \leq 2.5m, \\
0.5m \leq D_{\text{gt}} \leq 2.5m, \\
2m \leq D_{\text{gt}} \leq 20m \\
2m \leq D_{\text{gt}} \leq 20m \ldots
\end{align*}
\]
Methodology– Commercial Communication Satellite

• Value function formulation
  • Value function is augmented by inclusion of organization structure cost
  • True preferences are captured - net present profit (Commercial satellite company assumed)
  • Net present profit includes product and organization structure (process) cost

VDD formulation

\[ \min f(X, y) = -\text{Net present profit} = -V \]

\[ V = f(\text{Satellite Cost, Revenue}) = -\text{Satellite Cost} + \sum_{y=1}^{\text{OL}} \frac{\text{Revenue}_y}{(1+r_d)^y} \]

- \( r_d \): discount factor = 10%
- \( t_{dev} \): development time rounded up to years
- \( \text{OL} \): Operational Lifetime = 10 years
- \( y \): year
- Total Cost = Satellite Cost + Org Structure Cost
- Org Structure Cost = \( \sum_{n=1}^{s} n_c \cdot c_{\text{cost}_n} + \sum_{n=1}^{s} n_s \cdot c_{\text{cost}_n} \)
- \( c_{\text{cost}_n} \): cost of coordination of subsystem \( n \)
- \( s \): total number of subsystems
- \( n_c \): number of coordination executions
- \( n_s \): number of specialization executions
- \( n \): subsystem index
Methodology – Commercial Communication Satellite

- Prescription of system’s organization parameters
  - Time and cost
  - Specialization and coordination
Results – Pure Hierarchy Structure

- System value measured for a satellite system under a pure hierarchy organization structure.
  - Development dollars and time are focused higher up in the organization.
  - This creates an environment where changes at the bottom take a long time to be redistributed.

<table>
<thead>
<tr>
<th>Pure Hierarchy</th>
<th>Coordination Count</th>
<th>Specialization Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comm. Satellite</td>
<td>95</td>
<td>1</td>
</tr>
<tr>
<td>Payload</td>
<td>4</td>
<td>2</td>
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<tr>
<td>Ground</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Engine</td>
<td>11</td>
<td>9</td>
</tr>
<tr>
<td>Power</td>
<td>23</td>
<td>9</td>
</tr>
<tr>
<td>ADCS</td>
<td>12</td>
<td>7</td>
</tr>
<tr>
<td>Thermal</td>
<td>11</td>
<td>6</td>
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<tr>
<td>Structures</td>
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<td>7</td>
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<tr>
<td>Launch Vehicle</td>
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<td>9</td>
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<tr>
<td>Satellite Transponder</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Satellite Antenna</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Ground Transponder</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Ground Antenna</td>
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<td>1</td>
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<tr>
<td>Propellant</td>
<td>2</td>
<td>1</td>
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<tr>
<td>Power Source</td>
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<td>Power Storage</td>
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<td>1</td>
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<tr>
<td>Thermal Finish</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Radiator &amp; Heater</td>
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<td>1</td>
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<tr>
<td>Bus Material</td>
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<td>1</td>
</tr>
<tr>
<td>Satellite Transmitting Antenna</td>
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<td>1</td>
</tr>
<tr>
<td>Satellite Receiving Antenna</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Ground Transmitting Antenna</td>
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<td>1</td>
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<tr>
<td>Ground Receiving Antenna</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Propellant Tank</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

| Development Time | 3.35 years |
| Organization Cost | $34,432,000 |
| Net Present Profit |             |
| w/o Org. Structure | $307,226,000 |
| w/ Org. Structure  | $272,794,000 |
Results – Complete Mirrored Structure

- System value measured for a satellite system under a completely mirrored organization structure.
  - Development dollars and time are distributed according to subsystem involvement.
  - It is possible to identify the critical development path based on individual development times.

<table>
<thead>
<tr>
<th>Mirrored Structure</th>
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<th>Specialization Count</th>
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<tr>
<td>Engine</td>
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<td>9</td>
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<td>Power</td>
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<td>Ground Transponder</td>
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<td>Ground Antenna</td>
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<td>Power Storage</td>
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<td>Thermal Finish</td>
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<td>Radiator &amp; Heater</td>
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<tr>
<td>Satellite Transmitting Antenna</td>
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<tr>
<td>Satellite Receiving Antenna</td>
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<tr>
<td>Ground Transmitting Antenna</td>
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<td>Propellant Tank</td>
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<tr>
<th>Mirrored Structure</th>
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<th>Organization Cost</th>
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<tr>
<td>w/o Org. Structure</td>
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<td>w/ Org. Structure</td>
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<td>$307,226,000</td>
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<td>w/ Org. Structure</td>
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<td>$281,494,000</td>
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</table>
Conclusion

• Organization Design plays a vital role in the design and development of LSCESs.

