SPACEEA SYSTEMS

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Modeling Uncertainties of Spacecraft Design Parameters for Cost-Risk Analysis

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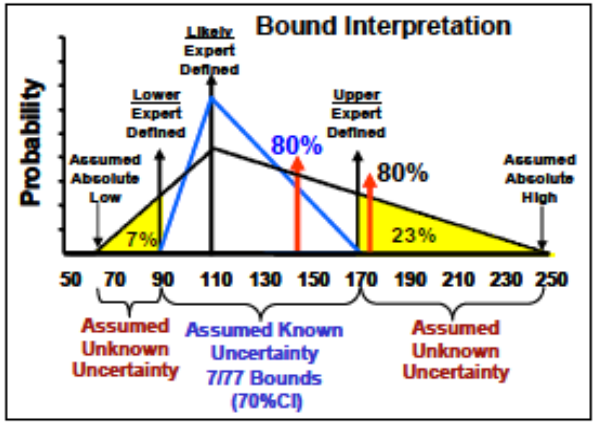
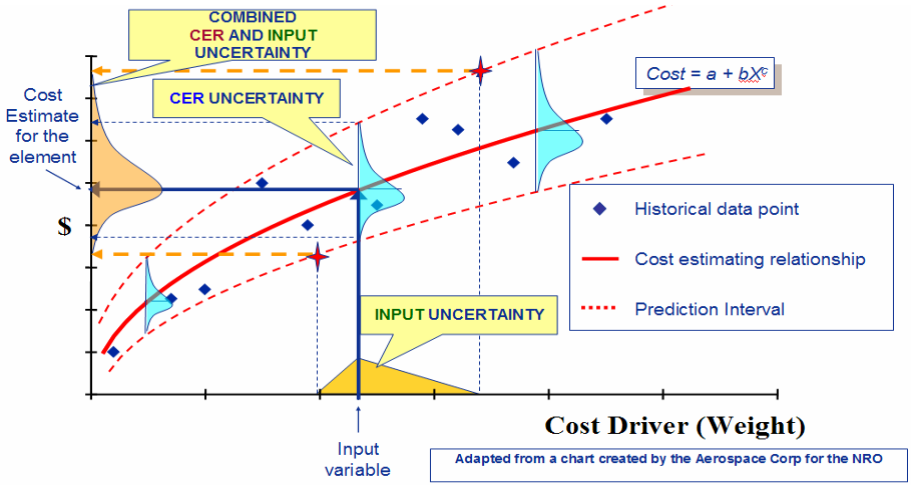
Outline

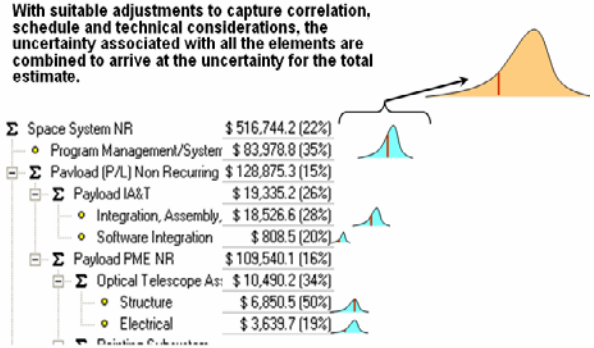
- **Cost-Risk Analysis "Best Practice"**
- **Critique of the "Cost-Risk Analysis Best Practice" – Frankenstein Spacecraft Designs**
- **Solution: Integrated System Modeling**
- **Model Development Approach**
- **Conclusions**

Cost-Risk Analysis "Best Practice"

