A Systematic Concept Exploration Methodology Applied to Venus In Situ Explorer

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Motivation

• Overarching Questions
  – On Day 1 of a design problem, what process can be followed to allow quick and efficient conversion of program objectives into a family of candidate engineering solutions?
  – How would such a process be applied for an interplanetary robotic mission?

• Challenges
  – Relatively little quantitative information is available
  – Concept search should be comprehensive, particularly applicable for exploration missions of classes that have never been attempted
  – Search must be accomplished in a time-efficient manner without spending years on concept analysis
Venus In Situ Explorer (VISE)

- New-Frontiers-class mission called for by NASA 2006 Solar System Exploration Roadmap
- Acceptable mission for proposal according to NF-3 Program Announcement ($650 million, excluding LV)
- Aerial mission (atmospheric study) with capability of descending to surface (surface study) and returning to altitude to analyze samples
- Earliest launch opportunity: 2013
- Precursor to 2025 Venus Mobile Explorer
### Brief History of Venus Exploration

<table>
<thead>
<tr>
<th>Launch Date</th>
<th>Missions with a Planned Venus Encounter</th>
</tr>
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<tbody>
<tr>
<td>1961-1965</td>
<td>16</td>
</tr>
<tr>
<td>1966-1970</td>
<td>7</td>
</tr>
<tr>
<td>1971-1975</td>
<td>5</td>
</tr>
<tr>
<td>1976-1980</td>
<td>4</td>
</tr>
<tr>
<td>1981-1985</td>
<td>6</td>
</tr>
<tr>
<td>1986-1990</td>
<td>2</td>
</tr>
<tr>
<td>1991-1995</td>
<td>0</td>
</tr>
<tr>
<td>1996-2000</td>
<td>1</td>
</tr>
<tr>
<td>2001-2005</td>
<td>2</td>
</tr>
</tbody>
</table>

- **Dec. 1962:** Mariner II Flyby
- **Dec. 1970:** Venera VII Landing
- **Dec. 1978:** Pioneer Probe Entry
- **June 1985:** Vega Balloon Operation
- **Dec. 1991:** Collapse of USSR

Cumulative Surface Time (hours):

- 1961-1965: 16 hours
- 1966-1970: 7 hours
- 1971-1975: 5 hours
- 1976-1980: 4 hours
- 1981-1985: 6 hours
- 1986-1990: 2 hours
- 1991-1995: 0 hours
- 1996-2000: 1 hour
- 2001-2005: 2 hours
Methodology Summary

Georgia Tech Generic IPPD Methodology

- Top-Down Design
- Decision Support Process
- Quality Engineering Methods
- Computer-Integrated Environment
- Systems Engineering Methods

1. Establish the Need
2. Define the Problem
3. Establish Value
4. Generate Feasible Alternatives
5. Evaluate Alternatives
6. Make Decision

- Robust Design Assessment & Optimization
- 7 M&P Tools and Quality Function Deployment (QFD)
- On-Line Quality Engineering & Statistical Process
- Requirements & Functional Analysis
- System Decomposition & Functional Allocation
- System Synthesis Through MDO
- System Analysis & Control
Methodology Summary

Georgia Tech Generic IPPD Methodology

1. ESTABLISH THE NEED
2. DEFINE THE PROBLEM
3. ESTABLISH VALUE
4. GENERATE FEASIBLE ALTERNATIVES
5. EVALUATE ALTERNATIVES
6. MAKE DECISION
Methodology Summary

Central Steps in the GT Generic IPPD Methodology

1. Objectives Definition and Prioritization
2. Engineering Characteristics Definition
3. Mapping of Objectives to Engineering Characteristics
4. Generation of Feasible Concept Alternatives
5. Evaluation of Alternatives with Modeling & Simulation discussion

Key Steps Covered Here

Tools Illustrated Here

- Tree Diagrams
- Analytical Hierarchy Process (AHP) Prioritization Matrices
- Interrelationship Digraphs
- Quality Function Deployment (QFD)
- Morphological Matrices
- Operational Architectures
- Pugh Concept Selection Matrices
- Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)
1. Objectives Definition and Prioritization

Tree Diagram

- One of the Seven Management & Planning Tools developed from post-WWII operations research and work in Total Quality Control (TQC).
- Structures brainstormed objectives ("What do you want to achieve?").

