A Multidisciplinary Coupling Analysis Method to Support Investigation of Ares 1 Thrust Oscillation

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Overview

- This project investigates whether system coupling sensitivities and/or coupling strengths would have identified potential issues with problematic interactions prior to late stage design.
- In-depth analysis of the Ares 1 rocket, specifically a phenomena called Thrust Oscillation
- 3 disciplines will be covered, Fluid-Dynamics, Acoustics and Structures.

Figure 1. Ares 1-X Basic Schematic
Back Story

- October 28, 2009 Nasa conducted successful test launch of Ares 1-X.
- Issues with high vibrations within engine chamber known as Thrust Oscillation.
- Led to development of T/O mitigation team.

http://apod.nasa.gov/apod/image/0911/ares1_duncan_big.jpg  
Figure 2. Ares 1-X Launch Image
Proposed Solution

- Investigate whether coupling strength model will predict TO issue
- Identify design variables and behavior variables
- Use data to model analysis and determine local and global coupling strengths

![Basic Coupling Schematic](image-url)

Figure 3. Basic Coupling Schematic
Thrust Oscillation Background

- T/O is a phenomenon that occurs in Solid Rocket Motors.
- Type of combustion instability between the coupling of acoustic energy with fluid dynamics and chemical phenomenon
- Periodic oscillation of thrust burn rate and pressure
- Pressure oscillations inside the chamber creates an oscillation effect similar to a mass-spring problem.

Figure 4. Spring and damper mounted body under dynamic forcing function
Acoustics Background

- Acoustics studies the generation and propagation of mechanical waves through a median
- These mechanical waves produce pressure changes, affecting the environment
- Mechanical waves also produce a frequency, which produces a level of vibrations with systems in an environment
Acoustics Background

- Related to SRMs, an acoustic noise is produced at the aft end of the motor
- Frequencies in SRMs are created by the rate of particle collision with the chamber’s internal walling
- 3 types of acoustic modes that occur inside SRMs
  - (a) Longitudinal
  - (b) Tangential
  - (c) Radial

Figure 4. Acoustic Modes
Fluid Dynamics Background

- Acoustic instabilities alone do not drive pressure oscillations.
- Vortex shedding can occur within combustion chamber.
- When frequencies coincide, magnitude of pressure oscillation increases.

Figure 5.
Fluids Dynamics Background

- Three types of vortex shedding
  - Obstacle-object protrudes into flow
  - Corner-cavity along boundary of flow
  - Parietal-result of natural combustion process instabilities
- Obstacle vortex shedding is most likely due to inhibitors

Figure 6.
Structures Background

- Forces impacted on structure are measured by forcing function.
- Excitation and Damping is the system’s response to these forces.
- Ares 1 Thrust oscillation team used two methods to decrease T/O event.
  - LOX dampener
  - C-Spring Clamps
Multidisciplinary Design Optimization

- Developed in the 1980s to address subsystem interactions in designing large-scale complex engineering systems
- Simulations are heavily used in modeling subsystem interactions
- Uses an objective function and addresses physical interactions within the system
- Captures coupling during analysis and optimization

![Basic Coupling Schematic](image)

Figure 7. Basic Coupling Schematic
System Coupling Strength Approach

- Ability to measure the strength of couplings in a systems context not just localized.
- Gives an understanding of how couplings can impact overall value of system.
- Two methods offered, local sensitivity approach and systems sensitivity approach.
- Calculating only local sensitivities doesn’t give an accurate representation of system changes.
Investigation of T/O Coupling Strengths And System Impact

• A simplified SRM is used in the 3 areas of interest; structures, fluid dynamics, and acoustics.

Figure 8. Simplified SRM Diagram
Methodology - Acoustics

- ANSYS 15.0 Acoustics ACT extension is used to model the acoustic modes of the SRM
- The SRM body is modeled as an acoustic body
- A modal response is used to determine the 3 longitudinal modes that occur inside the SRM’s chamber

<table>
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<tr>
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<th>Frequency (Hz)</th>
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<tr>
<td>1</td>
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<tr>
<td>2</td>
<td>842.62</td>
</tr>
<tr>
<td>3</td>
<td>1277.62</td>
</tr>
</tbody>
</table>

Figure 9. Acoustic Frequencies
Methodology - Acoustics

- Acoustic modes produce different acoustic pressure levels inside the SRM
- 1\textsuperscript{st} mode (top), 2\textsuperscript{nd} mode (middle), 3\textsuperscript{rd} mode (bottom)

Figure 10. Acoustic Pressures relating to Modes
Methodology – Fluid Dynamics

- Computational fluid dynamics (CFD) software STAR-CCM+ is used to simulate flow inside combustion chamber
- Cold flow test, i.e. no combustion, used to simplify simulation process
- Uses unsteady detached eddy physics model designed to capture vortex shedding effects

Figure 11. Vortex shedding effects of CFD
Methodology – Fluid Dynamics

- Force on inhibitor used to measure vortex shedding frequency
- Fast Fourier transform (FFT) used to plot force in frequency domain
- Frequency of 404 Hz has a 1.46% error compared to first acoustic mode frequency

![Vortex Shedding Frequency](image)

Figure 12. Vortex Shedding Frequency
Methodology – Structures

- A forcing function is created to model the time dependent dynamic pressures
- The dynamic system response is estimated using the forcing function that is applied to the structural model
- A model is created in ANSYS 15.0, using the transient method, a time step response is analyzed
Methodology – Structures

- Nodes along the SRM’s walling are set as fixed points and cannot deform.
- Transient forces are then applied to the structure of the SRM. These forces are created using a forcing function.
- The deformation shape is then determined based on the acoustic modes.