• Including organization cost in the value function allows for appropriate modeling and prediction of system designs and system value.

• It is possible to capture the relationship between product and process in the design of LSCESs.
Acknowledgements

National Science Foundation (NSF), grant CMMI-1300921
Appendix - Methodology

- Demonstration of Complex System

\[ V = 2A_{111} + A_{121} \]  
\[ A_{111} = 2A_{211} + A_{221} - A_{241} - 2x_2 \]  
\[ A_{121} = 3A_{231} + 2A_{241} - x_4 \]  
\[ A_{211} = x_1 - 2x_3 + x_1^2 + A_{221} \]  
\[ A_{221} = x_2^2 + \frac{A_{211}}{2} \]  
\[ A_{231} = x_3x_4 - 3x_3 - \frac{A_{241}}{2} + 5A_{211} \]  
\[ A_{241} = x_4 - x_6 + x_5^2 + A_{231} \]
Appendix - Methodology

\[ Cost_{org} = Cost_{spec} + Cost_{coord} \]  \hspace{1cm} (8)

\[ Cost_{spec} =Cost_{specS1} + \sum_{i=1}^{2} Cost_{specSSLi} \]  \hspace{1cm} (9)

\[ Cost_{coord} =Cost_{coorS1} + \sum_{i=1}^{2} Cost_{coorSSLi} \]  \hspace{1cm} (10)

\[ Cost_{specSSLi} = \sum_{j=1}^{m} (sc_{j})S_{j} \]  \hspace{1cm} (11)

where \( m \) = number of subsystems in SSLi

\( sc_{j} \) = number of specialization executions for the \( j^{th} \) subsystem

\[ S_{j} = \text{unit cost of specialization for the } j^{th} \text{ subsystem} \]

\[ Cost_{coorSSLi} = \sum_{j=1}^{m} (cc_{j})C_{j} \]  \hspace{1cm} (12)

where \( m \) = number of subsystems in SSLi

\( cc_{j} \) = number of coordination executions for the \( j^{th} \) subsystem

\[ C_{j} = \text{unit cost of coordination for the } j^{th} \text{ subsystem} \]

<table>
<thead>
<tr>
<th>Organization Parameter</th>
<th>Unit Cost</th>
<th>Unit Task Duration (months)</th>
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<td>Spec. S1 (V)</td>
<td>3.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Spec. S11 (A111)</td>
<td>1.2</td>
<td>1.0</td>
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<tr>
<td>Spec. S12 (A121)</td>
<td>1.15</td>
<td>1.0</td>
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<tr>
<td>Spec. S21 (A211)</td>
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<td>2.0</td>
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<td>Spec. S22 (A221)</td>
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<td>2.7</td>
</tr>
<tr>
<td>Spec. S23 (A231)</td>
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<tr>
<td>Coord. SSL2</td>
<td>0.03</td>
<td>0.25</td>
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</tbody>
</table>
Appendix - Methodology

Pure Hierarchy

Complete mirroring

Partial mirroring
## Appendix – Results: Value-Based Organization Structuring

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
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<td>0.00</td>
<td>4.30</td>
<td>0.00</td>
<td>14.75</td>
<td>0.00</td>
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<tr>
<td>Complete Mirror</td>
<td>71.38</td>
<td>60.75</td>
<td>2.83</td>
<td>5.58</td>
<td>1.47</td>
<td>-2.83</td>
<td>11.92</td>
<td>-2.83</td>
<td>3.96</td>
<td>9.19</td>
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<tr>
<td>Partial Mirror (A241 – A111)</td>
<td>71.10</td>
<td>60.45</td>
<td>2.55</td>
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### Appendix – Results: Coupling Suspension

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An Agent-Based Simulation Framework for Evaluating Flow-Down Approaches in Value-Driven Systems Engineering

Sean Vermillion
Big Picture: Delegation in SE

System-Level Designer

Required Domain Knowledge
Big Picture: Delegation in SE

System-Level Designer

Design Guidance

Design Specs

Domain Expert

Required Domain Knowledge

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Design Guidance Flow-Down in SE

**Requirement Flow-Down:**

*RFD Promise:* Verifiability

*RFD Peril:* Little guidance for choosing between feasible alternative.

