Trade Studies Module

Exploration Systems Engineering, version 1.0
Module Purpose: Trade Studies

♦ Describe the typical trade study process and show an example.

♦ Recognize that trade studies support decision making throughout the project lifecycle.

♦ Provide some trade study heuristics to improve the application and value of future trade studies.

♦ Describe and provide a trade tree - an option management graphic.
What is a Trade Study?

♦ A **trade study** (or trade-off study) is a formal tool that supports decision making.

♦ A **trade study** is an objective comparison with respect to performance, cost, schedule, risk, and all other reasonable criteria of all realistic alternative requirements; architectures; baselines; or design, verification, manufacturing, deployment, training, operations, support, or disposal approaches.

♦ A **trade study** documents the requirements, assumptions, criteria and priorities used for a decision. This is useful since new information frequently arises and decisions are re-evaluated.
Trade Studies Support Decision Making Throughout the Development Lifecycle

Trade studies support:

- Requirements development - e.g., to resolve conflicts; to resolve TBDs and TBRs
- Functional allocations - e.g., system architecture development
- System design - e.g., assess the impact of alternative performance or resource allocations
- Investigate alternate technologies for risk or cost reduction
- Assess proposed design changes
- Make/buy decisions (i.e., build the part from a new design or buy from commercial, existing sources)
The Trade Study Process (1/2)

1. Define the objectives of the trade study

2. Review inputs, including the constraints and assumptions

3. Choose the evaluation criteria and their relative importance (these can be qualitative)

4. Identify and select the alternatives

5. Assess the performance of each option for each criteria

6. Compare the results and choose an option

7. Document the trade study process and its results
**Trade Study Process**

**Study Inputs:**
- Constraints
- Ops Concept
- Existing requirements
- Assumptions
- Relevant plans & documents

**Trade Study**
- Define Evaluation Criteria/Weighting factors
- Determine Scope of the Trade Study
- Generate Viable Alternative Solutions
- Create Trade Tree
- Evaluate Alternatives Against Criteria
- Perform Sensitivity Analyses

**Trade Study Results**
- Data - graphical
- Recommended approach
- Benefits
- Resulting risk posture
- Summary of results
- Summary of approach
Decisions to Make Before Beginning a Trade Study

♦ Has success been defined?

♦ Which trades need to be done and at what phase of the project?

♦ For each trade what criteria will be used and what are their relative weights?

♦ How deep will the analysis go?
  • Deep enough to make a decision with confidence, but no deeper.

♦ Criteria for doing a trade study?
  • The easiest trade study to do is the one that does not have to be done.
  • Do not do a trade study just because you can.
Evaluation Criteria — Measures (1/2)

♦ Trade studies depend upon having criteria for making decisions based on *measures of effectiveness* (voice of the customer) and *measures of performance* (voice of the engineer).

♦ **Measure of Effectiveness** (MOE) - A measure of how well mission objectives are achieved. MOEs are implementation independent - they assess ‘how well’ not ‘how’.

♦ Example measures of effectiveness include
  - Life cycle cost
  - Schedule, e.g., development time, mission duration
  - Technology readiness level (maturity of concept/hardware)
  - Crew capacity
  - Payload Mass
Measure of Performance (MOP) - A quantitative measure that, when met by the design solution, will help ensure that an MOE for a product or system will be satisfied. There are generally two or more measures of performance for each MOE.

Example measures of performance
- Mass
- Power consumption
- Specific impulse
- Consumables required
- Propellant type

Both MOEs and MOPs are system figures of merit; an MOE refers to the effectiveness of a solution and an MOP is a measure of a particular design.
Trade Study Heuristics

1. Rules of Thumb:
   ✓ Manage the number of options under consideration
   ✓ Revisit the original problem statement
   ✓ If a baseline solution is established, use it as a ‘yardstick’ to measure the alternatives.