Figure 13. Structure Mesh with Pressure Load

Coupling Strength Implementation

- Determine weather T/O event could be avoided if structural dynamic feedbacks were molded
- Identify the importance of coupling, in particular, the impact of the absence or presence in the physics-based model
- Explore design variables (# of inhibitors, inhibitor height, etc.) with a fully coupled analysis and improve an understanding of the factors that influence T/O
Conclusion

- Instability in SRMs can cause damage to the structure and crew module
- T/O causes perturbations throughout the rocket, affecting crew module and crew onboard
- Coupling strengths will enable an investigation into the importance of coupling the physics models
- Models will explore design variable impact on the system coupling using coupling strength analysis
Future Work

- Perform MCA to identify coupling strengths associated with structural and acoustic integration
- Identify key coupling and design variables that have the greatest impact in causing the T/O event
- Investigate incorporation of dampers (clamps, actuator, etc.) at identified locations to determine impact on coupling and T/O
- Develop methods to investigate sensitivity and uncertainty
Thank you! Questions?
A novel approach to measuring the time-impact of oversight activities on engineering work

Samantha Marquart Brainard
Prof. Zoe Szajnfarber

Conference on Systems Engineering Research (CSER)
March 22-24, 2016 - Huntsville, Alabama
 Debate over the extent to which oversight impacts program costs

• Lots of debate about the value of oversight and the extent to which it impacts programs
  • Different stakeholders are focused on different aspects of oversight
  • Productive debate requires stakeholders to discuss the same aspects of oversight

• This work focuses on clearly defining the attributes of oversight and developing a method to gather data about these attributes
Defining oversight more clearly

Oversight

Rules

Contracts

FAR

Implementation of Rules

DoD 5000 Series Documents

Monitoring Activities
Different definitions lead to different estimates of time spent on oversight

Estimates based on all rules and regulations

“There is suggestive evidence that the cost of government-driven mission assurance and current Federal Acquisition Regulations (FAR) increase costs by factors of 3-5 times, not just 20-30%”

-Dr. Scott Pace, National Security Space Launch Programs - Testimony to Senate Committee on Defense Appropriations, Dirksen Senate Office Building 192, March 5 2014.

Estimates based on the implementation of mission assurance rules

“Mission assurance activities, such as tests and validation work, cost 2-5% of the total price of a rocket stack. This, he says, "is cheap insurance" in contrast to the price of losing a satellite that could cost more than $1 billion.”

Limitations of previous data collected on the burden of oversight

- Determining the real impact of oversight is extremely difficult to do
  - Retrospective studies tend to overestimate strongly positive and strongly negative memories
  - Many important impacts of oversight are indirect making it difficult to scope data collection in advance
  - There has been resistance to studies based on real-time observation of activities because they are considered too invasive

Analyzing the time engineers spend on oversight-related activities

Materials + Labor + Overhead = Total Product Cost
Collect data using the experience sampling method

- Commonly used in social science research to study the behaviors of different populations
  - Enables instantaneous sampling to capture random sample of naturally occurring behaviors in the aggregate
  - Method is minimally invasive using web based survey prompts
Experience Sampling Survey Method

1. Interviews & 24-Hour Time Recall Diaries
   - Researcher conducted Time Diaries of 16 Participants every other day for two weeks
   - Synthesized lists of tasks into master list of activities, consulted with company experts, iterated to create final list

2. Synthesizing Tasks
   - Developed web-based tool to distribute the survey via email and text message
   - Survey deployed to 400+ engineers over 6-months at prime defense contractor
Preliminary Results

• Previous methods were limited by:
  • Retrospective bias to overestimate strongly positive and strongly negative memories
  • Invasive, real-time observations of activities
  • Inability to capture the indirect nature of many oversight-related requests

• Our method overcomes this using a real-time, minimally invasive sampling technique to look at the activities performed by engineers over 6 months

• We can use this approach to develop insights about how people spend their time
Insights Gained Using Experience Sampling Method

- Previous Studies:

  DoD Program Office retrospective report on time spent on oversight-related activities over 2-weeks

<table>
<thead>
<tr>
<th>Regulatory Area</th>
<th>Focus of Regulation</th>
<th>Program A</th>
<th>Program B</th>
<th>Program C</th>
<th>Program D</th>
<th>Program E</th>
<th>Program F</th>
<th>Program G</th>
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Percentage of Program Office Time Spent on Regulatory Areas over 2 Weeks

7.43% 2.38% 6.29% 3.51% 3.70% 5.79% 7.18%

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Conclusions and Future Work

• This work demonstrates novel approach for collecting data to understand the time-burden of oversight-related activities
  • This method can also be used in other settings to study the real-time activities of different types of individuals

• Ongoing work:
  • Quantitative Results: Perform analysis of the data collected using this method
  • Qualitative Study: Conduct qualitative, interview based study to understand how oversight impacts the work being performed across multiple stakeholders in the acquisition value stream
SYSTEMS ENGINEERING PROCESSES IN NASA AND COMMERCIAL PROJECTS

Paul Componation
Kathryne Schomberg
Susan Ferreira
Jordan Hansen
# Systems Engineering and Project Success Studies in this Research Stream

<table>
<thead>
<tr>
<th>Study</th>
<th>Focus</th>
</tr>
</thead>
</table>
| 2007  | 12 NASA MSFC Flight Hardware Projects  
       | • SE Processes map to technical, budget, schedule and overall success  
       | • SE processes appear to impact budget and schedule more than technical success |
| 2013  | 130 commercially run projects studies  
       | • Commercial government-focused and commercial commercial-focused were studied.  
       | • Notable differences between the two populations with SE processes more important in commercial-government focused projects. |
| 2014  | 50 NASA projects studied  
       | • Evaluate government-focused, commercial-focused, and NASA-focused projects. |
| 2016  | 180 projects from the 2013 and 2014 studies.  
       | • Quantify the perceived impact of individual SE processes on individual project success metrics. |
The NASA Systems Engineering Engine
# Data Analysis

