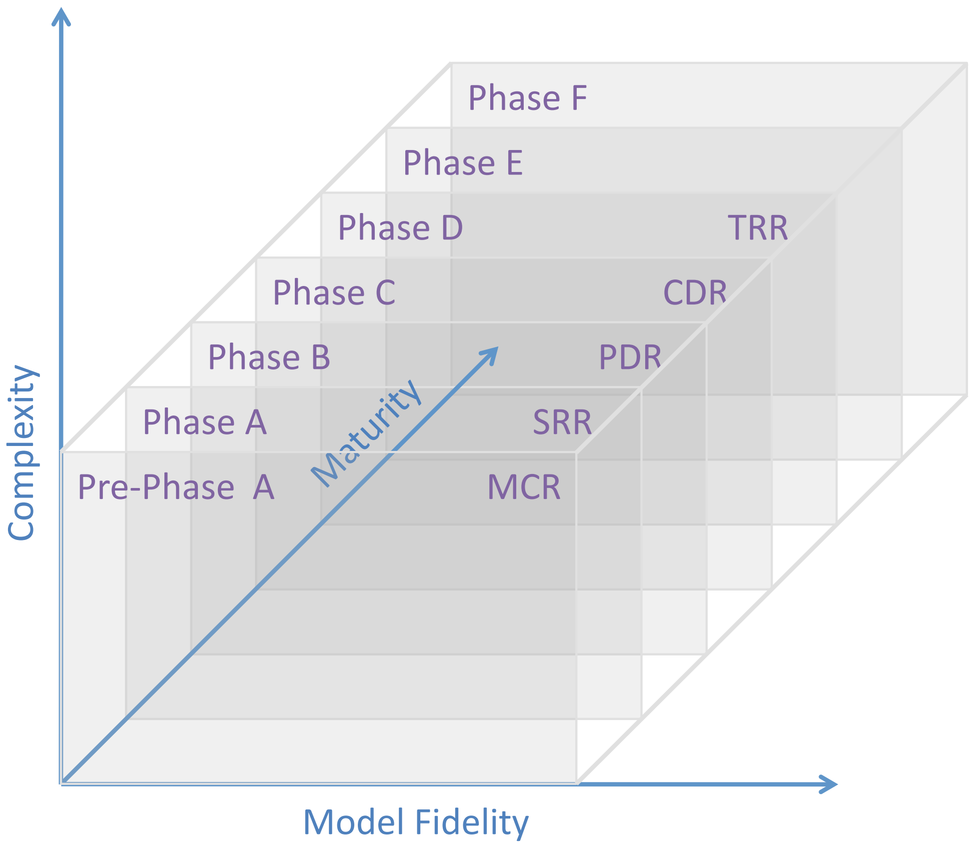
APA-09/NDA-01
Frontiers of Uncertainty Management for Complex Aerospace Systems (Invited)

Integrated Uncertainty Quantification for Risk and Resource Management: Building Confidence in Design



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Roadmap

- Background
- Motivation/technical challenge
- Proposed solution
- Assessment space
  - Design cycle
  - Uncertainty
    - Quantification
    - Classification
    - Integration
- Management of Risk and Resources
- Final Remarks

Background

Attempt to conceptualize and extend lessons learned from experience with NASA research and development programs and projects.

