Critique of Cost-Risk Analysis: Frankenstein Spacecraft Designs

NASA Cost Symposium

Pasadena, CA

August 27th , 2013

Mohamed Elghefari

melghefari@spaceea.com

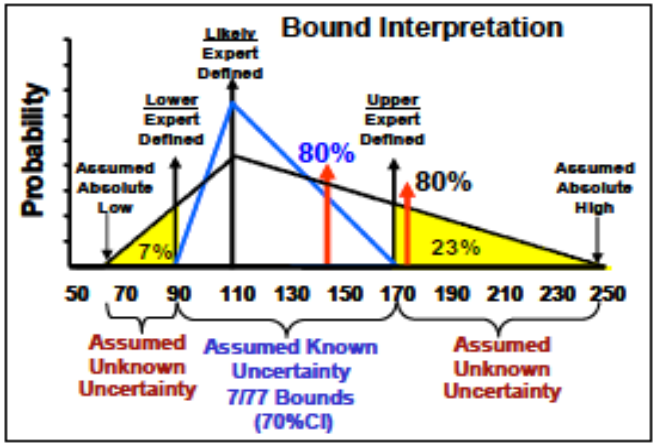
SPACEEA SYSTEMS

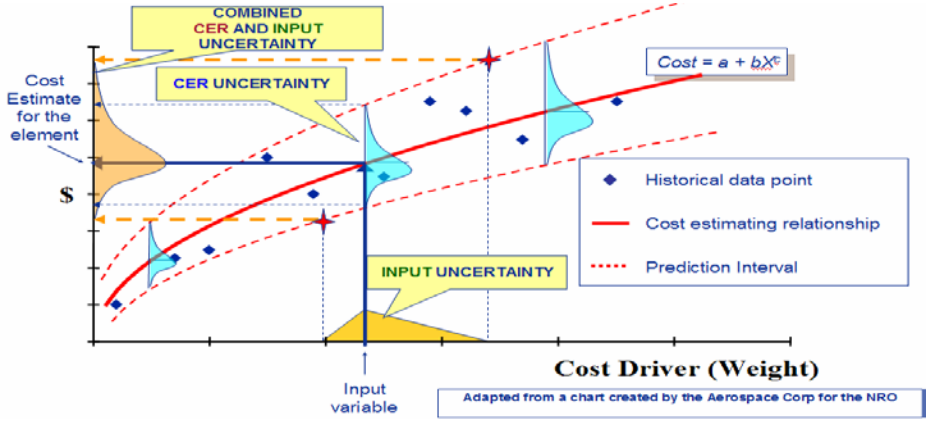
Outline

- Cost-Risk Analysis “Best Practice”
- Critique: “Frankenstein Spacecraft Design”
- Suggested Solution: Integrated System Modeling
- Suggested Solution: Probabilistic Cost Growth Model
- Terminology: “Percentile” rather than “Confidence Level”
- Conclusions

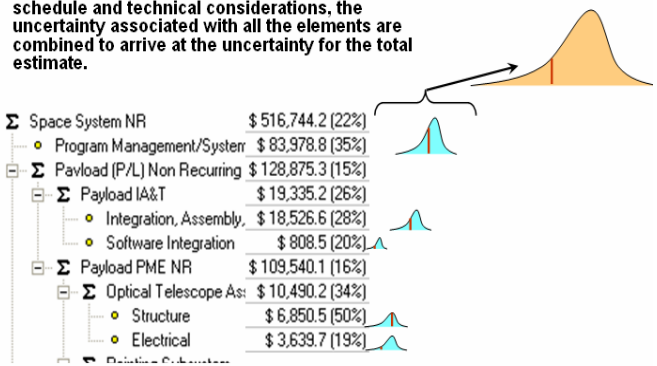
Cost-Risk Analysis "Best Practice"

	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%**		





With suitable adjustments to capture correlation, schedule and technical considerations, the uncertainty associated with all the elements are combined to arrive at the uncertainty for the total estimate.



To give a sense of "confidence" in a point estimate, cost analysts are expected to generate "credible" probabilistic distributions of potential costs that capture uncertainties associated with cost estimating methodology and cost drivers and account for correlation between cost elements

Cost-Risk Analysis "Best Practice" Mathematically

- Each simulation trial results in a set of values for spacecraft subsystems masses, subsystems power loads, and corresponding set of values for subsystems costs

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

- The total "simulated" spacecraft system dry mass, power requirement, and cost estimate are