<table>
<thead>
<tr>
<th>Participants</th>
<th>Commercially Run Commercial-Focused Projects</th>
<th>Commercially Run Government-Focused Projects</th>
<th>NASA Run NASA-Focused Projects</th>
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</thead>
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<tr>
<td>Project Description</td>
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<tr>
<td>Project Success Metrics</td>
<td></td>
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<td>Systems Engineering Processes</td>
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Modified Data Collection Instrument

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<th>Section</th>
<th>Question Set</th>
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<td>1</td>
<td>Basic demographics of the engineer’s organization</td>
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<tr>
<td>2</td>
<td>Descriptive information on a specific project the engineer worked on in the organization type</td>
</tr>
<tr>
<td>3</td>
<td>How successful was the project</td>
</tr>
<tr>
<td>4</td>
<td>What systems engineering processes were used</td>
</tr>
<tr>
<td>5</td>
<td>Information on how the engineer interacted with his/her distributed team members</td>
</tr>
<tr>
<td>6</td>
<td>Influence of non-technical variables in contributing to project success</td>
</tr>
<tr>
<td>7</td>
<td>Information on the project’s communication and organization level</td>
</tr>
<tr>
<td>8</td>
<td>Informal subsystems integration strategies</td>
</tr>
</tbody>
</table>

- Survey comprised of 82 questions. / 50 relevant to this study.
- Commercial and NASA SME teams – 8 team members each
- Beta Test – 25 engineers with a paper copy
  - No significant errors so this group was included in the full data set
- Data collection – 129 engineers from commercial organizations with paper and on-line surveys
  - 46 government-focused
  - 83 commercial-focused
- Data collection - 51 engineers from NASA with an on-line survey
Sample Questions from the Survey

8. This project had significant technical risk.
   - Strongly Agree
   - Agree
   - Neither Agree nor Disagree
   - Disagree
   - Strongly Disagree
   - Not Applicable

15. This project was a success when compared to the original technical requirements.
   - Strongly Agree
   - Agree
   - Neither Agree nor Disagree
   - Disagree
   - Strongly Disagree
   - Not Applicable

28. This project translated the requirements into a design solution.
   - Strongly Agree
   - Agree
   - Neither Agree nor Disagree
   - Disagree
   - Strongly Disagree
   - Not Applicable

38. This project identified, controlled, and preserved (recorded) the system configuration.
   - Strongly Agree
   - Agree
   - Neither Agree nor Disagree
   - Disagree
   - Strongly Disagree
   - Not Applicable
Analysis Plan

1. Analysis of Organizational Differences
   1.1 Differences between the organization types (commercial-focused, government-focused, NASA-focused)?
   1.2 Difference between the project description variables (relevant scope of work, schedule risk, budgetary risk, technical risk)?
   1.3 Interaction between organizational types and the project description variables?

2. Analysis of Project Success Metrics
   2.1 Difference between the organization types (commercial-focused, government-focuses, NASA-focused)?
   2.2 Difference between project success metrics (technical success x2, schedule success x2, budget success x2, management, overall success x2)?
   2.3 Interaction between organizational type and project success metrics?

3. Analysis of Systems Engineering Processes
   3.1 Difference between the organization types (commercial-focused, government-focuses, NASA-focused)?
   3.2 Difference between systems engineering processes (17 processes)?
   3.3 Interactions between organization type and systems engineering processes?
1. Analysis of Organizational Differences

1.1 There are significant differences between organizational types

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<tr>
<th>Level</th>
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<td>NASA</td>
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<td>Government</td>
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1.2 There are significant differences between project description variables

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<td>4. Schedule Risk</td>
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<td>3. Budgetary Risk</td>
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<td>2. Technical Risk</td>
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1.3 There is no interaction between organizational types and the project description variables
2. Analysis of Project Success Metrics

2.1 There are significant differences between organizational types

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<tr>
<th>Level</th>
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<tbody>
<tr>
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<td>Commercial</td>
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\[ \alpha = 0.05 \quad Q = 2.36365 \]

1.2 There are significant differences between project success metrics

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<td>Overall project success (organization view)</td>
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<tr>
<td>Technical success relative to similar projects</td>
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<td>Overall project success (stakeholder view)</td>
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<td>Technical success relative to initial requirements</td>
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<td>On budget relative to similar projects</td>
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<td>Satisfaction with project management process</td>
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<tr>
<td>On schedule relative to similar projects</td>
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</tr>
<tr>
<td>On budget relative to original project plan</td>
<td>C</td>
<td>2.74</td>
</tr>
<tr>
<td>On Schedule relative to original project plan</td>
<td>C</td>
<td>2.71</td>
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\[ \alpha = 0.05 \quad Q = 3.10657 \]

2.3 There is an interaction between organizational types and project success metrics

Success Metrics:
1. Technical relative to initial requirements
2. Technical relative to similar projects
3. Schedule relative to original plan
4. Schedule relative to similar projects
5. Budget relative to original plan
6. Budget relative to similar projects
7. Satisfaction with project management
8. Overall project success (organization)
9. Overall project success (stakeholder)
3. Analysis of Systems Engineering Processes

3.1 There are significant differences between organizational types

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<th>Level</th>
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3.2 There are significant differences between systems engineering processes

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<td>5. Product Implementation</td>
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<td>8. Production Validation</td>
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<tr>
<td>4. Design Solution</td>
<td>A B</td>
<td>3.28</td>
</tr>
<tr>
<td>9. Product Transition</td>
<td>A B C</td>
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<tr>
<td>15. Technical Data Management</td>
<td>A B C</td>
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<td>6. Product Integration</td>
<td>A B C</td>
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<td>14. Configuration Management</td>
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<td>12. Interface Management</td>
<td>B C</td>
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3.3 There is an interaction between organizational types and the system engineering processes.