See Walker AIAA 2011-3345

Motivation/Technical Challenge

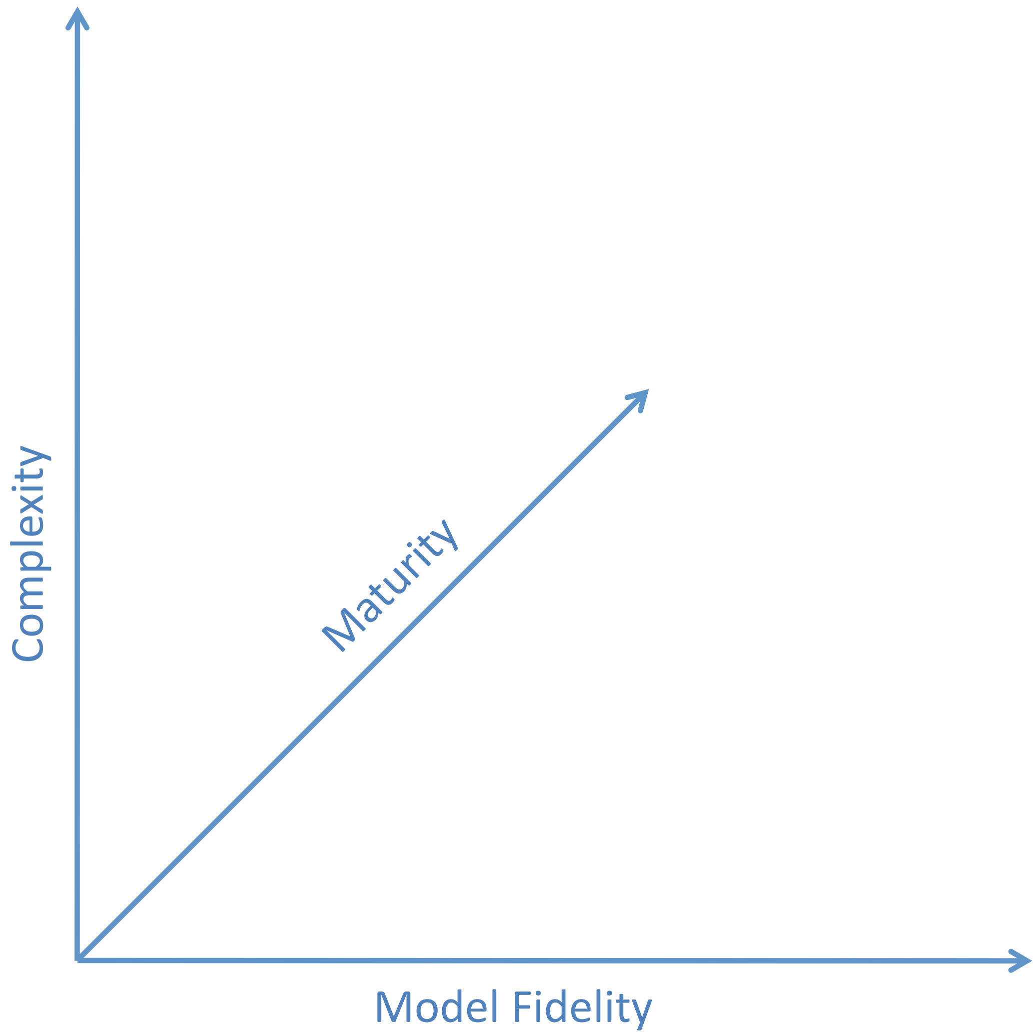
Development of confidence in design and analysis with limited resources.

Proposed Solution

Higher fidelity, integrated uncertainty quantification performed earlier in the design process should lead to:

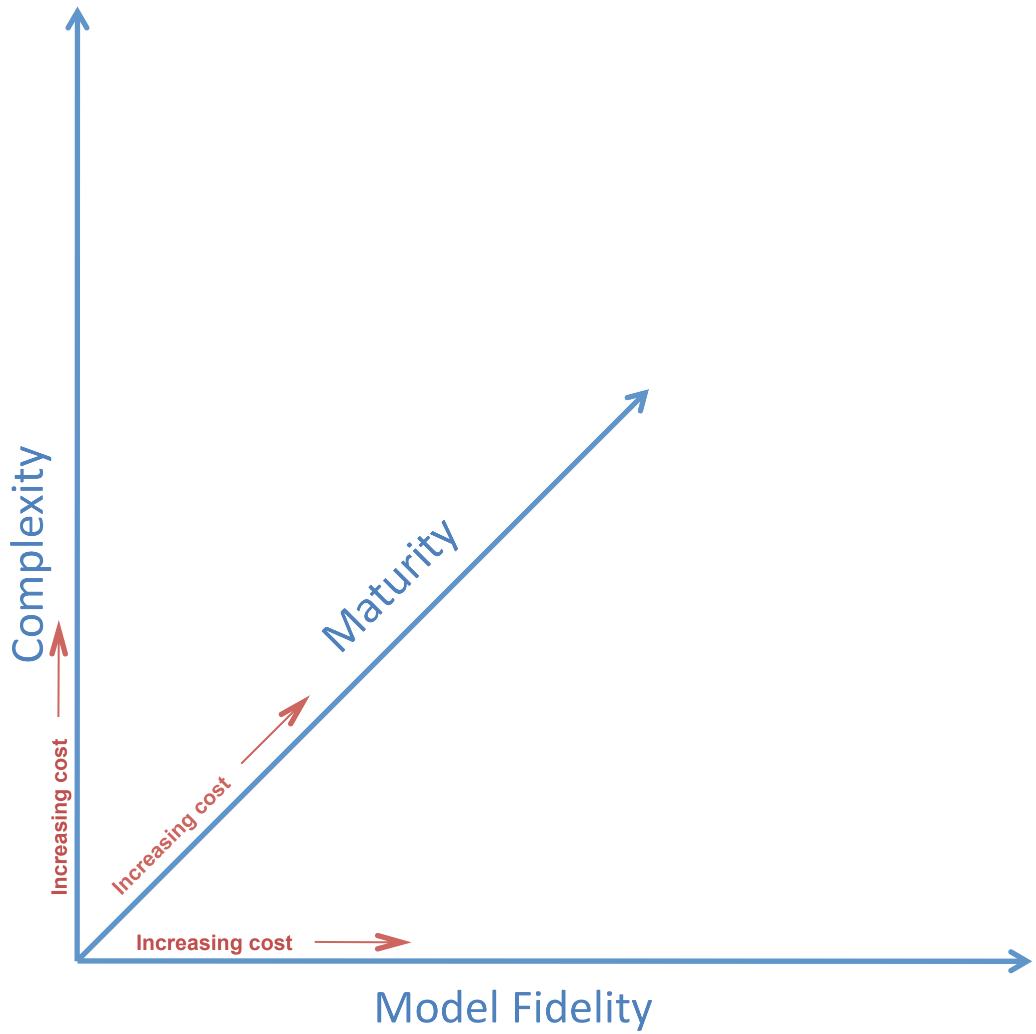
- **Better understanding of inherent risk**
- **Ability to better direct resources**
  - **More clarity between conducting further test and analysis versus redesign**
  - **Appropriate selection of model fidelity for applicable design maturity state**
- **More confidence in design and analysis**

Assessment Space



- Relates program/ project/design complexity and maturity to its representation (model fidelity)
- Costs typically increase away from the origin
- As the system matures, the costs of determining a problem and fixing it increase rapidly
- Axes have realistic limits
- Confidence: 4th axis