	CBE Mass	CBE Mass w/Contingency	CBE Power	CBE Power w/Contingency
Payload Total	**105 kg**	**139 kg**	**110 W**	**140 W**
Spacecraft (Dry)	**235 kg**	**268 kg**	**182 W**	**205 W**
Structures & Mechanisms	85 kg	97 kg	0 W	0 W
Thermal	9 kg	11 kg	15 W	19 W
Propulsion Dry Mass	12 kg	12 kg	1 W	1 W
Attitude Determination Subsystem	7 kg	8 kg	16 W	17 W
Attitude Control Subsystem	14 kg	15 kg	36 W	39 W
Electrical Power Subsystem	79 kg	90 kg	21 W	30 W
Communications	10 kg	10 kg	18 W	19 W
Command and Data Handling	20 kg	24 kg	75 W	81 W
Propellant & Pressurant	**65 kg**	**65 kg**		
Spacecraft Propellant & Pressurant	65 kg	65 kg		
Total (Dry)	**405 kg**	**472 kg**	**292 W**	**345 W**
Total (Wet)	**470 kg**	**537 kg**	**292 W**	**345 W**
LV Capability	755 kg	755 kg		
Launch Mass Margin	**61%**	**41%**		







Cost-Risk Analysis "Best Practice" Mathematically….

Each simulation trial results in a set of values for spacecraft subsystems masses, subsystems maximum power loads and corresponding set of values for subsystems costs and estimation error terms.

$$M_{SC}^{i} = \{m_j^i\} = \{m_{Str}^i, m_{Th}^i, m_{Propulsion}^i, m_{EPS}^i, m_{ADS}^i, m_{ACS}^i, m_{Com}^i, m_{CDH}^i\}$$
$$P_{SC}^{i} = \{p_j^i\} = \{p_{Str}^i, p_{Th}^i, p_{Propulsion}^i, p_{EPS}^i, p_{ADS}^i, p_{ACS}^i, p_{Com}^i, p_{CDH}^i\}$$
$$\varepsilon_{SC}^{i} = \{\varepsilon_j^i\} = \{\varepsilon_{Str}^i, \varepsilon_{Th}^i, \varepsilon_{Propulsion}^i, \varepsilon_{EPS}^i, \varepsilon_{ADS}^i, \varepsilon_{ACS}^i, \varepsilon_{Com}^i, \varepsilon_{CDH}^i\}$$
$$X_{SC}^{i} = \{X_j^i\} = \{X_{Str}^i, X_{Th}^i, X_{Propulsion}^i, X_{EPS}^i, X_{ADS}^i, X_{ACS}^i, X_{Com}^i, X_{CDH}^i\}$$

For simple illustration, we used simple spacecraft WBS and assumed subsystems CERs are functions only of their individual masses and power loads (i.e. cost drivers); that is $X_j^i = f_j(m_j^i p_j^i,) * \varepsilon_{ij}$

Using the ***"Roll Up"*** procedure, simulated total spacecraft system dry mass, power requirement and cost estimate are:

$$M_{SC\ Total}^{i} = \sum_{j=1}^{8} m_j^i$$
$$P_{SC\ Total}^{i} = \sum_{j=1}^{8} p_j^i$$
$$X_{SC\ Total}^{i} = \sum_{j=1}^{8} X_j^i$$

The probability of occurrence of each simulation outcome is given by

$$\forall\ i, f\left(M_{SC}^i, P_{SC}^i, \varepsilon_{SC}^i, X_{SC}^i\right) = \frac{1}{n} \neq 0$$

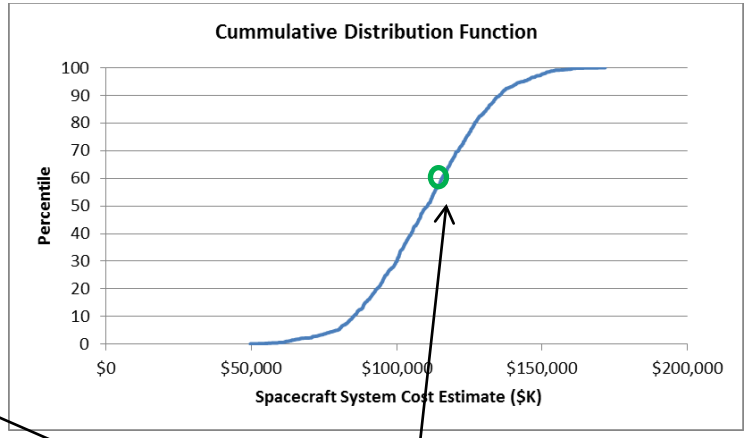
Where n is number of simulations and the Cumulative Density Function (CDF) or S-Curve is given by:

$$F\left(M_{SC}^i, P_{SC}^i, \varepsilon_{SC}^i, X_{SC}^i\right) = \sum_{X_{SC}^k \leq X_{SC}^i} f\left(M_{SC}^k, P_{SC}^k, \varepsilon_{SC}^k, X_{SC}^k\right)$$

Axioms of Probability and The Meaning of a Measurement in a Cost Estimating Experiment

- Now you've captured uncertainties associated with cost estimating relationships (CERs) , technical parameters that drive your CERs and used Pearson's correlation between subsystems costs
- So, you've run your Monte Carlo simulation and established your S-Curve.....
- Cost estimating speaks the language of probabilities and probabilities are defined in terms of "ensembles"
- What is the "*ensemble*" or "*sample space* " of your experiment?
- Are you estimating the cost of a "*valid integrated spacecraft point design* "or the cost of a set of "*independent spacecraft subsystems with randomly generated masses and power loads*"?

$$
\begin{matrix}
m^1_{Str} & m^2_{Str} & m^3_{Str} & \cdots & m^i_{Str} & \cdots & m^n_{Str} \\
m^1_{Th} & m^2_{Th} & m^3_{Th} & \cdots & m^i_{Th} & \cdots & m^n_{Th} \\
m^1_{Propulsion} & m^2_{Propulsion} & m^3_{Propulsion} & \cdots & m^i_{Propulsion} & \cdots & m^n_{Propulsion} \\
m^1_{EPS} & m^2_{EPS} & m^3_{EPS} & \cdots & m^i_{EPS} & \cdots & m^n_{EPS} \\
m^1_{ADS} & m^2_{ADS} & m^3_{ADS} & \cdots & m^i_{ADS} & \cdots & m^n_{ADS} \\
m^1_{ACS} & m^2_{ACS} & m^3_{ACS} & \cdots & m^i_{ACS} & \cdots & m^n_{ACS} \\
m^1_{Com} & m^2_{Com} & m^3_{Com} & \cdots & m^i_{Com} & \cdots & m^n_{Com} \\
m^1_{C\&DH} & m^2_{C\&DH} & m^3_{C\&DH} & \cdots & m^i_{C\&DH} & \cdots & m^n_{C\&DH} \\
p^1_{Str} & p^2_{Str} & p^3_{Str} & \cdots & p^i_{Str} & \cdots & p^n_{Str} \\
p^1_{Th} & p^2_{Th} & p^3_{Th} & \cdots & p^i_{Th} & \cdots & p^n_{Th} \\
\vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
p^1_{Com} & p^2_{Com} & p^3_{Com} & \cdots & p^i_{Com} & \cdots & p^n_{Com} \\
p^1_{C\&DH} & p^2_{C\&DH} & p^3_{C\&DH} & \cdots & p^i_{C\&DH} & \cdots & p^n_{C\&DH} \\
\varepsilon^1_{Str} & \varepsilon^2_{Str} & \varepsilon^3_{Str} & \cdots & \varepsilon^i_{Str} & \cdots & \varepsilon^n_{Str} \\
\varepsilon^1_{Th} & \varepsilon^2_{Th} & \varepsilon^3_{Th} & \cdots & \varepsilon^i_{Th} & \cdots & \varepsilon^n_{Th} \\
\vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
\varepsilon^1_{Com} & \varepsilon^2_{Com} & \varepsilon^3_{Com} & \cdots & \varepsilon^i_{Com} & \cdots & \varepsilon^n_{Com} \\
\varepsilon^1_{C\&DH} & \varepsilon^2_{C\&DH} & \varepsilon^3_{C\&DH} & \cdots & \varepsilon^i_{C\&DH} & \cdots & \varepsilon^n_{C\&DH} \\
X^1_{Str} & X^2_{Str} & X^3_{Str} & \cdots & X^i_{Str} & \cdots & X^n_{Str} \\
X^1_{Th} & X^2_{Th} & X^3_{Th} & \cdots & X^i_{Th} & \cdots & X^n_{Th} \\
\vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
X^1_{Com} & X^2_{Com} & X^3_{Com} & \cdots & X^i_{Com} & \cdots & X^n_{Com} \\
X^1_{C\&DH} & X^2_{C\&DH} & X^3_{C\&DH} & \cdots & X^i_{C\&DH} & \cdots & X^n_{C\&DH}
\end{matrix}
$$