Systems Engineering Processes:
1. Stakeholder expectations definition
2. Technical requirements definition
3. Logical decomposition
4. Design solution
5. Product implementation
6. Product integration
7. Product verification
8. Product validation
9. Product transition
10. Technical planning
11. Requirements management
12. Interface management
13. Technical risk management
14. Configuration management
15. Technical data management
16. Technical assessment
17. Decision analysis
Conclusions

1. Analysis of Organizational Differences
   1.1 Differences between the organization types (commercial-focused project, government-focuses, NASA-focused)?
   1.2 Difference between the project description variables (relevant scope of work, schedule risk, budgetary risk, technical risk)?
   1.3 Interaction between organizational types and the project description variables?

2. Analysis of Project Success Metrics
   2.1 Difference between the organization types (commercial-focused, government-focuses project, NASA-focused)?
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3. Analysis of Systems Engineering Processes
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   3.2 Difference between systems engineering processes (17 processes)?
   3.3 Interactions between organization type and systems engineering processes?
Threats to Validity

- Focus on NASA Systems Engineering model was a perceived threat, but reviews by SME teams and the alpha test group did not find this an issue.
- The use of parametric statistics is a concern by some researchers although these approaches have been shown to be relatively robust.
- To compare these results with other studies we need to assess the relative impact of each systems engineering process against each project performance metric.
Next Steps

- The first is to explore the use of other statistical analysis tools that may better fit the survey data. The use of parametric statistics to analyze categorical survey data is open to debate even though it is a common practice.
- Identifying the magnitude of the specific relationships between the project performance metrics and the systems engineering processes.
- More data
NASA systems engineering research consortium: Defining the path to elegance in systems

22 March 2016

NASA MSFC
Michael D. Watson, Ph.D.

UAH ISEEM
Phillip A. Farrington, Ph.D.

Consortium Team
UAH
George Washington University
Iowa State
MIT
Texas A&M
University of Colorado at Colorado Springs (UCCS)
University of Dayton
Missouri University of S&T
University of Michigan
Shafer Corporation
AFRL Wright Patterson
Outline

◆ Understanding Systems Engineering

◆ Systems Engineering Domain
  • Primary
    – System Design and Integration
    – Discipline Integration
  • Supporting
    – Processes

◆ Products
  • Engineering Elegant Systems: Theory of Systems Engineering
  • Engineering Elegant Systems: The Practice of Systems Engineering

◆ Summary
Understanding Systems Engineering
Motivation

- **Systems Engineering** - should be based on first principles and underlying physics
  - Key Research Question: What are SE first principles?

- **Reemphasize Product in Systems Engineering**

- **System Engineering of Complex Systems is Challenging**
  - System Engineering can produce elegant solutions in some instances
  - System Engineering can produce embarrassing failures in some instances
  - Within NASA, System Engineering is frequently unable to maintain complex system designs within budget, schedule, and performance constraints

- **“How do we Fix System Engineering?”**
  - Michael D. Griffin, 61st International Astronautical Congress, Prague, Czech Republic, September 27-October 1, 2010
  - Successful practice in System Engineering is frequently based on the ability of the lead system engineer, rather than on the approach of system engineering in general
  - The rules and properties that govern complex systems are not well defined in order to define system elegance

- **4 characteristics of system elegance proposed as:**
  - System Effectiveness
  - System Efficiency
  - System Robustness
  - Minimizing Unintended Consequences
Consortium

◆ **Research Process**
  - Multi-disciplinary research group that spans systems engineering areas
  - Selected researchers who are product rather than process focused
  - Space Launch Systems (SLS) provides the observation test bed for the research looking at the full development lifecycle of a complex system

◆ **List of Consortium Members**
  - Schafer Corporation: Michael D. Griffin, Ph.D.
  - Air Force Research Laboratory – Wright Patterson, Multidisciplinary Science and Technology Center: Jose A. Camberos, Ph.D., Kirk L. Yerkes, Ph.D.
  - George Washington University: Zoe Szajnfarber, Ph.D.
  - Iowa State University: Christina L. Bloebaum, Ph.D., Michael C. Dorneich, Ph.D.
  - Massachusetts Institute of Technology: Maria C. Yang, Ph.D.
  - Missouri University of Science & Technology: David Riggins, Ph.D.
  - NASA Langley Research Center: Anna R. McGowan, Ph.D., Peter A. Parker, Ph.D.
  - Texas A&M University: Richard Malak, Ph.D.
  - Tri-Vector Corporation: Joey Shelton, Ph.D., Robert S. Ryan
  - The University of Alabama in Huntsville: Phillip A. Farrington, Ph.D., Dawn R. Utley, Ph.D., Laird Burns, Ph.D., Paul Collopy, Ph.D., Bryan Mesmer, Ph.D., P. J. Benfield, Ph.D., Wes Colley, Ph.D.
  - The University of Colorado – Colorado Springs: Stephen B. Johnson, Ph.D.
  - The University of Dayton: John Doty, Ph.D.
  - The University of Michigan: Panos Y. Papalambros, Ph.D.
  - The University of Texas, Arlington: Paul Componation, Ph.D.

◆ **Previous Consortium Members**
  - Stevens Institute of Technology – Dinesh Verma
  - Spaceworks – John Olds (Cost Modeling Statistics)
  - Alabama A&M – Emeka Dunu (Supply Chain Management)
  - George Mason – John Gero (Agent Based Modeling)
  - Oregon State – Irem Tumer (Electrical Power Grid Robustness)
  - Arkansas – David Jensen (Failure Categorization)

30 graduate students and 3 undergraduate students supported to date
Definition – System Engineering is the engineering discipline which integrates the system functions, system environment, and the engineering disciplines necessary to produce and/or operate an elegant system.

