Characterizing Epistemic Uncertainty for Space Launch Designs

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Presentation Outline

- Establish the importance of estimating and characterizing the different types of uncertainty
- Identify an issue with estimating uncertainty for launch vehicle designs
- Propose two solutions for more accurately capturing uncertainty in launch vehicle designs
- Recommend a solution for future work

Uncertainty

- Essential Part of Probabilistic Risk Assessment (PRA) for Launch Vehicle Designs
  - Launch decisions
  - Trade studies (borderline scenarios)
  - Risk Management and Risk Acceptance
- Probabilistic Risk Assessment (PRA) Uncertainty for Space Launch Vehicles is present in
  - Models (e.g., assumptions and development)
  - Parameters (e.g., data, environments, demonstrated versus predicted)
  - Failure Scenario Development and Completeness
- Aleatory and Epistemic Uncertainty
  - Aleatory uncertainty represents natural randomness that occurs in systems
  - Epistemic uncertainty represents “lack of knowledge” or ignorance

Uncertainty Propagation

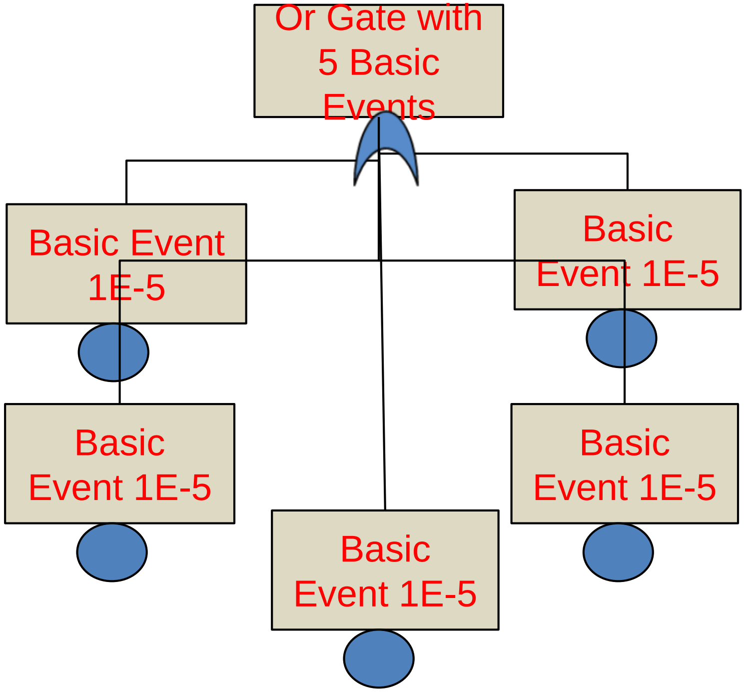
- NASA PRA propagates uncertainty via the probabilistic logic models (e.g., fault trees) using Monte Carlo simulation
- Uncertainty is characterized by parameter distributions
- The spread of parameter distributions reflect mostly epistemic uncertainty for space launch design
  - Based on heuristic guidelines or historical data
  - Data applicability