2. Decisions are frequently made with imperfect information.
   1. Do not get stuck in ‘analysis paralysis’.
   2. Decide how deep the analysis must go. {Deep enough to make a decision with confidence, but no deeper.}

3. Does the decision feel right? If not, why?

4. Conduct further what-if scenarios by changing assumptions.

5. Reject alternatives that do not meet an essential requirement.

6. Ignore evaluation criteria that do not discriminate between alternatives.

7. Trades are usually subjective; numeric results usually give a false sense of accuracy.

8. If an apparent preferred option is not decisively superior, further analysis is warranted.
### Example Decision Matrix Trade Study

#### Decision Matrix Example for Battery

<table>
<thead>
<tr>
<th>CRITERIA</th>
<th>Mandatory (Y=1/N=0)?</th>
<th>Weight</th>
<th>ENTER SCORES</th>
<th>Scale</th>
<th>Extend Old Battery Life</th>
<th>Buy New Batteries</th>
<th>Collect Experiment Data With Alternative Experiment</th>
<th>Cancelled Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mission Success (Get Experiment Data)</td>
<td>1</td>
<td>30</td>
<td></td>
<td>3 = Most Supportive 1 = Least Supportive</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>Cost per Option</td>
<td>0</td>
<td>10</td>
<td></td>
<td>3 = Least Expensive 1 = Most Expensive</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Risk (Overall Option Risk)</td>
<td>0</td>
<td>15</td>
<td></td>
<td>3 = Least Risk 1 = Most Risk</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Schedule</td>
<td>0</td>
<td>10</td>
<td></td>
<td>3 = Shortest Schedule 1 = Longest Schedule</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Safety</td>
<td>1</td>
<td>15</td>
<td></td>
<td>3 = Most Safe 1 = Least Safe</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Uninterrupted Data Collection</td>
<td>0</td>
<td>20</td>
<td></td>
<td>3 = Most Supportive 1 = Least Supportive</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>WEIGHTED TOTALS in %</td>
<td>100%</td>
<td>3</td>
<td></td>
<td>73%</td>
<td>60%</td>
<td>77%</td>
<td>0%</td>
<td></td>
</tr>
</tbody>
</table>
**Do A Reality Check On The Tentative Selection**

*Key questions to ask:*

- Have the requirements and constraints truly been met?
- Is the tentative selection heavily dependent on a particular set of input values and assumptions, or does it hold up under a range of reasonable input values (i.e., is it ‘robust’)?
- Are there sufficient data to back up the tentative selection?
- Are the measurement methods sufficiently discriminating to be sure that the tentative selection is really better than the alternatives?
  - If close results, is further analysis warranted?
- Have the subjective aspects of the problem been fully addressed?
- Test the decision robustness.
  - Is the tentative selection very sensitive to an estimated performance or constraint? If so, explore the full reasonable range of each performance variable to understand the domain where your tentative selection is appropriate.
A trade tree is a graphical method of capturing alternatives with multiple variables.

Each layer of the tree represents some aspect of the system that will be treated in a trade study to determine the best alternative.

Some alternatives can be eliminated (or ‘pruned’ ) a priori because of technical feasibility, launch vehicle constraints, cost, risk or some other disqualifying factor.

The total number of alternatives is given by the number of end points of the tree.

Even with just a few layers, the number of alternatives can increase quickly, so manage their numbers.
Top-level Trade Tree-Example for Mars

Mission Type
- Conjunction Class
- Long Surface Stay
- Opposition Class
- Short Surface Stay

Cargo Deployment
- Pre-Deploy
- All-up

Mars Capture Method
- Aerocapture
- Propulsive

Mars Ascent Propellant
- ISRU
- No ISRU

Interplanetary Propulsion
- NTR
- Electric
- Chemical

Decision Package 1
- Long vs Short

Special Case
- 1-year Round-trip

Human Exploration Of Mars

Exploration Systems Engineering: Trade Studies Module

NTR - Nuclear Thermal Rocket
Electric= Solar or Nuclear Electric Propulsion
Earth-Moon Transit Trade Tree

Earth-Moon Transit Trade Tree

H = Human Mission Segment
C = Cargo Mission Segment

Orbital Operations & Earth-Moon Transit; Propulsion Options

- All Chemical + Electric
- NTR
- Other Hybrid Options

Lunar Descent/Ascent Lander Options

- Integrated Crew Transit/Lander Function
- Modular Elements

Earth EDL Orbit Capture Options

- Aerocapture
- Propulsive Capture

Earth Entry Vehicle L/D Options

- Low L/D
- Medium L/D
- High L/D

Location
Destination
Dock
LowDock
Dock/Undock
Dock Optional
Transportation Functions