Venus In Situ Explorer: Customer Requirements

Science Return
- Surface Analysis
  - Composition
  - Morphology
- Atmospheric Study
- Mobility
- Survivability
- Communication
- Timely Mission Completion

Vehicle Attributes
- Environment Resistance
- Vertical
- Autonomy

Programmatic
- Data Capability
- Data Management
- Mission Simplicity
- Affordability
- Extension Potential
- Technology Demonstration
- Robustness
- Low Risk
- Operation Cost
- Weight
- Development Cost
1. Objectives Definition and Prioritization

Analytic Hierarchy Process (AHP) Prioritization Matrix

- Technique for prioritization of objectives based on pairwise comparisons on a ratio scale introduced by Saaty in 1970s.
- In this methodology, AHP is used to generate weights on objectives.
2. Engineering Characteristics Definition

Tree Diagram

- Structures brainstormed engineering characteristics ("How can we design the system?").

Venus In Situ Explorer: Engineering Characteristics

**Programmatic**
- Cost
- Risk
- Launch Date

**Mission Profile**
- Mission Duration
- Surface Time per Visit

**Flexibility & Mobility**
- Landing Site Altitude
- Cruise Altitude
- No. of Surface Visits

**Hardware Characteristics**
- Landed Mass
- Power Consumption
- Number of Vehicles
- Data Rate
Quality Function Deployment (QFD)

- Developed in Japan in 1970s (first used on a large scale by Kobe Shipyard of Mitsubishi Heavy Industries).
- Maps voice of customer (“whats”) to voice of engineer (“hows”).
- Can be deployed to lower-level characteristics.

3. Mapping of Objectives to Engr. Characteristics
3. Mapping of Objectives to Engr. Characteristics

### QFD Relationship Matrix

**Voice of Customer mapped to Voice of Engineer**

<table>
<thead>
<tr>
<th>VNE (Voice of Explorer)</th>
<th>Customer Importance</th>
<th>Mission Profile</th>
<th>Hardware Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cost</td>
<td>Launch Date</td>
<td>Mission Duration</td>
</tr>
<tr>
<td></td>
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</table>

#### Direction of Improvement

<table>
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<tr>
<th>Surface Analysis</th>
<th>14%</th>
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<tbody>
<tr>
<td>Atmosphere Study</td>
<td>16%</td>
</tr>
<tr>
<td>Mobility</td>
<td>8%</td>
</tr>
<tr>
<td>Survivability</td>
<td>23%</td>
</tr>
<tr>
<td>Communication</td>
<td>4%</td>
</tr>
</tbody>
</table>

#### Vehicle Attributes

<table>
<thead>
<tr>
<th>Timely/Mission Completion</th>
<th>4%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mission Simplicity</td>
<td>11%</td>
</tr>
<tr>
<td>Affordability</td>
<td>15%</td>
</tr>
<tr>
<td>Technology Demonstration/Classification</td>
<td>12%</td>
</tr>
<tr>
<td>Mission Extension Potential</td>
<td>2%</td>
</tr>
</tbody>
</table>
3. Mapping of Objectives to Engr. Characteristics

**QFD Targets & Importances**

What are the most critical VISE engineering characteristics?

Programmatic Cost and Risk are highest in relative importance, but difficulty of Surface Time and No. of Surface Visits raises them to most important.
4. Generation of Feasible Concept Alternatives