PRA Structure Influence on Uncertainty

Logic Structure influences uncertainty propagation

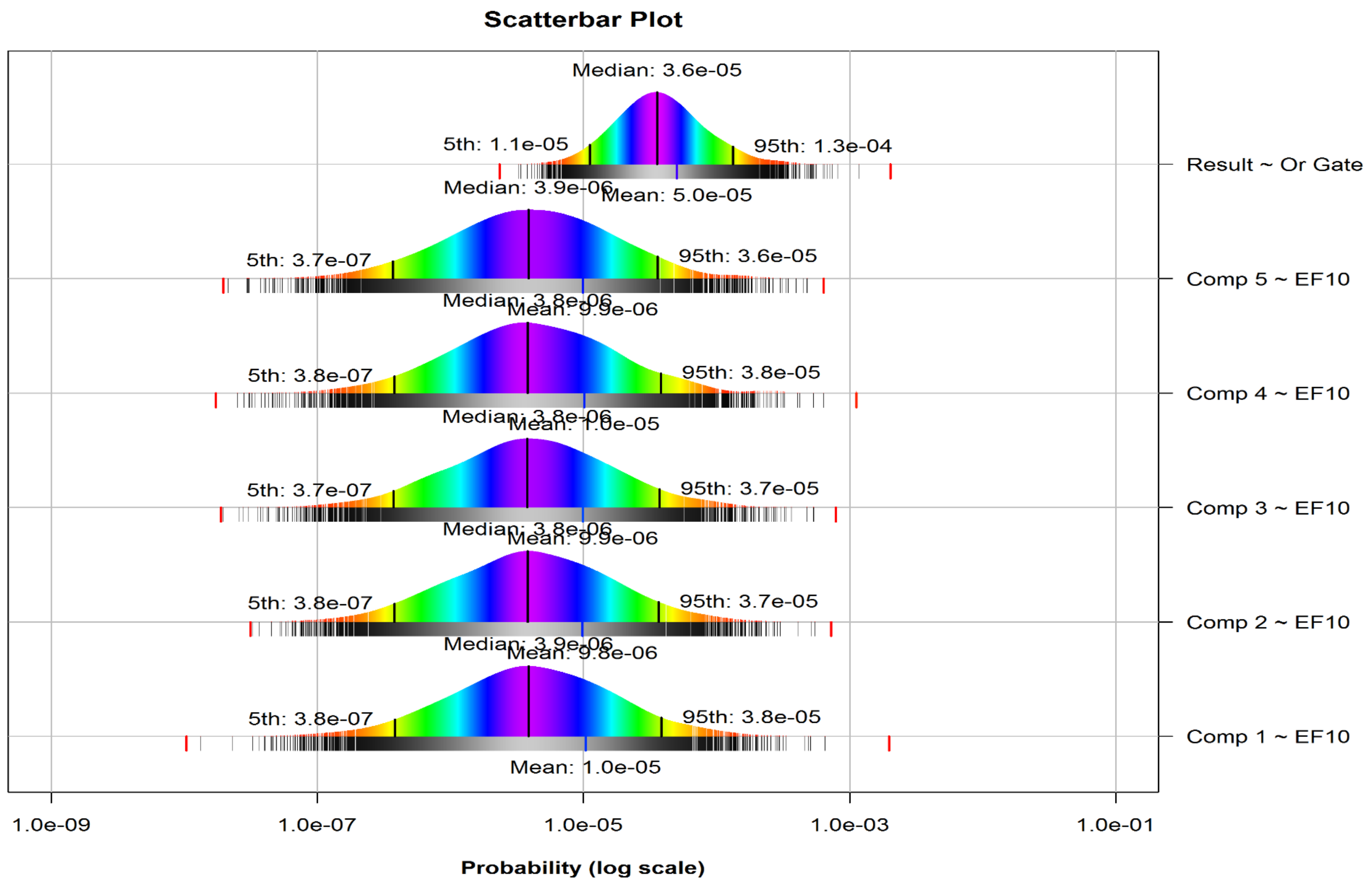
Basic events in OR gates (uncorrelated)

Number of Model Basic Events	Individual Basic Event Error Factor					Resultant Model Error Factor
	5	10	15	20	100	
2	3.4	6.1	8.6	11.1	44.5	
5	2.3	3.8	5.1	6.3	21.3	
10	1.9	2.8	3.7	4.5	13.8	
20	1.6	2.2	2.8	3.3	9.5	



OR Gate Uncertainty Results

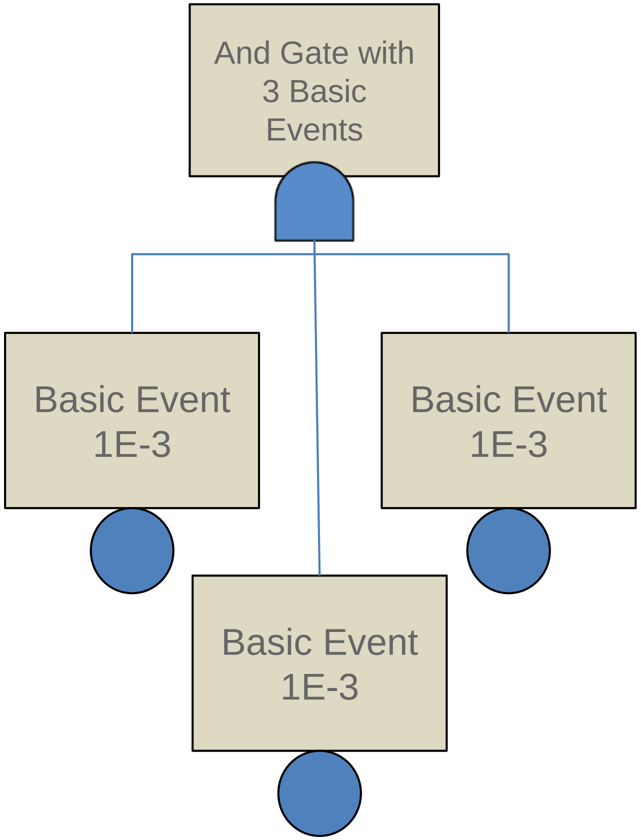
Example of : Five basic events EF = 10 in an OR Gate (EF~3.6); 10k iterations