Outbound
Lunar Surface (LS)
Inbound

High Priority
Medium Priority
Low Priority

1,4&C4,5-8,12
9,13
1-10
11
2,13
1,3-6,10,12
7,8
9,13

1-11,13
7,8
1-6,9-13

1-4, 7-13
5, 6

Pert-Depolyed Surface Cargo
**Example: Earth-Moon Transit Trade Option Analyses**

**Key measure of performance: mass**

- TLI stages dominate mass composition.
- Ascent/Descent stages for L1 approach are significantly higher than for LO approach (combination of higher ΔV and habitat masses).
- NTR propulsion applied to TLI function results in significant IMLEO benefit due to influence of TLI maneuver.
- Single crew module carried through entire mission has large scaling effect on all propulsive stages.
Trade studies are common decision-support tools that are used throughout the project lifecycle to capture and help assess alternatives.

The steps in the trade study process are:
1. Define the objectives of the trade study
2. Review inputs, including the constraints and assumptions
3. Choose the evaluation criteria and their relative importance
4. Identify and select the alternatives
5. Assess the performance of each option for each criteria
6. Compare the results and choose an option
7. Document the trade study process and its results

Trade trees are graphical tools that help manage multi-variable options.
Back-up Slides
for Trade Studies Module
Trade Studies

♦ The systems engineering method relies on making design decisions by the use of trade studies.

♦ Trade studies are necessary when the system is complex and there is more than one design approach.

♦ Trade studies involve the comparison of alternatives
  • Good to explore a number of different alternatives
  • Alternatives should be compared at the same level of detail
  • Key is for characteristics to be evaluated relative to one another

♦ Trade study approaches:
  • Comparing advantages and disadvantages of several alternatives; can be qualitative.
  • Using a formal ranking system based on multiple criteria and a weighting system; quantitative approach.
Example Trade Study Outline

Purpose of Study
- Resolve an Issue
- Perform Decision Analysis
- Perform Analysis of Alternatives (Comparative analysis)

Scope of Study
- State level of detail of study
- State Assumptions
- Identify Influencing requirements & constraints

Trade Study Description
- Describe Trade Studies To Be Performed
- The Studies Planned To Make Tradeoffs Among Concepts, User Requirements, System Architectures, Design, Program Schedule, Functional, Performance Requirements, And Life-cycle Costs
- Describe Trade Methodology To Be Selected
- Describe Technical Objectives
- Identify Requirements And Constraints
- Summarize Level of Detail of Analysis

Analytical Approach
- Identify Candidate solutions to be studied/compared
- Measure performance
  - Develop models and measurements of merit
  - Develop values for viable candidates
- Selection Criteria -- risk, performance, and cost are usually at least three of the factors
- Scoring
  - Measures of results to be compared to criteria
    - Weighted reflecting their relative importance in the selection process
- Sensitivity Analysis

Trades Results
- Select User/Operational Concept
- Select System Architecture
- Derive Requirements
  - Performing trade studies to determine alternative functional approaches to meet requirements
  - Alternate Functional Views
  - Requirements Allocations
- Derive Technical/Design Solutions
- Cost Analysis Results
- Risk Analysis Results
- Understand Trade Space
Focused Trade Study

Phase I Analysis

Mass Estimation Benchmark
“Pseudo-Apollo”

Baseline Reference Mission

Requirements
Design Environments
Subsystem Technologies

Architectural Variations
• 2-launch solution
• 3-launch solution
• 25mt launch constraint
• Initial CEV/lander mating in LEO
• Single pass aerocapture, deorbit phasing, and capability of land landing

Parametric Variations
• Alternate propellants.
• Alternate power sources.
• Variation in return payload
• Variation of delivered payload to the lunar surface
• All versus partial crew to the lunar surface
• Reduce crew size to 2
• Increase crew size to 6
• Change in time between launches (7 to 30 days)
• Reduce lunar surface stay time to 3 days
• Increase lunar surface stay time to 14 days
• Effects of elimination of CEV contingency EVA requirement
• Mass effect of supplemental radiation shielding

Architectural Variation
• Lunar Orbit Rendezvous of CEV/lander

Sensitivity Analyses

Exploration Systems Engineering: Trade Studies Module
Focused Trade Study Results

Mission Design

L1-Earth Co-Planar Inbound Delta V Requirement (m/s)

• Moon: Inclination near maximum, Distance near perigee
• L1 Departure Time in June 2006

Initial Mass in LEO

Reference Operations Concept

Key Figures of Merit

Safety
• # of Critical Events
• Mission Complexity
• Abort Options
• Crew Time
• Technology Risk
• Probability of launch success
• Etc.