Measurement or outcome of experiment = spacecraft point design and associated cost

There is a problem….

- Technical design parameters of various spacecraft subsystems are *interdependent*, *analytically* and *implicitly* related to one another via key physical relationships (see next slides)
- These key physical relationships are generally not upheld when cost analysts perform their cost-risk simulations
- The generated spacecraft point designs based on subjective statistics (i.e., simulated sets of CER input variables) may be neither technically feasible nor buildable (i.e., "Frankenstein" designs)
- Yet all simulation design outcomes are assigned non-zero probability of occurrence and consequently, the resulting spacecraft system CDF is invalid
- In other words, the cost-risk assessment may be too high or too low and the resulting "quantified" cost uncertainty may be too high or too low
- System-of-systems cost models that take ranges of input parameters and use the "roll up" procedure face the same problem

"Cost-Risk Analysis Best Practice" Violates Laws of Physics...

The rocket equation for spacecraft with chemical propulsion which is derived from Newton's law of gravitation:

$$m_{prop} = M^{i}_{SC\,Total}\,[e^{\left(\Delta V/I_{sp}g\right)} - 1\,]$$

Where m_{prop} the mass of the propellant, ΔV is the required total mission velocity increment, I_{sp} is the specific impulse of propulsion system and g is earth gravitational constant

- Is the fixed amount of propellant (not simulated) sufficient for all the randomly generated maximum total spacecraft dry mass values $M^{i}_{SC\,Total}$ to perform all required spacecraft maneuvers for the entire specified mission duration? ***Probably Not!***

The Stefan-Boltzmann law used to size the thermal radiator:

$$A = \frac{Q}{\sigma T^4}$$

where A is the surface area of the radiator, Q is the heat required to me removed, T is the radiator surface temperature, and σ is the Stefan-Boltzmann constant ($5.667 \times 10^{-5}\ W/m^2 - K^4$)

- Is the fixed area A of the radiator (not simulated) large enough to dissipate the required heat for all the randomly generated maximum total spacecraft power loads values $P^{i}_{SC\,Total}$?

Probably Not!

"Cost-Risk Analysis Best Practice" Violates Laws of Physics...

The solar arrays sizing equation is:

$$P_{EOL} = P_{BOL}\,(1.0 - \beta)^T = F_S A f_p \varepsilon_{BOL}(1.0 - \delta_{los})\left[1.0 - \gamma_T(t_0 - t_{REF})\right]\cos(\alpha)\,(1.0 - \beta)^T$$

Or

$$A = \frac{P_{EOL}}{F_S f_p \varepsilon_{BOL}(1.0 - \delta_{los})\left[1.0 - \gamma_T(t_0 - t_{REF})\right]\cos(\alpha)\,(1.0 - \beta)^T}$$