Morphological Matrix

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Alternatives</th>
<th>No. of Opt.'s</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1. Structure/Configuration</strong></td>
<td></td>
<td></td>
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<tr>
<td>1.1 Lander Configuration</td>
<td>Direct from Surface</td>
<td>Relay After Ascent</td>
</tr>
<tr>
<td>1.1.1 Data Relay</td>
<td>Solar Panel</td>
<td>Fuel Cell</td>
</tr>
<tr>
<td>1.1.2 Lander Platform</td>
<td>Cryocooler</td>
<td>Heat Iso</td>
</tr>
<tr>
<td>1.1.3 Battery Supplement</td>
<td>Vacuum Isol</td>
<td>Conventional</td>
</tr>
<tr>
<td>1.1.4 Active TCS</td>
<td>Cryocooler</td>
<td>Heat Concentrator</td>
</tr>
<tr>
<td>1.1.5 Passive TCS</td>
<td>Vacuum Isol</td>
<td>Conventional</td>
</tr>
<tr>
<td>1.1.6 Landing Gear</td>
<td>Conventional</td>
<td>Rigid Bellows</td>
</tr>
<tr>
<td>1.2 Structure Material</td>
<td>Aluminum</td>
<td>Titanium</td>
</tr>
<tr>
<td>1.3 Vehicle Split</td>
<td>Aluminum</td>
<td>Titanium</td>
</tr>
<tr>
<td>1.3.1 Number of Landers</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>1.3.2 Number of Orbiters</td>
<td>0</td>
<td>1</td>
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<td><strong>2. Mission</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.1 Earth Departure</td>
<td>Atlas</td>
<td>Delta</td>
</tr>
<tr>
<td>2.1.1 Launch System</td>
<td>Direct Insertion</td>
<td>Lower Energy Transfer</td>
</tr>
<tr>
<td>2.1.2 Type of Transfer</td>
<td>Propulsive</td>
<td>Parachutes</td>
</tr>
<tr>
<td>2.1.3 Direct to Venus</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>2.2 Venus ED&amp;L Methods</td>
<td>Buoyancy</td>
<td>Propulsive</td>
</tr>
<tr>
<td>2.3 Venus Orbit Insertion (Orbiter)</td>
<td>Aerocapture</td>
<td>Propulsive</td>
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<td>2.4 Science</td>
<td></td>
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<td>2.4.1 Surface Study</td>
<td></td>
<td></td>
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<td>2.4.1.1 Composition</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>2.4.1.2 Seismometry</td>
<td>Yes</td>
<td>No</td>
</tr>
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<td>2.4.1.3 Mapping</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>2.4.2 Atmospheric Study</td>
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<td></td>
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<td>2.4.2.1 Composition</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>2.4.2.2 Dynamics</td>
<td>Yes</td>
<td>No</td>
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</table>
4. Generation of Feasible Concept Alternatives

Traditional Concept

Concept Description Sheet
4. Generation of Feasible Concept Alternatives

Six concepts chosen for evaluation:

- Traditional
- Low-Cost
- Revolutionary
- Evolutionary
- Advanced
- Distributed
5. Evaluation of Alternatives

• Prime purpose of Step 5 is to evaluate concepts from Step 4 according to criteria developed in Steps 1-3.
  – Pugh Concept Selection Matrices
    • Simple
    • Suitable for “coarse” evaluation of alternatives
  – Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)
    • Similar in format to Pugh Matrices
    • Uses weights on objectives and finer resolution on alternative-objective correlations

• Extension to Modeling & Simulation
## 5. Evaluation of Alternatives

### Pugh Concept Selection Matrices

“Best” concept with regard to the reference mission

<table>
<thead>
<tr>
<th>Datum 1</th>
<th>Datum 2</th>
<th>Datum 3</th>
<th>Datum 4</th>
<th>Datum 5</th>
<th>Datum 6</th>
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<tbody>
<tr>
<td>Cost</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>S</td>
<td>-</td>
</tr>
<tr>
<td>Risk</td>
<td>+</td>
<td>S</td>
<td>-</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Launch Date</td>
<td>S</td>
<td>+</td>
<td>-</td>
<td>S</td>
<td>-</td>
</tr>
<tr>
<td>Mission duration</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Surface time / visit</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>S</td>
<td>+</td>
</tr>
<tr>
<td># of Surface Visits</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Landing Site Alt.</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Cruise Altitude</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Landed Mass</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Power Requirement</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td># of Vehicles</td>
<td>S</td>
<td>-</td>
<td>+</td>
<td>+</td>
<td>S</td>
</tr>
<tr>
<td>Max. Data Rate</td>
<td>+</td>
<td>S</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Score</td>
<td>6</td>
<td>2</td>
<td>0</td>
<td>5</td>
<td>-1</td>
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</tbody>
</table>
5. Evaluation of Alternatives

**TOPSIS**

- Each concept is rated in terms of its performance in terms of each criterion.
- Ratings can be qualitative (e.g. 1-3-5-7-9) or quantitative.