PRA Structure Influence on Uncertainty Continued

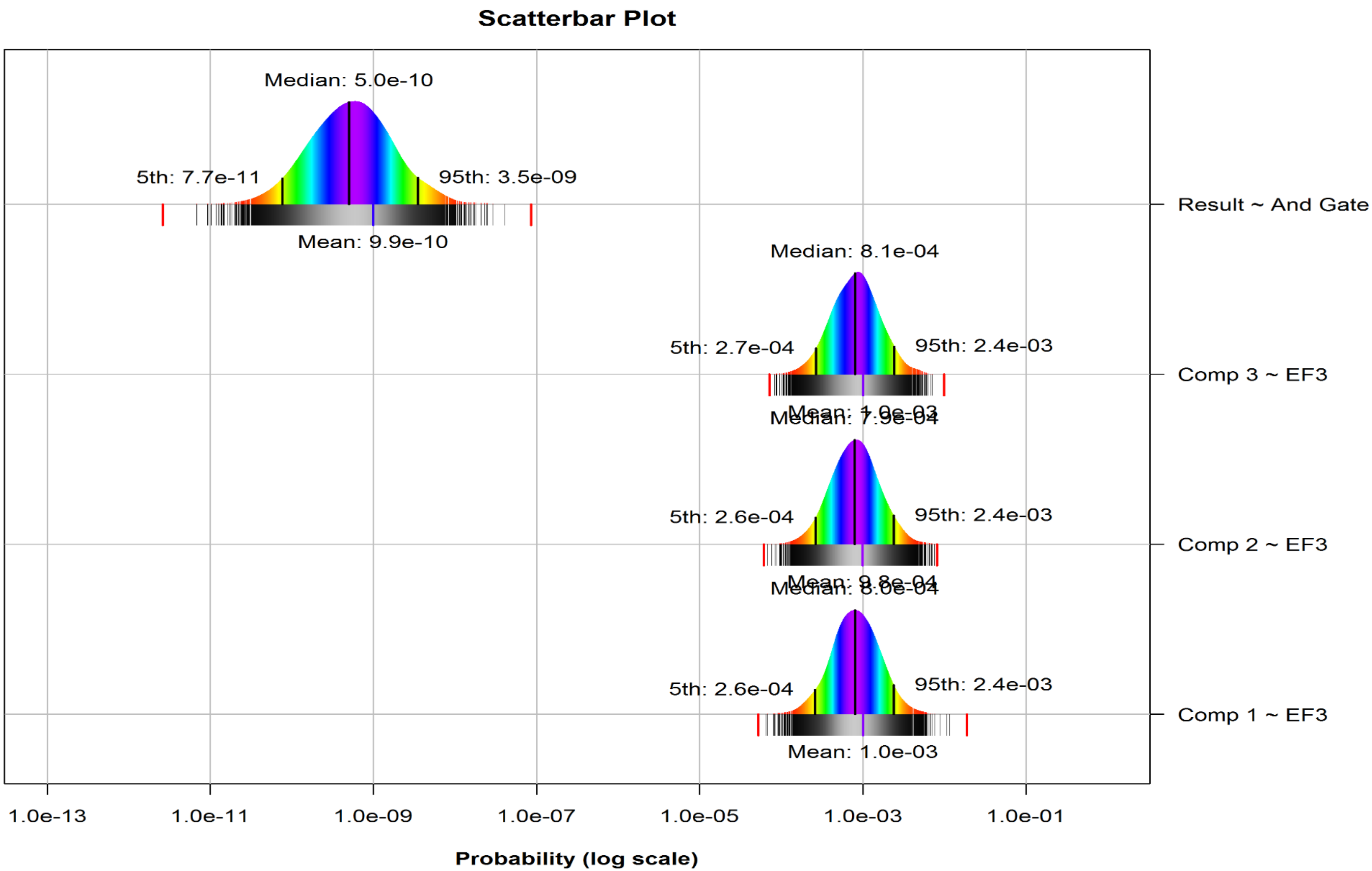
Basic events in AND gates(uncorrelated)