Primary Focus
- System Design and Integration
  - Identify system couplings and interactions
  - Identify system uncertainties and sensitivities
  - Identify emergent properties
  - Manage the effectiveness of the system
- Engineering Discipline Integration
  - Manage flow of information for system development and/or operations
  - Maintain system activities within budget and schedule

Supporting Activities
- Process application and execution
# System Engineering Framework Mapping

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<tbody>
<tr>
<td>System Value Model to capture Stakeholder Preferences</td>
<td>System Exergy, Optical Transfer Function, Structural Loads, Logic, etc.</td>
<td>Nanolauncher Cost Model, PBS</td>
<td>System Exergy, Optical Transfer Function, Structural Loads, Logic, etc.</td>
<td>Information Theory defines efficient decision making flows (boards)</td>
<td>Appropriate application of constraints (not as solutions)</td>
</tr>
<tr>
<td>Understand and Define Mission Requirements</td>
<td>Goal Function Tree, System State Model, Engineering Statistics (AILC), Multidisciplinary Coupling Analysis</td>
<td>Mission and Derived Technical Requirements as basis for Verification</td>
<td>Goal Function Tree, System State Model, Engineering Statistics (AILC), Multidisciplinary Coupling Analysis</td>
<td>Biased Information Sharing, Mediated Learning</td>
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<tr>
<td>System Capability mapped to Mission Value</td>
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<td>Robust Organization: Able to produce an elegant system with unstable inputs (e.g., Budget, Schedule, Mission Objectives)</td>
<td>Robust to Policy and Law: The degree to which System Value is insensitive to changes</td>
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<td>Nanolauncher Cost Model, PBS</td>
<td>Unanticipated Consequences Categories</td>
<td>Unanticipated Consequences Categories must be managed</td>
<td>Appropriate application of constraints (not as solutions)</td>
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</table>

System Attributes:
- System Effectiveness
- Robustness
- Efficiency
- Unintended Consequence
Postulate 1: Systems Engineering is product specific.

Postulate 2: The Systems Engineering domain consists of subsystems, their interactions among themselves, and their interactions with the system environment.

Postulate 3: The function of Systems Engineering is to integrate engineering disciplines in an elegant manner.

Postulate 4: Systems Engineering influences and is influenced by organizational structure and culture.

Postulate 5: Systems Engineering influences and is influenced by budget, schedule, policy, and law.

Postulate 6: Systems Engineering spans the entire system life-cycle.

Postulate 7: Understanding of the system evolves as the system development or operation progresses.
Hypothesis 1: If a solution exists for a specific context, then there exists at least one ideal Systems Engineering solution for that specific context.

Hypothesis 2: System complexity is greater than or equal to the ideal system complexity necessary to fulfill all system outputs.

Hypothesis 3: Key Stakeholders preferences can be accurately represented mathematically.
Methods of System Design and Integration

Goal: Techniques to Enable Integrated System Design and Analysis by the Systems Engineer
System Physics and System Integrating Physics

Goal: Utilize the key system physics to produce an elegant system design
Consortium is researching the significance of identifying and using the System Integrating Physics for Systems Engineering:

- First Postulate: Systems Engineering is Product Specific.
  - States that the Systems are different, and therefore, the Integrating Physics for the various Systems is different.

SLS is the complex system control for the Consortium:

- Thermodynamic System
  - Other Thermodynamic Systems:
    - Crew Modules
    - Fluid Systems
    - Electrical Systems
    - Power Plants
    - Automobiles
    - Aircraft
    - Ships

- Not all systems are integrated by their Thermodynamics:
  - Optical Systems
  - Logical Systems:
    - Data Systems
    - Communication Systems
  - Biological Systems

System Integrating Physics provides the engineering basis for the System Model.
What is the Integrating Physics for the System?

- SLS – Propulsion Exergy: \( \Delta m_{\text{propellant}} (h_{\text{prop}} + \frac{V_e^2}{2}) - X_{\text{des}} = \Delta KE_{\text{vehicle}} + \Delta PE_{\text{vehicle}} \)
  - Mass is an input to the equation
  - System Exergy provides a useful work metric

- MPCV
  - Life Support System Exergy: \( \sum \left( 1 - \frac{T_{\text{cabin}}}{T_{\text{equipment}}} \right) Q_{\text{equipment}} + \sum_{\text{process}} \Delta m_{\text{air}} (h_{\text{process}} - T_{\text{cabin}} (s_{\text{process}} - \ldots) \)

2 Relationships
Engineering Statistics

Goal: Utilize statistical methods to understand system uncertainties and sensitivities

Systems Engineering makes use of Frequentist Approaches, Bayesian Approaches, Information Theoretic Approaches as appropriate
Optimal Sensor Information Configuration

- Applying Akaike Information Criteria (AIC) corrected (AICc) to assess sensor coverage for a system

\[
AICc(F) = -2 \left( I^{KL}(F|G) \right) + 2K + \frac{2K(K+1)}{n-K-1}
\]

- Two Views of Information Content
  - AIC Information
    - Information is viewed as the number of meaningful parameters
      - Parameters with sufficient measurements to be reasonable estimates
  - Fisher Information Matrix
    - Defines information as the matrix of partial second derivatives
      - Information is the amount of parameters with non zero values (so provides an indication of structure)
      - This value converges to a maximum as the number of parameters goes to infinity
      - Does not contain an optimum, always increases with added parameters

- AIC/AICc has an adjustment factor to penalize sensor arrangements where:
  number of sensors < 3x(number of measurements)

- Provides an optimization tool for use with System Models
Goal: Utilize system state variables to understand the interactions of the system in relation to system goals and system execution
System State Models represent the system as a whole in terms of the hardware and software states that the system transitions through during operation.