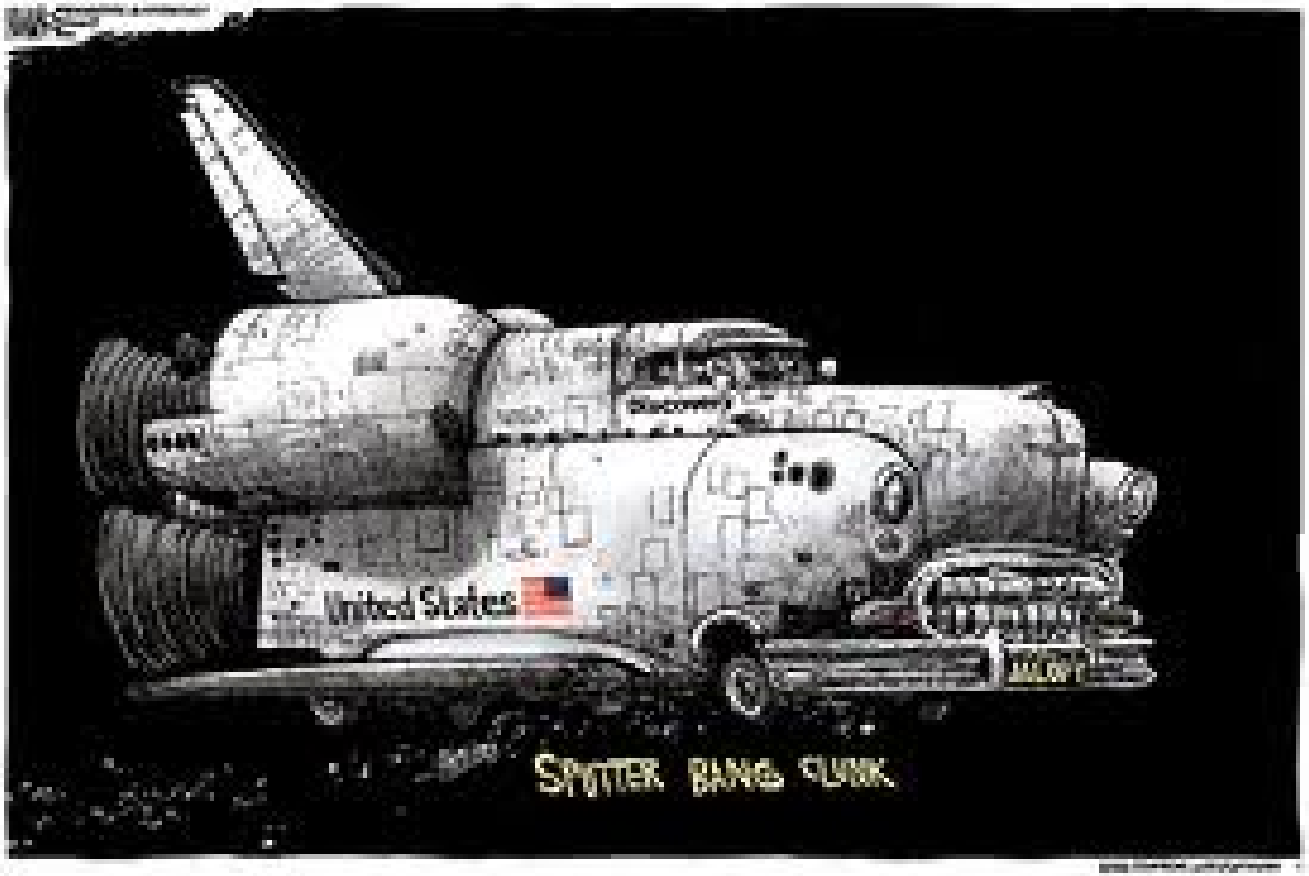
Where P_{BOL} is the power generated by solar arrays at the beginning of life (i.e. start of mission), P_{EOL} is the power generated by solar arrays at the end of life (i.e. end of mission), F_S is the solar flux, A is the area of solar arrays, f_p is the packing factor to account for active area loss due to cell packing, ε_{BOL} is the cell BOL efficiency, δ_{los} is loss factor to account for cell mismatch, diodes and other losses, γ_T is the thermal loss, t_{REF} is reference temperature usually 28°C, t_0 is the nominal operating temperature, α is the illumination angle, β is annual loss due to space environment and T is the mission duration.

