The Engineering System: A LEO Space Station

• Assembled and supplied by Space Shuttle over a 10 year period
  – Comprised of multiple segments, each requiring a Space Shuttle launch

• An astronaut crew is needed to process payload
  – The maximum amount of payload that can be processed is directly proportional to the crew size
  – Crew is transferred to and from station on Space Shuttle and Soyuz

• Processed payload is assumed to be worth $21,000/kg
Model of the Engineering System

Production Function:

\[ Y_{\text{payload returned}} = \min \left( \left( \eta \times N_{\text{Shuttle Flights}} \times M_{\text{Shuttle return capacity at given inclination}} \right), P_{\text{crew}} \right) \]

Input Cost Function:

\[ C = C_{\text{Shuttle variable cost}} \times N_{\text{Shuttle Flights}} + C_{\text{Soyuz variable cost}} \times N_{\text{Soyuz Flights}} \]

Cash Flows:

\[ \text{Cash Flow}_i = V \times \left( Y_{\text{payload returned}}^i \right) - C_i \quad \text{for all } i \]

Net Present Value:

\[ \text{NPV} = \sum \text{Cash Flow}_i / (1+r)_i \quad \text{for all } i \]

Uncertainties of the Engineering System

- Launch Vehicle Flight Rate
  - Determines the amount of payload returned
- Launch Vehicle Success Rate
  - Success criteria for missions to space stations are among the most stringent of missions to LEO
  - Launch sequencing is critical for space station assembly & supply
- Annual Budget of Space Programs
  - Proposed by President, approved by Congress
- Presidential Agendas
  - Presidents define goals of space station programs & reserves the right to change them
- And Many More
Model of the Key Uncertainty

- The uncertainty analyzed is the annual Space Shuttle Launch Rate
  - Historical data from 1983 to 2006 (after the initial test flights) used to derive average and standard deviation
  - Launch rate is assumed to decay to 2.5 flights per year over the 10 years of assembly and supply

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average # of Flights per Year</td>
<td>4.67</td>
</tr>
<tr>
<td>Minimum # of Flights over a Year</td>
<td>0</td>
</tr>
<tr>
<td>Maximum # of Flights over a Year</td>
<td>9</td>
</tr>
<tr>
<td>Median # of Flights per Year</td>
<td>6</td>
</tr>
<tr>
<td>Standard Deviation Annual Flight Rate (%)</td>
<td>2.63</td>
</tr>
<tr>
<td>Standard Deviation Annual Flight Rate (%)</td>
<td>56.4</td>
</tr>
</tbody>
</table>

\[ S_T = Se^{\nu T} \Rightarrow \ln(S_T/S)/T = \nu \]
\[ \nu = -6.24\%/\text{year} \]

System Design Alternatives

- **Alternative 1 (A1)**
  - 28.5° orbital inclination
  - Crew of four astronauts
  - Station only able interface with U.S. vehicles

- **Alternative 2 (A2)**
  - 51.6° orbital inclination
  - Crew of seven astronauts—4 from the U.S. and 3 from Russia
    - Requires two $20M Soyuz launches per year

- **Alternative 3 (A3)**
  - 51.6° orbital inclination
  - Maximum crew size of seven (A3A) with option to terminate Russian participation (A3B)
    - Option leads to an extra charge of $5M per Soyuz flight
    - In the decision analysis, the option can be exercised after five years
    - In the lattice analysis, the option can be exercised in the 0, 2nd, 4th, 6th, or 8th year
Two-Stage Decision Analysis of Uncertainty

- Three events are possible at each stage
  - \( E_1 = \) The Space Shuttle averages 5 launches/year
  - \( E_2 = \) The Space Shuttle averages 4 launches/year
  - \( E_3 = \) The Space Shuttle averages 3 launches/year
- The probability of each event is as follows:
  - \( P(E_1) = 0.625 \)
  - \( P(E_2) = 0.042 \)
  - \( P(E_3) = 0.333 \)
  - The probability of events in the second stage are assumed to be independent of events in the first stage

<table>
<thead>
<tr>
<th>Combinations of Events</th>
<th>Successful Space Shuttle Missions over the 10 Year Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E_1 ) and ( E_1 )</td>
<td>50</td>
</tr>
<tr>
<td>( E_1 ) and ( E_2 )</td>
<td>45</td>
</tr>
<tr>
<td>( E_1 ) and ( E_3 )</td>
<td>40</td>
</tr>
<tr>
<td>( E_2 ) and ( E_2 )</td>
<td>40</td>
</tr>
<tr>
<td>( E_2 ) and ( E_3 )</td>
<td>35</td>
</tr>
<tr>
<td>( E_3 ) and ( E_3 )</td>
<td>30</td>
</tr>
</tbody>
</table>

Binomial Lattice Analysis of Uncertainty

<table>
<thead>
<tr>
<th>OUTCOME LATTICE (Annual Launch Rate)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step 0</td>
</tr>
<tr>
<td>4.67</td>
</tr>
<tr>
<td>2.10</td>
</tr>
<tr>
<td>0.95</td>
</tr>
<tr>
<td>0.43</td>
</tr>
<tr>
<td>0.19</td>
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<td></td>
</tr>
</tbody>
</table>

\[ u = e^{(\sigma \sqrt{\Delta T})} = 2.22 \]
\[ d = e^{(-\sigma \sqrt{\Delta T})} = 1/u = 0.45 \]
\[ p = 0.5 + 0.5(v/\sigma) \sqrt{\Delta T} = 0.422 \]
Results

• According to the Decision Analysis:
  – The option adds no value when $A_1$ or $A_2$ is available
• According to the Lattice Analysis:
  – The option adds no value when $A_1$ is available
  – The option is worth $109M when $A_1$ is not available and should be executed at Time Step 0
• Decisions are sensitive to the assumed parameters for both techniques

<table>
<thead>
<tr>
<th></th>
<th>$EV(A_1)$</th>
<th>$EV(A_2)$</th>
<th>$EV(A_3)$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Decision</strong></td>
<td>$(1,588M)$</td>
<td>$(1,547M)$</td>
<td>$(1,592M)$</td>
</tr>
<tr>
<td><strong>Analysis</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Lattice</strong></td>
<td>$(3,581M)$</td>
<td>$(3,707M)$</td>
<td>$(3,598M)$</td>
</tr>
<tr>
<td><strong>Analysis</strong></td>
<td></td>
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</tbody>
</table>

**CREW SIZE LATTICE**

<table>
<thead>
<tr>
<th></th>
<th>Step 0</th>
<th>Step 1</th>
<th>Step 2</th>
<th>Step 3</th>
<th>Step 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 Crew</td>
<td>4 Crew</td>
<td>7 Crew</td>
<td>7 Crew</td>
<td>7 Crew</td>
<td>4 Crew</td>
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<td>4 Crew</td>
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Concluding Remarks

• Decision Analysis and Lattice Modeling are useful for gaining qualitative insights into the management of uncertainty in this system
• LEO space stations may be too complex and unique to derive useful quantitative information through decision and lattice analyses
  – Numerous assumptions were necessary to perform trivial calculations
  – Some of the results (e.g. 252 Space Shuttle launches in one year) will not be taken seriously by those who actually work with the system
• Decision Analysis can be more accurate than lattice analysis, but it can add a great deal of complexity to the analysis

*No analytic tool is equipped to answer every research question; care must be taken in selecting the right tool for the job*
References


References (cont’d)

- United States, National Aeronautics and Space Administration. NASA Budget Request Website: [http://www.nasa.gov/about/budget/index.html](http://www.nasa.gov/about/budget/index.html)