Effectiveness
• Total Mass
• Dry Mass
• Surface Time
• Etc.

Extensibility
• Long-Stays
• Mars
• Other destinations
• Etc.
Affordability Trades

“Best Bang for the Buck”

Objective (Goal) vs. Threshold (No Greater Than)

Region for Marginal Performance Improvement

Region for “Best Bang for Buck”

High Cost Payoff Small Performance Penalty... Consider

Cost vs. Performance

Augustine’s Law of Insatiable Appetites
The last 10 percent of performance generates $\frac{1}{3}$ of the cost and $\frac{2}{3}$ of the problems.
**Broad Trade Study Overview**

- Multi-center team assessed potential mission concept trade options around two broad Lunar Mission Scenarios
  - LMS-1 - global access, 7-day surface stays
  - LMS-2 - south pole access, 30-90 day surface stays
- Screening of breakthrough technologies conducted for applicability to Spirals 1 and 2
- Trade tree defined for each LMS served as the basis for trade option identification
- Initial down-selection of major trade tree branches was performed to:
  - Establish data/rationale for potentially infeasible mission concepts
  - Provide focus on trade options to be analyzed in more detail
- Analysis of numerous trades and options conducted
  - LMS-1: 10 trade options + alternatives
  - LMS-2: 13 trade options + alternatives
Example: Trade Option Analyses

LMS-1, TO 2 - Propellant Trade

Percent Increase of IMLEO (%)

- Storables
- LOX/RP1
- LOX/Methane

Ascent Only  Ascent + Descent  Ascent + Descent + TEI  All Stages

Note - Percent Increase of IMLEO compared to Baseline (All LOX/LH2)
## ECLSS Design Options for a Lunar Rover

<table>
<thead>
<tr>
<th>Design Factor</th>
<th>Option 1</th>
<th>Option 2</th>
<th>Option 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovery</td>
<td>Open</td>
<td>Partially Closed</td>
<td>Totally Closed</td>
</tr>
<tr>
<td>Consumables</td>
<td>Non-regenerate</td>
<td>Base regenerate</td>
<td>Vehicle regenerate</td>
</tr>
<tr>
<td><strong>O\textsubscript{2}</strong></td>
<td>Carry all</td>
<td>Carry all</td>
<td>Carry part; recover part from CO\textsubscript{2} &amp; H\textsubscript{2}O</td>
</tr>
<tr>
<td><strong>CO\textsubscript{2}</strong></td>
<td>Absorb, dump</td>
<td>Absorb, carry back to base</td>
<td>Regenerate in vehicle</td>
</tr>
<tr>
<td><strong>H\textsubscript{2}O</strong></td>
<td>Absorb, dump</td>
<td>Condense and carry back or sublimate</td>
<td>Electrolysis in vehicle</td>
</tr>
<tr>
<td>Cooling</td>
<td>Sublimator</td>
<td>Sublimator</td>
<td>Radiator</td>
</tr>
<tr>
<td>Losses</td>
<td>O\textsubscript{2} &amp; H\textsubscript{2}O</td>
<td>Only lose water for cooling by sublimator; O\textsubscript{2} is recovered at base</td>
<td>Nothing</td>
</tr>
</tbody>
</table>
## Example Qualitative Decision Matrix
### For a Lunar Thermal Control Trade Study

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Single Phase Fluid</th>
<th>Two Phase Fluid</th>
<th>Heat Pipe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Safety: (3)</td>
<td>Low</td>
<td>High</td>
<td>Low-Medium</td>
</tr>
<tr>
<td>Operating</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pressure</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Safety:</td>
<td>Fluid Dependent</td>
<td>Fluid Dependent</td>
<td>Fluid Dependent</td>
</tr>
<tr>
<td>Toxicity</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Safety:</td>
<td>Fluid Dependent</td>
<td>Fluid Dependent</td>
<td>Fluid Dependent</td>
</tr>
<tr>
<td>Flammability</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reliability</td>
<td>High</td>
<td>Fair</td>
<td>Fair</td>
</tr>
<tr>
<td>(1)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Performance:</td>
<td>Low</td>
<td>High</td>
<td>Fair</td>
</tr>
<tr>
<td>(2)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pumping Cost</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Complexity:</td>
<td>Simple</td>
<td>Nominal</td>
<td>Complex</td>
</tr>
<tr>
<td>(4)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Controls</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Complexity:</td>
<td>Simple</td>
<td>Nominal</td>
<td>Complex</td>
</tr>
<tr>
<td>(5)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manufacturing</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Difficulty</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The Trade Study Process (2/2)