<table>
<thead>
<tr>
<th></th>
<th>Concept 1 Traditional</th>
<th>Concept 2 Low-Cost</th>
<th>Concept 3 Revolutionary</th>
<th>Concept 4 Evolutionary</th>
<th>Concept 5 Advanced</th>
<th>Concept 6 Distributed</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cost</strong></td>
<td>600</td>
<td>350</td>
<td>1500</td>
<td>700</td>
<td>850</td>
<td>750</td>
</tr>
<tr>
<td><strong>Risk</strong></td>
<td>5</td>
<td>9</td>
<td>8</td>
<td>6</td>
<td>6</td>
<td>3</td>
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<tr>
<td><strong>Launch Date</strong></td>
<td>1</td>
<td>1.3</td>
<td>0.85</td>
<td>0.9</td>
<td>0.95</td>
<td>0.9</td>
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<tr>
<td><strong>Mission Duration</strong></td>
<td>90</td>
<td>90</td>
<td>110</td>
<td>105</td>
<td>100</td>
<td>90</td>
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<td><strong>Surface Time per Visit</strong></td>
<td>4</td>
<td>2</td>
<td>6</td>
<td>4</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td><strong>Number of Surface Visits</strong></td>
<td>6</td>
<td>6</td>
<td>8</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td><strong>Landing Site Altitude</strong></td>
<td>1.5</td>
<td>2</td>
<td>0.5</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td><strong>Cruise Altitude</strong></td>
<td>55</td>
<td>40</td>
<td>60</td>
<td>55</td>
<td>55</td>
<td>55</td>
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<tr>
<td><strong>Landed Mass</strong></td>
<td>200</td>
<td>200</td>
<td>400</td>
<td>300</td>
<td>200</td>
<td>600</td>
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<tr>
<td><strong>Power Requirement</strong></td>
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<td>75</td>
<td>600</td>
<td>100</td>
<td>400</td>
<td>600</td>
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<td><strong>Number of Vehicles</strong></td>
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<td>1</td>
<td>5</td>
<td>3</td>
<td>2</td>
<td>5</td>
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<tr>
<td><strong>Maximum Data Rate</strong></td>
<td>30</td>
<td>15</td>
<td>65</td>
<td>40</td>
<td>30</td>
<td>65</td>
</tr>
</tbody>
</table>
5. Evaluation of Alternatives

**TOPSIS**

- Positive and Negative Ideal Designs are identified in a (weighted) n-dimensional objective space.
- Alternatives are scored based on their Euclidean distances to the Positive and Negative Ideal Designs.
5. Evaluation of Alternatives

**TOPSIS**

- TOPSIS requires criteria weights.
- In this example, weights are determined from combination of QFD and AHP.
- Outputs are relative scores of alternatives

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Concept 1 Traditional</th>
<th>Concept 2 Low-Cost</th>
<th>Concept 3 Revolutionary</th>
<th>Concept 4 Evolutionary</th>
<th>Concept 5 Advanced</th>
<th>Concept 6 Distributed</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>0.53</td>
<td>0.38</td>
<td>0.40</td>
<td>0.50</td>
<td>0.53</td>
<td>0.66</td>
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<tr>
<td>Rank</td>
<td>2</td>
<td>6</td>
<td>5</td>
<td>4</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>
5. Evaluation of Alternatives

Lander Model
- Payload Class
  - Structures & Mechanisms
  - Thermal Control System
  - Propulsion & Mobility System
    - GNC System
    - Communications System
    - C&DH System
    - Power System

Entry System Model
- Aeroshell Structure
- Thermal Protection System
- Vehicle Diameter
- Vehicle Lift-to-Drag Ratio
- Loads, Heating
- Opacity

Orbiter/Cruise Stage Model
- Payload Class
  - Structures & Mechanisms
  - Thermal Control System
  - Propulsion System
    - GNC System
    - Communications System
    - C&DH System
    - Power System

Mission Model
- Launch & Arrival Dates
  - Launch Vehicle
- Entry State
- Insertion ΔV
- Pressure, Temp.
- Cruise Altitude
- Mission Duration
- Surface Time per Visit
- Number of Surface Visits
- Landed Altitude

Green Block
- Model Input
- White Block
- Calculated Result
- Gradient Block
- Conversion Function

Key Cost Driver (key input into cost estimate)
Key Risk Driver (key input into risk estimate)
Eclipse Time
Mass, Power Budgets
Methodology Summary

Central Steps in the GT Generic IPPD Methodology

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- Interrelationship Digraphs
- Quality Function Deployment (QFD)
- Morphological Matrices
- Operational Architectures
- Pugh Concept Selection Matrices
- Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)
Concluding Remarks

- Overall, this has outlined a systematic process for exploring the broad concept space in the early stages of design.
  - Basic steps identified
  - Tools identified and demonstrated
- Applicability has been demonstrated for Venus In Situ Explorer (and, likely by extension, for other interplanetary robotic exploration missions as well).
Questions?
Backup
Why Venus?

