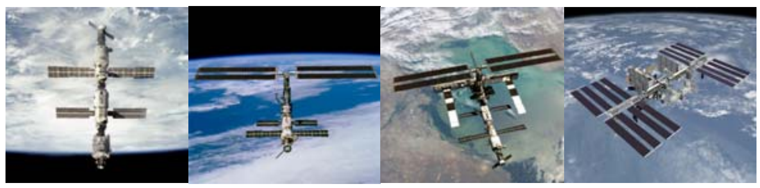
An Engineering Systems Analysis of Space Station Assembly & Supply



Application Portfolio
ESD.71 – Engineering Systems Analysis for Design
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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:

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

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:

$\text{Cash Flow}_i = V \times (Y_{\text{payload returned}})_i - C_i$ for all i

Net Present Value:

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

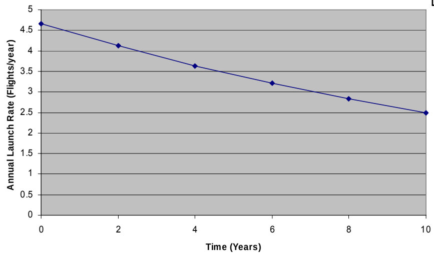
Uncertainties of the Engineering System

- 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

Average # of Flights per Year	4.67
Minimum # of Flights over a Year	0
Maximum # of Flights over a Year	9
Median # of Flights per Year	6
Standard Deviation Annual Flight Rate	2.63
Standard Deviation Annual Flight Rate (%)	56.4 %



$S_T = Se^{vT} \rightarrow \ln(S_T/S)/T = v$

v = <u>-6.24%/year</u>

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
  - E1 = The Space Shuttle averages 5 launches/year
  - E2 = The Space Shuttle averages 4 launches/year
  - E3 = The Space Shuttle averages 3 launches/year
- The probability of each event is as follows:
  - P(E1) = 0.625
  - P(E2) = 0.042
  - P(E3) = 0.333
  - The probability of events in the second stage are assumed to be independent of events in the first stage

Combinations of Events	Successful Space Shuttle Missions over the 10 Year Period
E_1 and E_1	50
E_1 and E_2	45
E_1 and E_3	40
E_2 and E_2	40
E_2 and E_3	35
E_3 and E_3	30

Binomial Lattice Analysis of Uncertainty

OUTCOME LATTICE (Annual Launch Rate)					
Step 0	Step 1	Step 2	Step 3	Step 4	Step 5
4.67	10.36	23.00	51.08	113.40	251.78
	2.10	4.67	10.36	23.00	51.08
		0.95	2.10	4.67	10.36
			0.43	0.95	2.10
				0.19	0.43
					0.09

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

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 the assumed parameters for both techniques

	EV(A_1)	EV(A_2)	EV(A_3)
Decision Analysis	$(1,588M)	$(1,547M)	$(1,592M)
Lattice Analysis	$(3,581M)	$(3,707M)	$(3,598M)

CREW SIZE LATTICE				
Step 0	**Step 1**	**Step 2**	**Step 3**	**Step 4**
4 Crew	4 Crew	7 Crew	7 Crew	7 Crew
	4 Crew	4 Crew	4 Crew	7 Crew
		4 Crew	4 Crew	4 Crew
			4 Crew	4 Crew
				4 Crew

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

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