Mission Reliability Trade Studies for Lunar Exploration Architectures Using 
MODELCENTER® and CENTERLINK™

Revision A
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Overview:
- Engineering services firm based in Atlanta (small business concern)
- Founded in 2000 as spin-off from the Georgia Institute of Technology
- Averaged 130% growth in revenue each year since 2001
- 85% of SEI staff members hold degrees in engineering or science

Core Competencies:
- Advanced Concept Synthesis for launch and in-space transportation systems
- Financial engineering analysis for next-generation aerospace applications and markets
- Technology impact analysis and quantitative technology portfolio optimization

Introduction to SpaceWorks Engineering, Inc. (SEI)
Modeling Lunar Architectures in ModelCenter®
Approach to Reliability Modeling
Introduction of Sample Problem
ModelCenter® / CenterLink™ Demonstration
Lessons Learned
Modeling Lunar Architectures in ModelCenter®
ESAS Lunar Exploration Architecture Overview (circa September 2005)

Note: Notional representation of lunar exploration architecture. Architecture elements may not be in scale.
SpaceWorks Engineering, Inc. (SEI) developed **MSAT (Mission Scenario Assessment Tool)** in 2002 and 2003 as a fast and flexible modeling environment for space exploration architectures (moon, Mars, asteroids). Several instances of MSAT have been created, including a simulation of NASA’s recent ESAS architecture.

**Phoenix Integration’s ModelCenter®:**
- Integration framework automates execution
- Data management and collection

**Pi Blue Software’s OptWorks® and ProbWorks®:**
- Top-Level Optimization and Monte Carlo functions

**Individual Element Models:**

- **Stage Sizer**
  - Parametric EDS stages, upper stages, landers, ascent stages
  - Off-line calculations for mission ΔV’s are included as response surface equations

- **CapSize**
  - Capsule sizer including ECLSS and recovery components

- **Cost**
  - NAFCOM-derived CERs for non-recurring costs
  - Ground and flight operations costs, life-cycle cost summaries

- **Reliability**
  - Probabilistic simulations for mission reliability and crew safety

**Exploration Architecture**
**Individual Vehicle Elements**

**Modeling Approach**
MSAT: Mission Scenario Analysis Tool (in ModelCenter®)
Approach to Reliability Modeling
Top-level reliability and safety metrics are calculated using two proven approaches. Each technique is relatively easy to implement at various desired levels of modeling fidelity. Uncertainties in basic assumptions and other input parameters can be included explicitly and propagated to top-level forecast variable distributions using Monte Carlo probabilistic simulation approaches.

**Fault Tree Analysis (FTA)**
- Used for loss of mission (LOM) calculations
- Element-based structure
  - Each architecture flight element is modeled to 2 or 3 levels of FTA detail

**Reliability Block Diagrams (RBD)**
- Used for loss of crew (LOC) calculations
- Event-based structure
  - Each initiator event can result in one or more outcomes with associated probabilities
Uncertainty distributions in the probability of failure ($P_f$) can be introduced at lowest levels, then propagated to top-level forecast variable as a probability density function.

Fault Tree Analysis (FTA)

Notional data for illustration only

Top-level chance of mission failure is 22%

- **Or gate** (subsystems are not redundant. Failure of either leads to element failure):
  - $P_f = 0.19$
  - $P_f = 0.1$
  - $P_f = 0.1$

- **And gate** (subsystems are redundant so both must fail before element fails):
  - $P_f = 0.04$
  - $P_f = 0.2$
  - $P_f = 0.2$

Uncertainty distributions in the probability of failure ($P_f$) can be introduced at lowest levels, then propagated to top-level forecast variable as a probability density function.
Launch abort failure contributes .002 LOC events to every mission. All LOC contributors are summed to get an overall estimate of LOC per mission.

Reliability Block Diagrams (RBD)
## Loss of Crew (LOC)
**Reliability Block Diagram**

### Input/Output ProbWorks

#### Output Distribution Statistics

## Loss of Mission (LOM)
**Fault Tree for Multiple Architecture Elements**

## Components of SEI’s Architecture Reliability Model

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<tr>
<th>Name</th>
<th>Value</th>
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<th>Likeliest Value</th>
<th>Upper Value</th>
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Introduction to Sample Problem
Problem Statement

Objectives

NASA’s Exploration Program Managers wish to understand the implications of operating the lunar lander descent module engines at a reduced throttle to improve their reliability. The assumption is that engines operating at a de-rated thrust level will be more reliable than those operating at 100% throttle (or even >100% throttle based on nominal thrust points). Uncertainties in the reliability calculations must be simulated throughout the trade study, and reported results should be tabulated at the 80% confidence level.

The following trends are expected, but can they be quickly quantified?

- Engine reliability will increase with reduced operating throttle and this should have a positive effect on overall mission reliability.

Note: in the present simulation, we will temporarily disable some of the built-in redundancy of the LSAM lander in order to show larger effect on this trade. In reality, the ESAS lander has built-in engine redundancy on the descent module that mitigates potential engine failures.

- Operating the engine at reduced thrust levels has the disadvantage of requiring more ΔV to perform the lunar orbit insertion (LOI) lunar descent maneuvers. In addition, engine Isp is reduced at lower operating throttle. Therefore, the vehicle must be designed to carry more propellant to complete the baseline mission. Overall launch mass is expected to be higher as a result.
Descent Module Engine **Shutdown Probability** vs. Throttle

Descent Module Engine **Thrust** vs. Throttle

Descent Module Engine **Isp** vs. Throttle

**Various Descent Module Engine Parameters vs. Throttle**

Notional data for illustration only
Subproblem Setup in MSAT
- Note: Individual PCs are each running Windows XP Professional and not clustered

**Distributed Computing Resources**
ModelCenter® / CenterLink™ Demonstration
Sample Results from Demonstration

Trade Studies
Various Descent Module Engine Parameters vs. Throttle
Lessons Learned
Lessons Learned from Using CenterLink™ in ModelCenter®

- **Setup**
  - 2-3 days for installation and configuration of CenterLink™
  - 1-2 days for testing and verification of new models and pxc file

- **Speed**
  - Improvements of 4-5x in execution time (for today’s demo) relative to sequential execution of trade study points
  - Expected speed-up is proportional to number of computers in network

- **Improvements to Design Process**
  - Allows the designer more opportunities to evaluate “what-if” scenarios in real time
  - Enables exploration of larger design spaces
    - Should improve efficiency of non-gradient based optimizers (genetic algorithms, coordinate pattern search, grid-search, random walk, etc.)
  - Use of Monte-Carlo simulation becomes more practical in multi-disciplinary design optimization (MDO)
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