- **Earth’s Twin (sort of)**
  - Roughly same size and distance from Sun
  - Except:
    - CO₂ atmosphere with H₂SO₄ clouds
    - Runway greenhouse effect
    - Extreme surface conditions

- **Key Unsolved Mysteries**
  - Atmospheric H₂O & D₂ content suggests loss of the equivalent of an ocean of water
  - Cloud-level atmosphere rotates nearly as a solid body, 60 times faster than surface
  - Rich geologic history but no evidence of plate tectonics
  - Volcanic features but no evidence of active volcanism

- **What can Venus’ fate tell us about Earth?**

<table>
<thead>
<tr>
<th>Distance from Sun:</th>
<th>0.7 AU</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface Gravity:</td>
<td>8.9 m/s²</td>
</tr>
<tr>
<td>Surface Temperature:</td>
<td>730 K</td>
</tr>
<tr>
<td>Surface Pressure:</td>
<td>90 atm</td>
</tr>
</tbody>
</table>
Brief History of Venus Exploration

• **Orbiters**
  – Venera Series (USSR)
  – Pioneer Venus I (USA)
  – Magellan (USA)
  – Venus Express (ESA)

• **Probes & Aerial Platforms**
  – Pioneer Venus II (USA)
  – Venera Series (USSR)
  – Vega Series (USSR)

• **Landers**
  – Venera Series (USSR)

• **Flybys**
  – Mariner II, V, X (USA)
  – Galileo (USA)
  – Cassini (USA)
  – MESSENGER (USA)
**Brief History of Venus Exploration**

- **Venus in the News:**
  November 28, 2007
  - ESA’s Venus Express discovers lightning on Venus
    - Extrapolated to 50 flashes per second (half that of Earth)
    - Not expected due to lack of water (associated with sulfuric acid)
    - Important because lightning is thought to drive atmospheric chemistry processes
  - Venus Express confirms oxygen being swept from the Venusian atmosphere
Venus In Situ Explorer Objectives

**Notional Venus In Situ Explorer**
2013 timeframe

**Notional Venus Mobile Explorer**
2025 timeframe

**Notional Venus Sample Return**
Operational Architecture

Launch and Mission Control Centers
Tracking Networks

Ascent

Earth Orbit?

Venus Transit

Venus Orbit?

Venus Entry, Descent & Landing

Venus Surface Phase

Venus Orbit?
Functional Architecture

Perform Mission

- Perform Earth Ascent
- Enter Earth Orbit
- Execute Venus Transit
- Enter Venus Orbit
- Perform Venus Entry, Descent, & Landing
- Execute Surface Phase

- Lift Off
- Perform Roll Maneuver
- Enter Earth Escape Trajectory
- Stage

- Perform System Checkout
- Perform Trans-Venus Injection Burn
- Perform Midcourse Corrections

- Venus Orbit Insertion
  - Aerobraking/Aerocapture
  - Propulsive Maneuvers

- Descent Orbit Insertion
- Parachute Deployment
- Touchdown
- System Checkout

- Sample Collection
- Sample Examination
- Data Relay
- Partial Ascent for Cooling
Management & Planning Tool Utilization

• Target determined based on current and future desired capabilities.
  – 2006 Solar System Exploration Roadmap
  – NASA Venus Exploration Analysis Group future mission (VSE, VSR) projections
  – Previous interplanetary probes

<table>
<thead>
<tr>
<th>Engineering Characteristic</th>
<th>Target Value</th>
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<tbody>
<tr>
<td>Cost</td>
<td>$700 million</td>
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<tr>
<td>Risk</td>
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</table>
Overall Evaluation Criterion Formulation

- Feasibility criteria taken directly from QFD engineering characteristics (covered all major feasibility factors)
- QFD target values used as baseline values for normalization
- OEC criteria weight based on arithmetic average of
  - AHP prioritization importances
  - Normalized unweighted QFD importances
  - Normalized weighted QFD importances
**Overall Evaluation Criterion Formulation**