Assessment Space



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Complexity

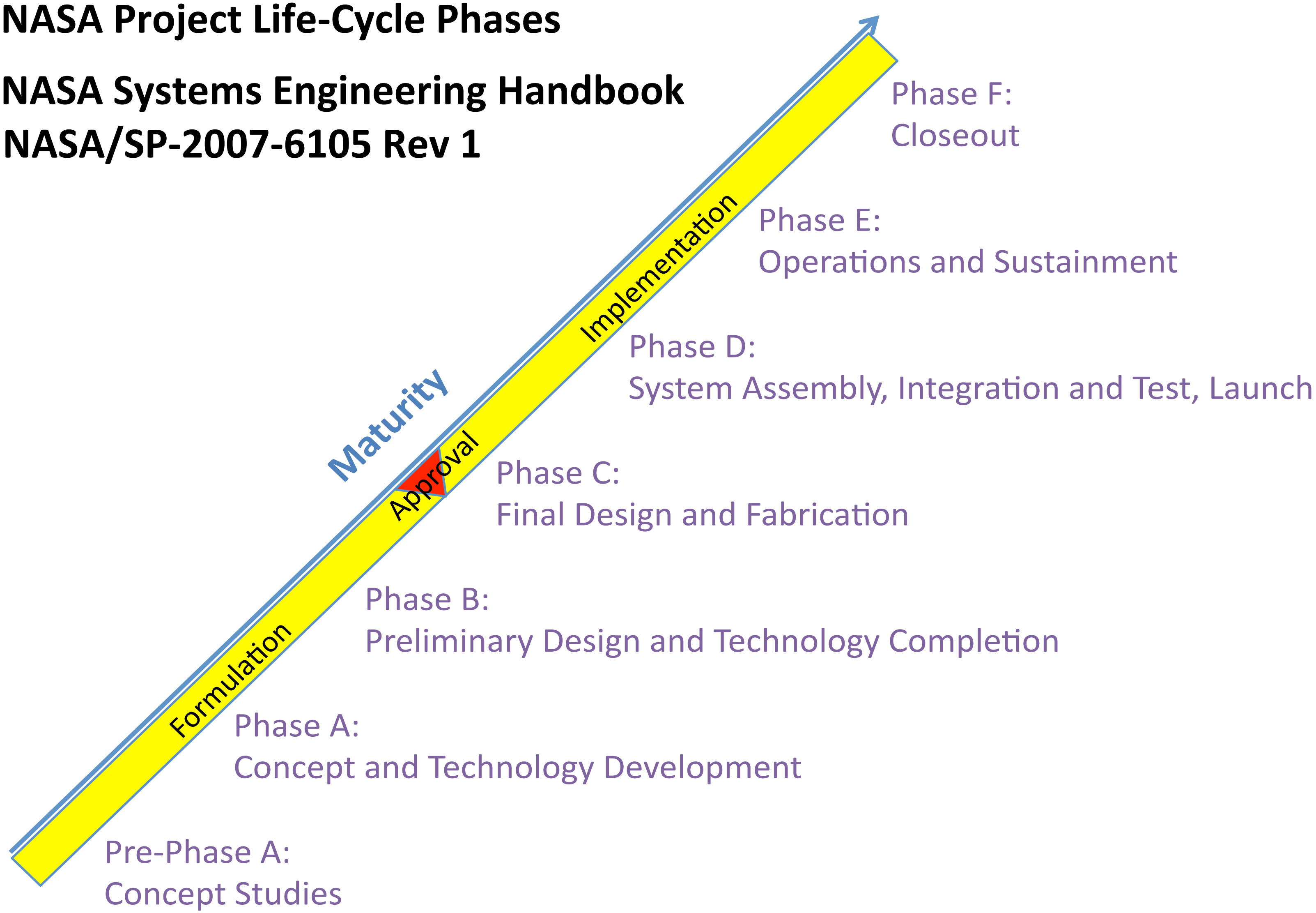
Complexity (arrow, increasing upward):

- Architecture
- System of Systems/Vehicle
- System
- Sub-system
- Component

- **Complexity refers to the object of analysis**
- **Increase in complexity involves progressively more disciplines**