- Are the solar arrays with fixed area (not simulated) large enough to generate enough power to meet all the randomly generated maximum spacecraft power load values $P^i_{SC\,Total}$? ***Probably Not!***

More problems….

- Some randomly generated spacecraft system mass $M^i_{SC\ Total}$ may exceed the selected launch (fixed) vehicle capability to place the spacecraft in the desired orbit and/or may not meet natural frequency requirements for rigidity to counter launch vehicle load factors
- Each simulated set of subsystems masses $\{m^i_j\}$ results in different mass properties of the spacecraft such as its total mass, moments of inertia and location of its center of gravity. Subsystems dimensions and placement within the spacecraft are assumed fixed (not simulated)
  - Does the corresponding randomly generated m^i_{ACS} reflect appropriately sized attitude control hardware with sufficient momentum storage and dumping for both induced and natural disturbances for spacecraft design outcome$\{m^i_j\}$? ***Probably Not!***
- Nowadays, Reaction Wheel Assembly (RWA), Star tracker, battery cells, Onboard Computer, Interface Cards and other components are catalogued "off-the-shelf" items supplied by a handful of manufacturers
  - Their mass values are quantized and we model their uncertainty with continuous triangular distribution!!
  - Can a vendor supply 1.356 battery cell, 2.419 RWA, 0.978 star tracker? ***Probably Not!***
- The randomly generated spacecraft point designs based on subjective statistics may not be "*technically feasible*", "*buildable*" (i.e., "Frankenstein" designs) or "*flyable*". Yet all of them are assigned non-zero probability of occurrence and consequently, *the resulting spacecraft system CDF (i.e. S-curve) is invalid*

The Problem Pictorially… "Frankenstein Design[1]"



Points on S-curve may be more representative of a "flying truck" than a spacecraft! Or something else…

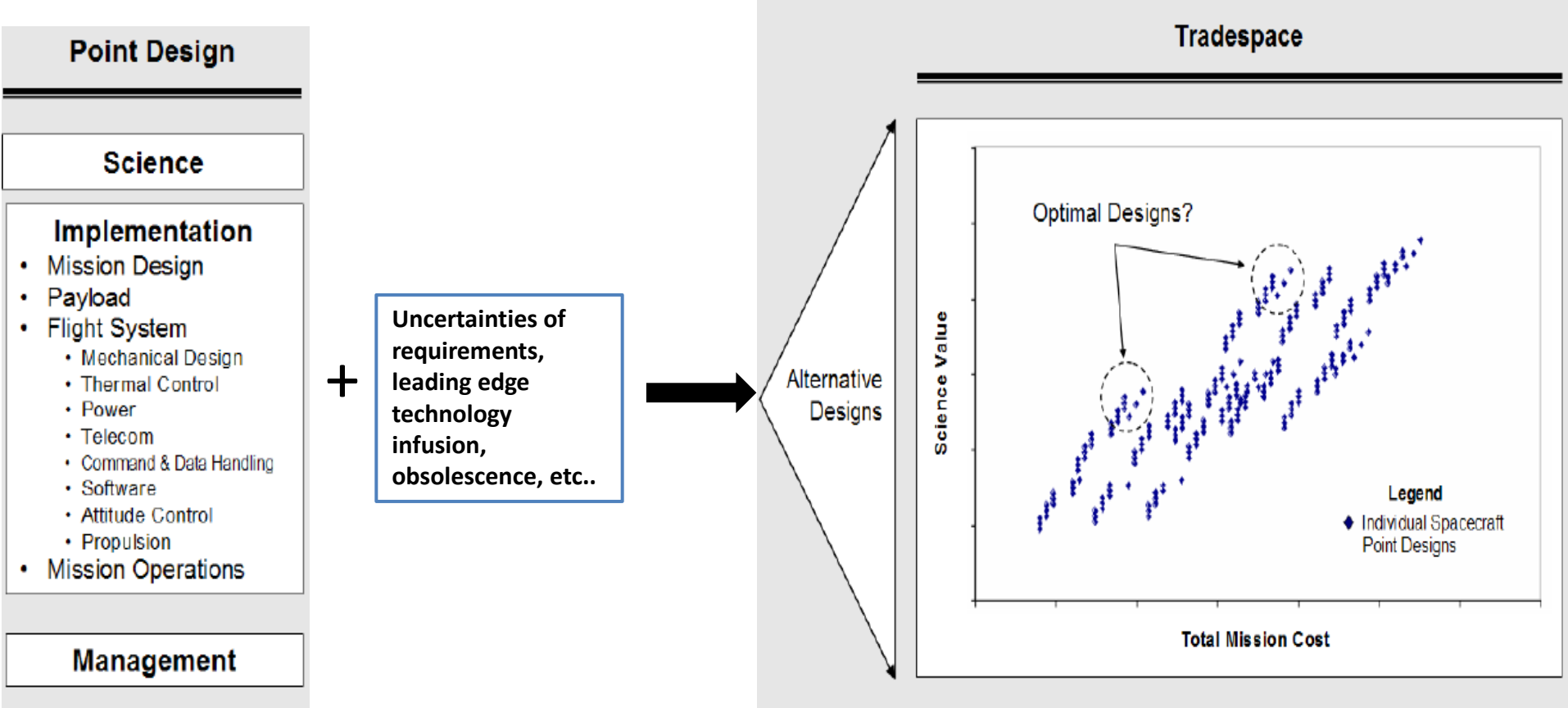
One Solution…. Integrated System Modeling