**Final OEC Equation**

\[
OEC = \frac{0.169 \frac{\text{Risk}_{BL}}{\text{Risk}} + 0.045 \frac{\text{LD}_{BL}}{\text{LD}} + 0.113 \frac{\text{MD}}{90} + 0.253 \frac{\text{STV}}{4} + 0.170 \frac{\text{NSV}}{6} + 0.060 \frac{1.5}{\text{LSA}} + 0.038 \frac{55}{\text{CA}} + 0.037 \frac{\text{LM}}{200} + 0.043 \frac{100}{\text{PR}} + 0.053 \frac{\text{NV}}{2} + 0.016 \frac{\text{MDR}}{10}}{\text{Cost}} \frac{}{700,000,000}
\]

- **Risk**: Risk (risk unit)
- **LD**: Launch Date (time)
- **MD**: Mission Duration (days)
- **STV**: Surface Time per Visit (hours)
- **NSV**: Number of Surface Visits (Visits)
- **LSA**: Landing Site Altitude (kilometers)
- **CA**: Cruise Altitude (kilometers)
- **LM**: Landed Mass (kilograms)
- **PR**: Power Requirement (watts)
- **NV**: Number of Vehicles (Vehicles)
- **MDR**: Maximum Data Rate (kilobytes per second)
- **Cost**: Cost (US dollars)
Management & Planning Tool Utilization

• An Interrelationship Digraph was constructed and identified “Risk” and “Data Rate” as the key indicators.

• In contrast, there is no single strong root cause; instead there are many important drivers with Number of Vehicles being the highest.
Quality Function Deployment

Customer Requirements

**SCIENCE RETURN**
1. Surface Analysis
2. Atmospheric Study

**VEHICLE ATTRIBUTES**
3. Mobility
4. Survivability
5. Communication

**PROGRAMMATIC**
6. Timely Mission Completion
7. Mission Simplicity
8. Affordability
9. Extension Potential
10. Technology Demonstration

Engineering Characteristics

**MISSION PROFILE**
1. Mission Duration
2. Surface Time per Visit
3. Landing Site Altitude
4. Cruise Altitude
5. No. of Surface Visits

**HARDWARE CHARACTERISTICS**
1. Landed Mass
2. Power Consumption
3. No. of Vehicles
4. Data Rate

**PROGRAMMATIC**
10. Cost
11. Risk
12. Launch Date
2. Engineering Characteristics Definition

Interrelationship Digraph

<table>
<thead>
<tr>
<th>Category</th>
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Key Indicators (Arrows Into Box)
3. Mapping of Objectives to Engr. Characteristics

QFD Correlation Matrix
Correlations among Engineering Characteristics

![QFD Correlation Matrix Diagram]
### Evaluation of Alternatives

#### Pugh Concept Selection Matrices

<table>
<thead>
<tr>
<th></th>
<th>Concept 1 Traditional</th>
<th>Concept 2 Low-Cost</th>
<th>Concept 3 Revolutionary</th>
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*Best concept*

*Not distinguishable*
Pugh Matrix Evaluation

- Allows a comparison of several design concepts against an established datum, and ranks those concepts with respect to design criteria
- Criteria obtained from the HOWs of QFD
- Concepts from Morphological Matrix

QFD

Pugh Matrix

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Score

Morphological Matrix

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<td>S_{nim}</td>
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Subjective Evaluation

Best Alternative
• The Distributed concept dominates the rankings in the second run, but not in the first one
  – Due to the fact that it has the same number of ‘pluses’ as the traditional concept in the first run, but more ‘minuses’
  – The ‘pluses’ of the Distributed concept are stronger than those of the traditional one
• Low-Cost and Advanced are clearly weaker solutions
• Traditional, Evolutionary and Revolutionary cannot be differentiated due to the too high level of analysis
• Surprisingly, the revolutionary scenario has very few negative effects
  – Due to the lack of qualitative comparison
  – Due to the absence of criteria weightings
\[ \rightarrow \text{Need to use TOPSIS to get more precise results} \]
TOPSIS Evaluation

Computation of Decision Estimators

Data Matrix

<table>
<thead>
<tr>
<th>Concept 1</th>
<th>Concept 2</th>
<th>Concept 3</th>
<th>Concept 4</th>
<th>Concept 5</th>
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Relative Unweighted Importance

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EC’s Weights

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Weighted Data Matrix

Relative Closeness to Positive/Negative Ideal Concept
5. Evaluation of Alternatives

- Pugh Matrix: Iteration 1
  - Traditional concept is best
  - Distributed and Evolutionary close behind
- Pugh Matrix: Iteration 2
  - Distributed concept is best
  - Traditional, Revolutionary, and Evolutionary close behind
- TOPSIS
  - Advanced concept is best
  - Traditional, Distributed, and Evolutionary close behind
- Resolution does not exist at this qualitative stage to exclude Traditional, Distributed, Advanced, or Evolutionary solutions (quantitative analysis needed)
- However, Low-Cost and Revolutionary options can be reasonably excluded based on this qualitative evaluation
5. Evaluation of Alternatives

Modeling & Simulation

• While two concepts can be easily eliminated based on qualitative considerations, four are too close to call.