**Goal Function Tree (GFT) Model**
- “Middle Out” model of the system based on the system State Variables
- Shows relationship between system state functions (hardware and software) and system goals
- Does not contain system physical or logical relationships and is not executable

**System State Machine Model**
- Models the integrated State Transitions of the system as a whole (i.e., hardware states and software states)
- Confirms system functions as expected
  - Checks for system hazardous, system anomalies, inconsistent state progression, missing states, improper state paths (e.g., short circuits in hardware and/or software design)
  - Confirms that the system states progress as stated in the system design
- Executable model of system
System Design and Optimization

Goal: Apply system design and optimization tools to understand and engineer system interactions
Investigating Multidisciplinary Coupling Assessment (MCA) as a technique to analysis integrated system behavior coupling
- Based on Multidisciplinary Design Optimization (MDO) techniques
- Seeks to identify system couplings and their relationships to allow optimization/mitigation during design
  - Quicker assessment of the couplings
  - Significantly smaller effort to produce understanding of coupling and assess design options

SLS is the system control for the analysis
- Selected Ares I Thrust Oscillation as a representative case to compare across the Ares I Integrated Stack (i.e., Ares I and MPCV)

MCA is a form of the system model focusing on the coupled behaviors of the system as a whole
System Value

Goal: Utilize system state variables to understand the interactions of the system in relation to system goals and system execution
A System Value Model is a mathematical representation of Stakeholders Preferences (Expectations) for the system

- The basic structure is straightforward
- The sociology/psychology of representing the Preferences can be a challenge

The System Value Model is the Basis of System Validation!!!

- The Requirements and Design Models form the basis of System Verification
- The System Value Model forms the basis of System Validation

Constructing an SLS Value Model to compare to System Validation results

- Can expand to Integrated Stack with input from MPCV and GSDO

System Value model also provides basis for a measure of System Robustness

- How many mission types are supported by the system?
System Cost Models are an important tool in both Development Phase and Production and Operations Phase cost control

• Unit Cost is critical to understand system cost
  – Product Breakdown Structure (PBS) provides unit cost
  – Work Breakdown Structure (WBS) provides common labor structure and can mask unit cost

• Parametric models do not properly predict cost
  – Based on historical data
    • Accurate prediction based on following the same methods and approach as the historical program (NAFCOM using Titan IV)
  – Mass Based parametrics do not properly reflect System Integrating Physics and can have inverted relationships
    • Predicts higher cost for higher mass, the inverse is often more true

• The cultural impact of cost models is important
  – Does the knowledge of the predicted cost bias decision making?
    • Does the predicted cost create a minimum cost mind set or a maximum cost mind set?
  – Is the only result of the cost prediction to forecast what the system will not cost??
Mapping System Capability to Value

- **Will it work?** (Reliability)
- **What can it carry?**
  - Load Factors
  - Shock Loads
  - Payload Volume
  - Payload Services
  - Injection Accuracy
- **How expensive is it?**
  - Production cost
  - Launch cost
  - etc.

<table>
<thead>
<tr>
<th>Mission</th>
<th>Details</th>
</tr>
</thead>
</table>
| **A**   | 20,000 m/s dV required  
          | Value = $50000 * m  
          | Demand = 25% of total |
| **B**   | 15,000 m/s dV required  
          | Value = $30000 * m  
          | Demand = 60% of total |
| **C**   | 32,000 m/s dV required  
          | Value = $80000 * m  
          | Demand = 15% of total |

- Missions Attempted
- Missions Succeeded
- Total Value Delivered by Launch Vehicle
Methods of Discipline Integration

Goal: Understand How Organizational Structures influence Design and Operations Success of Complex Systems
Decision Making and Information Flow

Goal: Understand the Decision Making Relationship to Information Flow in the System Development and Operations Organizations

Information Theory
Decision Making Processes
Biased Information Sharing
◆ **Chief Engineer Interviews**

• Current focus is on design and launch (non-recurring engineering), not life cycle (recurring) costs
  – Observed differences in understanding of robustness, efficiency, affordability.
  – Early involvement in M&A, Operations missing

• SE focus on process needs balance with product focus
  – Skills to cross SE&I technical areas important

• SLS Program currently driven by schedule risk and cost (high complexity, constrained time)
  – Program challenges over time in mission clarity, mission stability, and funding stability
  – Testing still critical to identifying unintended consequences.

◆ **Organizational Communication**

• Various design communication models need to be managed.
• Error propagation can occur in communication process.
  – Communication deficiencies can be reduced through iterative discussion and improvement.
• Design engineers maintaining redundant margin early in design process.
Simulation Results

No margin: \( m = 1 \)

Static margin, \( m = 1.3 \)

Descending margin, \( m = 1.3 - 0.1i \) until \( m = 1 \)

- No margin condition reaches optimality quickest
- Descending margin still reaches optimal, but requires more iterations
- Margins are an issue
  - Interviews highlight real-world consequences
  - Simulations quantify extent of the problem
  - Still possible to achieve optimal design with descending margin, but takes additional time to achieve
Information Flow

- Information Flow through a program/project/activity is defined by Information Theory
  - Organizational communication paths
  - Board Structure

- Decision Making follows the First Postulate
  - Decision Process is specific to the decision being made
  - Tracked 3 SLS CRs, with 3 separate task team processes, all had equally rated effectiveness

- Margin is maintained by the Organization, not in the margin management tables
  - Biased Information Sharing
  - Margin Management is focused on Managing the Disciplines (informed by the System Integrating Physics)

- SLS Organizational Structure was defined by the LSE as a recommendation to the Chief Engineer and the Program Manager
**Information Theory Model**
- Information Theory can be used to understand decision making structures and information flow

\[ I = H = - \sum p_n \log p_n \]

**Practitioner’s Guidance**
- Understand and define the scope of each needed decision body

- Ensure that each decision body has all affected or contributing disciplines represented, including understanding of the types and magnitudes of uncertainties affecting decisions within that decision body’s scope, but no more

  \[ H(p_1, p_2, \ldots, p_n, q_1, q_2, \ldots q_m) \geq H(p_1, p_2, \ldots, p_n) \]

- Minimize the number of decision bodies based on scope. The efficiency of the structure decreases with distributed and overlapping scopes.

  \[ H(S, D, X, Y, Z) \leq H(S) + H(D) + H(X) + H(Y) + H(Z) \]
Sociology of Systems Engineering

Goal: Understand the Relationship of Sociological Factors and Cognitive Abilities to Successful System Engineering
Unintended Consequences are the result of human mistakes.