Establish the study problem
- Develop a problem statement
- Identify requirements and constraints
- Establish analysis level of detail

Select and set up methodology
- Choose trade-off methodology
- Develop and quantify criteria, including weights where appropriate

Review inputs
- Check requirements and constraints for completeness and conflicts
- Develop customer-team communication

Identify and select alternatives
- Identify alternatives
- Select viable candidates for study

Analyze results
- Calculate relative value based on chosen methodology
- Evaluate alternatives
- Perform sensitivity analysis
- Select preferred alternative
- Re-evaluate results

Measure performance
- Develop models and measurements of merit
- Develop values for viable candidates

Document process and results
Further Considerations for Trade Studies and Class Discussion

Based on Observations from The University of Texas at Austin Senior Mission Design Class, 2007 (Department of Aerospace Engineering)
Trade Study Considerations (1/4)

Assumptions

♦ Trade studies are based on assumptions the team makes.

♦ *Examples* of driving assumptions:
  - Crew size assumption drives the amount of consumables and the viability of an open ECLSS versus partially closed ECLSS.
  - Mission duration assumption drives the amount of power required which in turn drives the choice of power subsystem.
  - Landing location on the moon drives delta-v requirements which in turn drives best orbit selection and propulsion subsystem.

♦ Changing assumptions within the trade study allows the team to perform a ‘what-if’ analysis.
  - Allows the team to understand the integrity of the design alternative selected
  - Shows the importance of that assumption
Trade Study Considerations (2/4)

Mission environment

♦ The trade space for subsystem alternatives is often defined by the space environment for the mission.
  • Why use RTGs when the mission is at 1 AU or on the Moon. When do we use RTGs? For deep space missions where solar intensity is less.
  • Types of thermal control - need to consider the operating temperature extremes
  • Types of rendezvous and ‘landing’ with a NEO - need to understand the orbit, spin and known composition of asteroid
  • Sometimes the worst of the space environment, such as a solar particle event (SPE) for radiation, can be avoided by operational solutions rather than design solutions, i.e., perform the mission during the minimum of the solar cycle or using early warning sentinel satellites.
  • Lunar missions - is your system operating at one particular location or region (like Apollo at equatorial latitudes), or at global sites depending on the particular mission?
Importance of information for each alternative

♦ Trade study analysis should use information that is relevant. Extraneous information can distract the decision maker.

♦ ‘Materials’ example:
  • Do material characteristics such as tensile strength and Poisson’s ratio really matter in the selection process.
  • In considering so many material alternatives, was heritage considered as a design factor, i.e, has this material flown on previous space missions?
    • If not, what is the cost to your project for bringing that technology up to flight-ready status?
    • Did you violate one of your original mission scope assumptions of using current state-of-the-art technology?
  • In considering material alternatives, were other correlated factors included which would shorten the trade space to begin with, such as material’s impact on radiation protection; use for a pressure vessel vs. landing struts.
Trade Study Considerations (4/4)

Trade study vs. spacecraft design

♦ Is a trade study really necessary?
  - Cargo capsule example:
    - Structural design of capsule is not a trade. Evaluation criteria are the design characteristics; heritage is reference information for actual design work.
  - Seismic vehicle example:
    - Two existing concepts versus determining which characteristics are most valuable for your team design to include
  - Mars habitat example:
    - What are the communications requirements for the mission (voice, video, etc) => amount of bandwidth to specify for comm subsystem.

♦ What makes for a successful mission? Answer defines which trades are of most importance & might drive additional trades.
  - Maximum surface exploration time => robust power and ECLSS
  - Precise NEO orbit tracking for X years => tracking method
  - 1-week cargo delivery => launch vehicle availability and mission plan