• Modeling & Simulation is required to:
  – Generate data to allow more educated selection among the remaining four alternatives during Strategic Design (e.g. generate quantitative values to plug into TOPSIS)
  – Enable Robust Design Simulation and Parametric Exploration within the Design Space

• A first step might be the development of a physics-based VISE Vehicle and Mission Modeling Sizing & Synthesis Tool.
Modeling & Simulation Motivation

- While two concepts can be easily eliminated based on qualitative considerations, four are too close to call.
- Modeling & Simulation is required to:
  - Generate data to allow more educated selection among the remaining four alternatives during Strategic Design.
  - Enable Robust Design Simulation and Parametric Exploration within the Design Space.

Georgia Tech ASDL TIES Methodology
Product Design Specification

- **In-Use Purposes**
  - First US Lander on Venus
  - Aerial/Terrestrial mission

- **Functional Requirements**
  - Performance
  - Physical constraints: Vehicle package, Landed mass...
  - Service Environment: Space radiation, Venus environment

- **Agency Constraints**: Launch date, Manufacturing requirements...

- **Social, Political and Legal Requirements**: compliance with all applicable treaties
VISE Modeling Framework: Lander Model

- Payload Class specified by user
- Structures & Mechanisms and GNC, Communications, C&DH, and Power Systems receive input from Mission Model conversion functions
- Inputs used in EXAMINE model for completion of mass/power estimates
  - EXAMINE model originally developed for architectural study of the future lunar campaign
  - Currently undergoing modification for application to a Human Mars Mission
  - EXAMINE model could be further modified to size the appropriate systems for the VISE Lander Model
VISE Modeling Framework: Lander Model

Modification required for the current EXAMINE model

- The payload class is a single input in EXAMINE
- EXAMINE models for Power, C&DH, Communications, and GNC Systems would require little to no modification
- EXAMINE models for Structures & Mechanisms and Thermal Control Systems would require moderate modifications to account for the high temperature and harsh environment of Venus
  - New material information would have to be added to the material database
  - New algorithms to estimate environmental wear due to the acidic atmosphere
- EXAMINE models for the Propulsion & Mobility System would have to be modified to account for the new inflatable balloon propulsion system
  - New mass estimating relationships to determine sizing/power consumption of propulsion system.
VISE Vehicle and Mission Modeling Framework

- Framework intended as an integrated set of physics-based models and simulations which could be used to create a credible VISE point design from minimal inputs.
- Framework principally applicable to the Traditional Concept because of time constraints, but may be easily extensible to all 4 highly-ranked concepts.
- Ultimately, tool could be run parametrically through a DoE to produce RSEs for an interactive, probabilistic design environment.

DOE Generation → VISE Modeling Framework → RSE Regression → RSEs → Parametric Trade Environment, Rapid Probabilistic Design Space Exploration
VISE Modeling Framework: Cost Model

Launch Year

Launch Vehicle Selection

Launch Vehicle Cost Database

Lander & Entry System Dry Mass

SSCM, WeLCCM98, SVLCM

Lander & Entry System DDT&E + TFU Cost

GDP Deflator

Program, Operations, Software Development Cost Estimation (SSCM/SMAD)

Orbiter Dry Mass

SSCM, WeLCCM98, SVLCM

Orbiter DDT&E + TFU Cost

Total VISE Cost
VISE Modeling Framework: Risk Model

- **Risk Divisions**
  - Technical Development Risk
  - Cost Risk
  - Operational Risk
- **As in OEC, total risk is taken as average of the three divisions, each rated on a 1-5 scale**

**Development Risk Model**

- Average TRL of Critical Systems converted to a 1-5 scale (e.g. R&D³)