**Objective Flow-Down:**

*OFD Promise:* Explicit Preferences

*OFD Peril:* Ambiguous when to keep searching for optimal alternative.
Research Motivation

**Looming Question:** Requirements or objectives?

This Research: *How can we compare approaches while considering agency?*

Proposition: *agent-based framework* to simulating flow-down approaches
Framework Overview

Model-Based Validation

- Requirement Flow-Down
- Objective Flow-Down

SE Process Model

- Req. FD Value
- Obj. FD Value

Representative System Design Scenario

Agent Model: Heterogeneous Engineers in Configurable Organizations (HEICO)
A Principal incentivizes an agent to act in a way that maximizes the Principal’s utility.
HEICO Foundations: Modeling Flow-Down

Model flow-down approaches as incentives

$$v_{req}^{i} = \begin{cases} K_{1}^{req} & \text{if req met} \\
K_{2}^{req} & \text{if req not met} \end{cases}$$

$$v_{obj}^{i} = K_{1}^{obj} \times g_{i} + K_{2}^{obj}$$
HEICO Foundations: Modeling Agents

Agent effort provision

Principal

Agent

maximize w. r. t. \[ E[u(v_i(f(a|\theta_i)) - c_a(a|\theta_i)|\theta_i)] \]

Value of Effort
Production Technology
Risk Attitude
Type

\( c_a(\cdot) \) Disutility for applying effort
\( f(\cdot) \) Mapping from effort to outcome
\( u(\cdot) \) Tolerance for uncertain outcomes
\( \theta_i \) Specific characteristics of the agent
HEICO Foundations: Modeling Value of Effort

- Convex Function
  \[ c_a(a) = \rho \frac{a^2}{2} \]

- Parameter:
  - \( \rho \): Marginal increase in effort costs

- Convexity assumption common in agency theory literature

\[
\begin{align*}
\text{maximize} & \quad E[u(v_i(f(a|\theta_i)) - c_a(a|\theta_i)|\theta_i)] \\
\text{w. r. t.} & \quad a
\end{align*}
\]
HEICO Foundations: Modeling Production Technology

- Generalized Logistic Function
  \[ f(a) = z_o + \frac{z_f - z_o}{1 + Q \exp(-ra)} \]

- Parameters:
  - \( \mu \): Where maximum growth rate occurs
  - \( r \): Marginal growth rate
  - \( z_o \): Initial capability \( z_o = g_i(x_o) \)
  - \( z_f \): Optimal capability \( z_f = g_i(x^*) \)

- Approximation of trends observed in design literature

\[
\text{maximize} \quad E[u(v_i(f(a|\theta_i)) - c_a(a|\theta_i)|\theta_i)] \\
\text{w. r. t.} \quad a
\]
HEICO Foundations: Modeling Risk Attitude

- Power Utility Function

\[ u(\pi) = \begin{cases} \pi^{\alpha} & \pi \geq 0 \\ -\lambda (-\pi)^{\beta} & \pi < 0 \end{cases} \]

- Parameters:
  - \( \alpha \): Relative risk aversion for positive \( \pi \)
  - \( \beta \): Relative risk aversion for negative \( \pi \)
  - \( \lambda \): Negative outcome aversion

- Based on empirical trends of how people form their risk attitudes

- Other functional forms exist...same basic structure

\[
\text{maximize} \quad E[u(v_i(f(a|\theta_i)) - c_a(a|\theta_i)|\theta_i)]
\]

w. r. t. \( a \)
HEICO Foundations: Linking Effort Provision and Physics

minimize \[ \| f(a_i^*) - g_i(x_i, x_{-i}) \|^2 \]

w. r. t.

Other Agents

Leader-Follower

Concurrent

System Coordinator

…etc.

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HEICO Summary

Design Guidance

Effort Provision → Link to Physics → Share Info
Illustrative Example: Study Design

**AAO analysis:**
- $z_1^* = 0.070$
- $z_2^* = 0.179$
- $v_0^* = 0.3372$

**Requirement**
$$v_{i}^{req} = \begin{cases} 1000 & z \geq z_i^* \\ 0 & z < z_i^* \end{cases}$$

**Objective**
$$v_{i}^{obj} = 1000 \times \frac{\partial v_0}{\partial z_i} \bigg|_{z_i^*}$$

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Illustrative Example: Results

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Summary

How can we compare approaches while considering agency?

- Computation framework with theoretical background
- **Not** to replace empirical research or rigorous mathematics
- Agency impacted results compared to All-at-Once analysis
Aggregated Effort across Iteration

\[ \rho = \{\text{Low, Low}\} \]
\[ \rho = \{\text{High, Low}\} \]
\[ \rho = \{\text{Low, High}\} \]
\[ \rho = \{\text{High, High}\} \]

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Relaxing the Requirements

$$\rho = \{ \text{Low, Low} \}$$

$$\rho = \{ \text{High, Low} \}$$

$$\rho = \{ \text{Low, High} \}$$

$$\rho = \{ \text{High, High} \}$$

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