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

$$X_j^i = f_j(m_j^i p_j^i,) * \varepsilon_{ij}$$

- The probability of occurrence of each simulation outcome

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

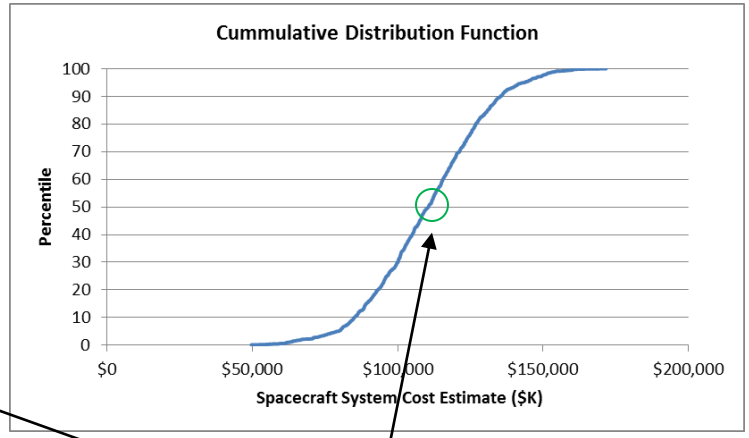
- The Cumulative Density Function

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

What's the Meaning of a Measurement or Event in Cost Estimating Experiment?

What is the "ensemble" or "sample space " of your experiment?

$$
\begin{array}{ccccccc}
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{array}
$$



outcome of experiment = Spacecraft point design and associated cost

Points that make up the s-curve represent not only possible spacecraft cost outcomes but spacecraft design outcomes as well!

There is a Problem….

- Technical design parameters of spacecraft subsystems are *interdependent*, *analytically* and *implicitly* related to one another via key physical relationships
- These key physical relationships are generally not upheld when cost analysts perform cost-risk simulations
- The generated spacecraft point designs (i.e., simulated sets of CER input variables) based on subjective statistics 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 cost CDF is invalid
- The resulting cost-risk assessment may be too high or too low

Design parameters of spacecraft subsystems are related to one another via key physical relationships which are generally NOT upheld in cost-risk simulations

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:

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

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! Probably

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….

Solar array sizing equation

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

or

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

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 spacecraft power load values?

Probably not!

More Problems…

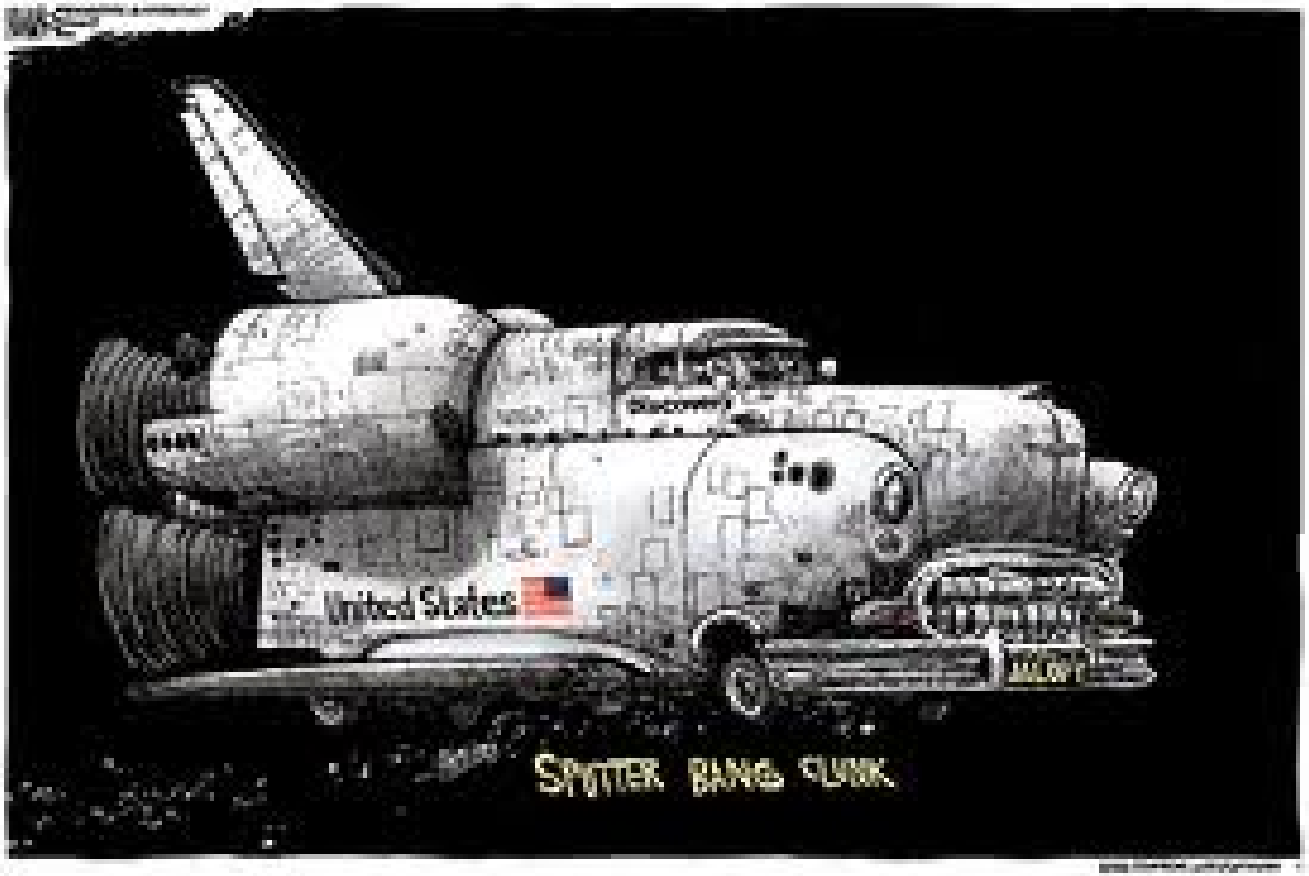
- Some randomly generated spacecraft system mass $M^{i}_{SC\ Total}$ may exceed the selected launch (fixed) vehicle capability to place the spacecraft in the desired orbit and/or may not meet natural frequency requirements for rigidity to counter launch vehicle load factors
- Each simulated set of subsystems 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 Assemblies (RWA), star trackers, battery cells, onboard computers, Interface Cards, and other components are catalogued "off-the-shelf" items supplied by a handful of manufacturers
  - Their mass values are quantized, and yet we model their uncertainty with continuous triangular distribution!!
  - Can vendor supply 1.356 battery cell, 2.419 RWA, 0.978 star tracker? ***Probably Not!***