- Physics do not fail, we do not recognize the consequences.

Based on cognitive science, followed the work of Robert K. Merton in classifying unintended consequences.

- "The Unanticipated Consequences of Social Action", 1936

Classification

- Ignorance (limited knowledge of the problem)
- Historical Precedent (confirmation bias)
- Error (mistakes in calculations, working from habit)
- Short Sightedness (imperious immediacy of interest, focusing on near term and ignoring long term consequences)
- Cultural Values (cultural bias in what can and cannot happen)
- Self Defeating Prophecy (by stating the hypothesis you induce a set of conditions that prevent the hypothesis outcome)
Research Goal: Identify some of the key cognitive and organizational challenges in engineering complex systems and the implications to Systems Engineering

- University of Michigan, Design Science
  - Topic: Cognitive Science Perspective of Systems Thinking
    - Mapping Engineering Terminology to Cognitive Science Terminology to provide a scientific basis for the engineering cognitive concepts
    - Investigating Mediated Learning as a method to teach system thinking

<table>
<thead>
<tr>
<th>Cognitive Competencies from Frank, 2012</th>
<th>Related Concepts from Cognitive Psychology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Understand the whole system and see the big picture</td>
<td>Sensemaking; information integration; mental model formation; generalization</td>
</tr>
<tr>
<td>Understand interconnections</td>
<td>Induction; classification; similarity; information integration</td>
</tr>
<tr>
<td>Understand system synergy</td>
<td>Deductive inference</td>
</tr>
<tr>
<td>Understand the system from multiple perspectives</td>
<td>Perspective taking (direct mapping)</td>
</tr>
<tr>
<td>Think creatively</td>
<td>Creativity (direct mapping)</td>
</tr>
<tr>
<td>Understand systems without getting stuck on details</td>
<td>Abstraction; subsumption</td>
</tr>
<tr>
<td>Understand the implications of proposed change</td>
<td>Hypothetical thinking</td>
</tr>
<tr>
<td>Understand a new system/concept immediately upon presentation</td>
<td>Categorization; conceptual learning; inductive learning/inference</td>
</tr>
<tr>
<td>Understand analogies and parallelism between systems</td>
<td>Analogical thinking (direct mapping)</td>
</tr>
<tr>
<td>Understand limits to growth</td>
<td>Information integration</td>
</tr>
<tr>
<td>Ask good (the right) questions</td>
<td>Critical thinking</td>
</tr>
<tr>
<td>(Are) innovators, originators, promoters, initiators, curious</td>
<td>Inquisitive thinking</td>
</tr>
<tr>
<td>Are able to define boundaries</td>
<td>Functional decomposition</td>
</tr>
<tr>
<td>Are able to take into consideration non-engineering factors</td>
<td>Conceptual combination</td>
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<tr>
<td>Are able to “see” the future</td>
<td>Prospection</td>
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<tr>
<td>Are able to optimize</td>
<td>Logical decision-making</td>
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</table>
Policy and Law Application

Goal: Understand How Policy and Law Constrain the Design and Operations of a System and How the System Engineer Should Interpret These Constraints
Impact of Government Oversight Time Allocation Study

- Motivation: Industry and government leaders agree that government oversight leads to cost growth, but there is less agreement on how much and through what mechanisms.

“There is suggestive evidence that the cost of government-driven mission assurance and current Federal Acquisition Regulations (FAR) increase costs by factors of 3-5 times, not just 20-30%”

- Dr. Scott Pace, National Security Space Launch Programs - Testimony to Senate Committee on Defense Appropriations, Dirksen Senate Office Building 192, March 5 2014.

- Research:
  - Developed an empirical basis for measuring the extent and nature of the impact of oversight
  - Non-invasive “Time Allocation Study:” Statistically valid aggregated observations of how engineers actually spend their time throughout a product’s life cycle.
    - Part One: Collect time-recall diaries to develop a composite list of activities performed
    - Part Two: Survey Population over several months at random times per day to accurately observe amount of time spent on activities

Space Policy Implication on Engineering Decisions

- For Example
  - Capability driven solutions have soft schedule limits
    - SLS
    - Constellation
  - International agreements have harder schedule limits
    - Apollo-Soyuz
    - International Space Station
  - Political implications should be considered at the end of the decision process, not at the beginning
System Engineering Supporting Activities

Process Application and Execution for the Specific System


Each research task individually publishes results (18 journal and conference papers)

Conference on Systems Engineering Research (CSER) 2016

- 9 Papers on consortium research
  - “NASA Systems Engineering Research Consortium: Defining the Path to Elegance in Systems”, Michael D. Watson, Phillip A. Farrington, MSFC, University of Alabama in Huntsville
  - “Systems Engineering Processes in NASA and Commercial Projects”, Paul J. Componation, Kathyne Schomberg, Susan Ferreira, Jordan L. Hansen, University of Texas – Arlington, Iowa State University
  - “Use of Akaike’s Information Criterion to Assess the Quality of the First Mode Shape of a Flat Plate”, John H. Doty, University of Dayton
  - “A Multidisciplinary Coupling Analysis Method to Support Investigation of Ares 1 Thrust Oscillation”, D. Kis, M. Poetting, C. Wenger, and C. L. Bloebaum, Iowa State University
  - “Uses of Exergy in Systems Engineering”, Andrew Gilbert, Dr. Bryan Mesmer, Dr. Michael D. Watson, University of Alabama in Huntsville, MSFC
Systems Engineering Research Consortium has made considerable progress in the definition of systems engineering and the approaches to it.