- Concepts with *low maturity level* (pre-PDR)
  - Due to the number of possible combinations of spacecraft components and systems, use spacecraft concept modeling software tool (e.g. CEM, GAJAT, SMAD, STM, etc…)
  - These tools should be augmented to address sources of design uncertainty by specifying their range of values and number of steps the tool should iterate through (e.g. operational orbital altitude range is between 600 and 700 Km because of competing science requirements)
    - Incomplete definition of initial requirement and their subsequent volatility
    - Infusion of beyond state-of-the-art technology
    - Biases and optimistic technical assumptions
    - Parts obsolescence and uncontrolled vendor changes
  - To ensure credible point designs , these tools maintain key physical relationships within, such as the rocket equation
  - *Tens to hundreds* of design parameters are exchanged between subsystem design modules
  - These tools then rapidly generate deltas from existing spacecraft point design while capturing system and subsystems ripple effects caused by the uncertainties driving the spacecraft design
  - These integrated system modeling tools can be thought of as *"Auto CADRe part B Generators"*
  - CADRe part B is the cost input vector

One Solution…. Integrated System Modeling

- Concept with *high maturity level* (post-PDR)
  - Integrate subsystem models and data that the cognizant system and subsystem design engineers already possess in one form or another
  - Higher fidelity system modeling tool with more technical depth
  - Potentially *Thousands* of design parameters are exchanged between subsystem design modules
  - Again, the resulting integrated system modeling tool can be thought of as *"Auto CADRe part B Generators"*

Example of Integrated System Modeling*



The results of incorporating uncertainties in Integrated System Modeling tools can be seen on MEL, power modes, science data returned and other design parameters that drive system cost and schedule

* This chart is adapted from a paper "Conceptual Design Methods and the Application of a Trade space Modeling Tool for Deep Space Missions" by Melissa Jones and James P. Chase