Number of Model Basic Events	Individual Basic Event Error Factor					
	5	10	15	20	100	
2	9.6	26.5	47.1	70.9	700.3	Resultant Model Error Factor
3	17.5	NA	NA	NA	NA	
4	NA	NA	NA	NA	NA	
20	NA	NA	NA	NA	NA	



AND Gate Uncertainty Results

Example of 3 basic events EF = 3 in an AND Gate (EF~6.7); 10k iterations



Examples of PRA Structures

- Launch Vehicle Designs
  - Due to mass, volume, and cost limitations
    - Redundancy at the subsystem level
    - Single point failures at the element level
    - Increased dependencies between elements
- Other Industries
  - Defense-in-depth
    - Redundant safety systems
      - Cost
    - Increased independence at the system level
      - Due to diversity and special separation

Ramifications of this Issue

- This is a known issue
  - Ginsberg and Ferson; *Different Methods are needed to propagate ignorance and variability*;
- Reduction in uncertainty estimates for launch designs
    - Assuming a lognormal result is an EF ~ 2.5
  - Insensitive to increased epistemic uncertainty
    - Lack of knowledge of components does not contribute to uncertainty
      - Environmental factors
      - Data applicability
  - Uncertainty-Importance routines
    - Inability to prioritize components to reduce uncertainty

Solutions to Uncertainty Reduction

- Partial Correlation :Solution 1
  - Allows ranked MC sampling from partially correlated variables
  - Pros
    - Represents what is most likely occurring in launch vehicles
    - A form of assigning partial dependency to components
    - Will account for uncertainty anomalies in any logic structure
  - Cons
    - Knowledge to determine partial correlation to different components and subsystems is not available
      - How will we know if the partial correlation is correct?
      - Will this add uncertainty to our results?
    - Current fault tree tool sets only account for full positive correlation with components that have the same failure rates
      - (PRA group is working on developing a tool)
    - Challenging to implement even if the data was available
      - 100 components will require 10,000 correlation relationships (NxN matric)

Solutions to Uncertainty Reduction Continued

- Interval Analyses: Alternative Solution 2
  - Estimates the uncertainty of the logic tree by calculating a 5^{th} and 95^{th} solution from all the basic events
    - If (X + Y + Z) is your logic equation then:
      - Lower Bound ($X^{5th}+Y^{5th}+Z^{5th}$)
      - Upper Bound ($X^{95th}+Y^{95th}+Z^{95th}$)
  - Pros
    - Easy to implement
    - Estimates the entire uncertainty band
    - Shows reasonable results for large complex system fault trees for launch vehicle designs
      - EF = 3-5 with component EFs between 3-12
    - Is sensitive to Uncertainty and Importance routines
  - Cons
    - Is an alternative to partial correlations
    - May increase the spread of the uncertainty

Future Solutions

- Identify where uncertainty for launch vehicle designs may be underestimated
- Develop tools to assign (positive and negative) partial correlation to elements of a Boolean expression
- Estimate partial correlation from environmental factors for subsystems

Is this something dynamic PRA using physics-based models may solve?

Conclusions

- Uncertainty is an important part of PRA and Risk-Informed decisions
- Launch Vehicle Designs have unique models structures due to mass and space limitations
- Current PRA models for Launch Vehicle designs probably underestimate uncertainty (Shuttle PRA ~2)
- Partial correlation would account for uncertainty
- Until tools or physics-based dynamic PRA is a reality the interval analyses provides a good interim solution

Questions?

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