**Cost Risk Model**

- 80% Confidence on Cost

**Cost Risk Model**

- Convert to 1-5 Scale

**VISE Vehicle & Mission Model**

- Lander & Entry System Dry Mass
- Launch Vehicle
- Orbiter Dry Mass

**Launch Year**

- Distributions on Inputs
VISE Modeling Framework: Risk Model

Altitude Risk Factor

Altitude Risk Factor

Orbiter and Lander Mission Reliability Model

Historical Satellite/Orbiter Failure Rate Database

Historical Lander Failure Rate Database

Operational Risk Model

\[ P(s, \text{segment 1, lander}) = e^{-\alpha \lambda t} \]

\[ P(s, \text{segment 1, orbiter}) = e^{-\alpha \lambda t} \]

Convert to 1-5 Scale

Probability of Mission Success

Operational Risk Rating
VISE Modeling Framework: Entry System

**EDL Simulation**
- Trajectory (POST, ADAMS)
- Aerothermodynamics (LAURA)
- Stability & Guidance (DSENDTS)

**Aeroshell Model**
- Lift-to-Drag ratio
- Flight Stability
- Aero Configuration
- Heating Peak Rate
- Heat Load

**TPS Model**
- Atmosphere and wind model (Venus-GRAM)

**Launch Vehicle**
- Entry velocity
- Entry angle
- Cruise altitude
- Lander Mass

**Max Volume**
- Aeroshell Geometry
- Aeroshell Material
- TPS Thickness
- TPS Material

**Parachute model**
VISE Modeling Framework: Orbiter Model

- Orbiter Model also accounts for any cruise stage functionality (lander maintenance)
- Sizing & Synthesis accomplished via historical satellite and interplanetary orbiter mass estimating relationships (e.g. *Space Mission Analysis and Design* by Wertz & Larson)
VISE Modeling Framework: Mobility System

- Buoyancy
- Leakage rate
  - From balloon to atmosphere
  - From storage to space/atmosphere
- Gas storage methods/volume
- Inflation/deflation rates
  - Ability to target landings via deflation rate
- Chemical degradation of balloon material
  - Exposed to sulfuric acid in atmosphere, dust on ground
- Physical degradation of balloon material exposed to
  - Surface and atmospheric temperatures, surface materials/abrasion, wind, dust
- Mass of balloon system
- Volume of balloon system
- Power requirements of balloon system
- Cruise speed as a function of altitude
VISE Modeling Framework: Mobility System

Balloon Model

- Lander Mass
- Cruise Altitude
- Number of Surface Visits

Atmospheric Model → Ideal Gas Law Buoyancy Model

Gas Storage Tank Model

Balloon Material/Surface Area Model

Balloon Packing Factor

Required Gas Stores for Inflation

Balloon System Mass

Balloon Stored Volume
VISE Modeling Framework: Thermal System

- Surface Time per Visit
- Mission Duration
- Lander P&T
- P&T at Altitude

- Life Expectancy
- Structure & Electronics
- Power Consumption
- Control System
- Temperature Gradient
- Recharge Mode ON\OFF

Thermal Control System Mass and Power
VISE Modeling Framework: Mission Model

**Input**
- Lander Mass
- Orbiter/Cruise Stage Mass
- Entry System Mass
- Launch & Arrival Dates
- Entry Flight Path Angle
- Orbiter Altitude
- Launch & Arrival Dates
- Cruise Altitude
- Landed Altitude
- Cruise Altitude
- Landed Altitude

**Conversion**
- Launch Vehicle Model and Selector
- Two-Body Orbital Mechanics (Patched Conics, Gauss' Problem)
- Two-Body Orbital Mechanics (Patched Conics, Gauss' Problem)
- Venus Atmosphere Model (e.g. Venus-GRAM, mission data)
- Venus Atmosphere Model (e.g. Venus-GRAM, mission data)

**Output**
- Launch Vehicle
- Entry State
- Insertion ΔV
- Opacity
- Pressure, Temp.
Concluding Remarks

Potential Alternative Process Linkages

1. Objectives Definition and Prioritization
2. Engineering Characteristics Definition
3. Mapping of Objectives to Engineering Characteristics
4. Generation of Feasible Concept Alternatives
5. Evaluation of Alternatives with Modeling & Simulation discussion

Objectives & Weights
Engr. Characteristics
QFD Weights
Most Relevant Engr. Char.’s
Concept Alternatives

Link Demonstrated in this Example
Potential Link Modification

Note: End-to-beginning iteration is possible as a feedback loop if necessary but is not considered in this study.