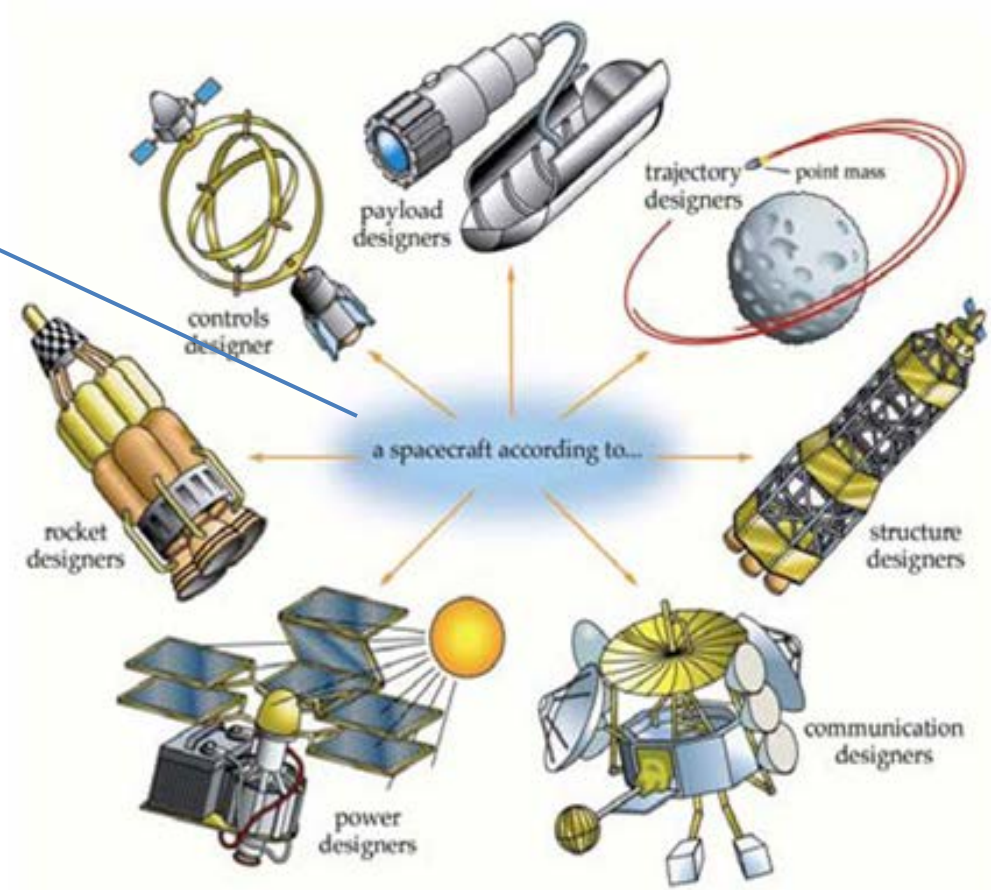
Integrated System Model development Approach

Another Solution…

Conclusions

- Cost analysts need to understand that while spacecraft design parameters are not typically known with sufficient precision, their uncertainties should NOT be modeled with *subjective distributions*
  - *Let's not abuse theory of probability!!*
  - *Know what's being simulated, define your event and sample space*
  - *Identify what's driving uncertainty in your system design*
- Spacecraft subsystem design parameters are *analytically* and *implicitly* related by physical and engineering relationships
- Every program should develop and maintain an integrated system and cost engineering tool that auto-generates sets of design parameters (cost model input vectors) reflecting "*feasible*", "*buildable*" and "*flyable*" system points designs
  - "CADRe part B Auto-Generator"
- System-of-systems cost models (e.g. USCM, NAFCOM, NICM) should ensure the validity of input vectors
- Be wary of traditional cost estimate S-curve, it's just a measure of an individual's belief
  - *We will always lack the normalization condition unless we find a way to apply Quantum Field Theory in cost-risk analysis!!!*

cost engineer



Questions?

References

- AFCAA Cost Risk Uncertainty Handbook
- “Conceptual Design Methods and the Application of a Tradespace Modeling Tool for Deep Space Missions” Melissa A. Jones and James P.Chase, 2008 IEEEAC
- “Design-to-Cost for Space Missions”, Robert Shishko, Edward J. Jorgensen
- Google Images