Some of the randomly generated spacecraft point designs based on subjective statistics are not technically feasible, buildable, or flyable. Yet they are assigned non-zero probability of occurrence and consequently cost-risk assessment is invalid

The Problem Pictorially…



Points on S-curve may represent cost of a Frankenstein spacecraft Design!

One Solution: Probabilistic Cost Growth Model

- Model does not require cost driver uncertainty input
- Requires only two parameters:
  - Current Best Estimate(CBE)
  - CBE maturity relative to project milestones, which is reasonably objective
- Based on historical analogous systems (available in CADRe database)
- Predicts cost growth (or shrinkage)
- Produces cost growth factor distribution result (embodies uncertainty) that recognizes the possibility of growth or shrinkage of cost driver
- Provides decreasing mean growth factor and growth factor uncertainty (decreasing CV) as estimate relative maturity increases

Provides probabilistic cost growth adjustment to Current Best Estimate

Another Solution: Integrated System Modeling

- For advanced concepts, use space system modeling software tools
- For designs 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
- These design tools should be augmented to address uncertainties of design drivers by specifying their range of input values and number of steps the tool should iterate through (e.g., unknown power density of solar arrays using new PV cell technology)
- To ensure credible and valid point designs , these tools maintain key physical relationships governing spacecraft design and use technical parameters and specifications from database of actual catalogued hardware components
- These tools should rapidly generate deltas from existing spacecraft point design reflecting the uncertainties of spacecraft design drivers and their system and subsystems ripple effects
- These integrated system modeling tools can be thought of as “Auto CADRe part B Generators”
- CADRe part B is the cost input vector
- Apply cost estimating uncertainty and appropriate cost and schedule correlations to all generated point designs and construct your overall system cost CDF

Terminology: "Percentile" rather than "Confidence Level"

- No matter what the extent and depth of our cost-risk assessment and analysis, our resulting cost probability distribution cannot be proven to meet the normalization condition

$$\int_{All\ Space} \psi(r,t)dr = 1$$

where $\boldsymbol{\psi}$**(r,t)** is system cost PDF at time **t** and **r** is system state descriptor

- No one knows the true cost probability distribution
- Using "Confidence Level" term can give decision makers false sense of confidence
- Using "XX Percentile" estimate is more appropriate than "XX Confidence Level" estimate

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 you are simulating, define your event and sample space
- Spacecraft subsystem design parameters are analytically and implicitly related by physical and engineering relationships
- One suggested solution is probabilistic growth cost model which embodies cost driver uncertainty
- Every program should develop and maintain an integrated system modeling tool that auto-generates sets of "technically feasible", "buildable" and "flyable" system points designs reflecting system cost driver uncertainties
  - "CADRe part B Auto-Generator"
- System-of-systems cost models 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!!!

Questions?

References

- AFCAA Cost Risk Uncertainty Book
- Google images