System Engineering is the engineering discipline which integrates the system functions, system environment, and the engineering disciplines necessary to produce and/or operate an elegant system.

2 Primary Focuses defined in a Systems Engineering Framework

- System design and integration
- Discipline integration

- Systems Engineering Processes are a supporting function

Developed Systems Engineering Postulates and Hypotheses

Developed several methods and tools for conducting integrated system design, analysis, and integration, and discipline integration

- System Integration
  - System Integrating Physics
  - Engineering Statistics
  - State Variable Analysis
  - System Design and Optimization
  - System Value

- Discipline Integration
  - Decision Making and Information Flow
  - Sociology of Systems Engineering
  - Policy and Law Application

- Processes Application
Backup
Systems Engineering Principles

◆ Principle 1: Systems engineering is driven by the characteristics of the specific system

◆ Principle 2: Complex Systems build Complex Systems

◆ Principle 3: The focus of systems engineering during the development phase is a progressively deeper understanding of the interactions, sensitivities, and behaviors of the system
  
  • Sub-Principle 3(a): Requirements are specific, agreed to preferences by the developing organization
  • Sub-Principle 3(b): Requirements are progressively defined as the development progresses
  • Sub-Principle 3(c): Hierarchical structures are not sufficient to fully model system interactions and couplings
  • Sub-Principle 3(d): A Product Breakdown Structure (PBS) provides a structure to integrate cost and schedule with system functions

◆ Principle 4: Information Theory is a fundamental mathematical concept of systems

◆ Principle 5: Systems engineering has an essential role during operations and decommissioning

◆ Principle 6: Systems engineering influences and is influenced by organizational structure and culture

◆ Principle 7: Systems engineering maps and manages the discipline interactions within the organization that represent the interactions of the system

◆ Principle 8: Decision quality depends on the system knowledge represented in the decision making process

◆ Principle 9: Both Policy and Law must be properly understood to not over constrain or under constrain the system implementation

◆ Principle 10: Systems engineering decisions are made under uncertainty accounting for risk
Interviewed 12 Marshall engineers/designers (w/J. Shelton)
- Understand strategies used to integrate subsystems with each other

Common strategy across subsystems – margins
- Keep some percentage of a parameter in “back pocket” as hedge for future negotiations
- Biased Information Sharing
- (Here, “margins” different from “safety margin”)

How does maintaining a margin affect optimality of the final design?
- Model as simple 2 Player System with 2 design parameters
- 15 problem test suite
## ORIGINAL NASA STUDY AND NEW STUDY COMMERCIAL FOCUSED PROJECTS

Correlation of 0.4 or greater noted Project Success and System Engineering Processes

<table>
<thead>
<tr>
<th>Process</th>
<th>Agriculture</th>
<th>Aerospace</th>
<th>Defense and Security</th>
<th>Transportation</th>
<th>Communications</th>
<th>Electronics</th>
<th>Energy</th>
<th>Infrastructure</th>
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<tr>
<td>Technical success relative to initial req.</td>
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<td>Technical success relative to similar projects</td>
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<td>On schedule relative to original project plan</td>
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<td>On schedule relative to similar projects</td>
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<td>On budget relative to original project plan</td>
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<td>Satisfaction with project management process</td>
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<td>Overall project success (organization view)</td>
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<td>Overall project success (stakeholder view)</td>
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</tbody>
</table>

Processes with > 3 Correlations ≥ .4
Processes with < 3 Correlations ≥ .4

Original Study Correlations
<table>
<thead>
<tr>
<th>Process</th>
<th>Original Study</th>
<th>New Study</th>
<th>Correlations</th>
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</thead>
<tbody>
<tr>
<td>Technical success relative to initial req.</td>
<td>.5</td>
<td>.6</td>
<td>.4</td>
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<tr>
<td>Technical success relative to similar projects</td>
<td>.5</td>
<td>.6</td>
<td>.5</td>
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<tr>
<td>On schedule relative to original project plan</td>
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<td>.6</td>
<td>.4</td>
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<tr>
<td>On schedule relative to similar projects</td>
<td>.5</td>
<td>.4</td>
<td>.4</td>
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<tr>
<td>On budget relative to original project plan</td>
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<td>.6</td>
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<tr>
<td>On budget relative to similar projects</td>
<td>.4</td>
<td>.4</td>
<td>.5</td>
</tr>
<tr>
<td>Satisfaction with project management process</td>
<td>.5</td>
<td>.5</td>
<td>.4</td>
</tr>
<tr>
<td>Overall project success (organization view)</td>
<td>.5</td>
<td>.5</td>
<td>.5</td>
</tr>
<tr>
<td>Overall project success (stakeholder view)</td>
<td>.6</td>
<td>.4</td>
<td>.4</td>
</tr>
</tbody>
</table>

Processes with > 3 Correlations ≥ .4
Processes with < 3 Correlations ≥ .4
1. **Stakeholder Expectations**
2. **Technical Requirements Definition**
   a. Logical Decomposition
3. **Design Solution Definition**
4. **Product Implementation**
5. **Product Integration**
6. **Product Verification**
   a. Product Validation
7. **Product Transition**
8. **Product Operation and Sustainment**
9. **Technical Planning**
   a. Technical Risk Management
   b. Technical Assessment
   c. Decision Analysis
10. **Configuration Management**
    a. Technical Data Management
    b. Requirements Management
    c. Interface Management

Focus on the intent of the processes not the processes themselves.