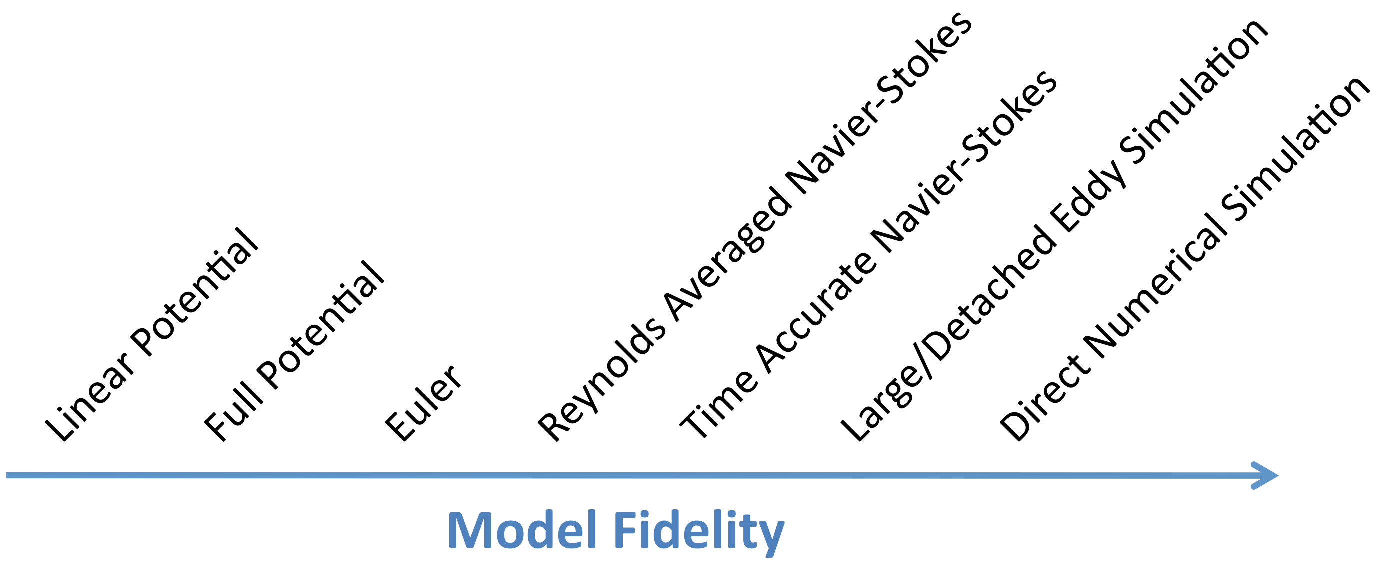
Maturity

- **NASA Project Life-Cycle Phases**
- **NASA Systems Engineering Handbook NASA/SP-2007-6105 Rev 1**

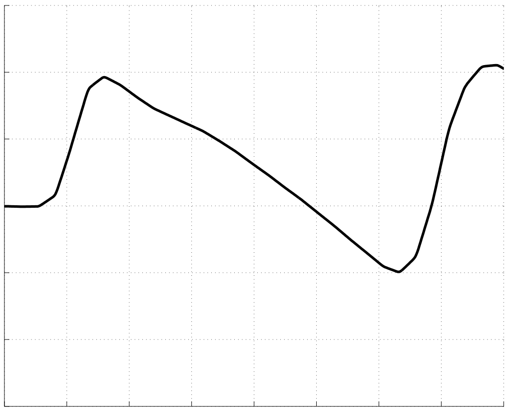


Model Fidelity

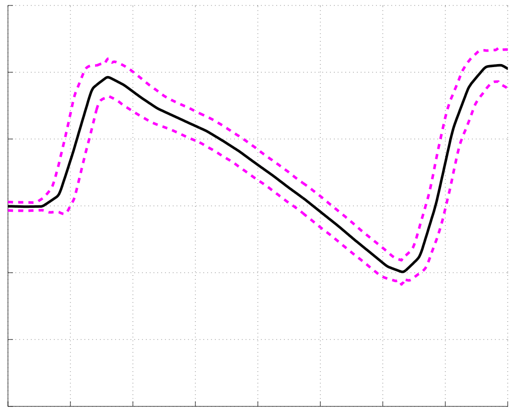
- Computational aerodynamics example
- Similar example could be constructed with test and evaluation or other disciplines



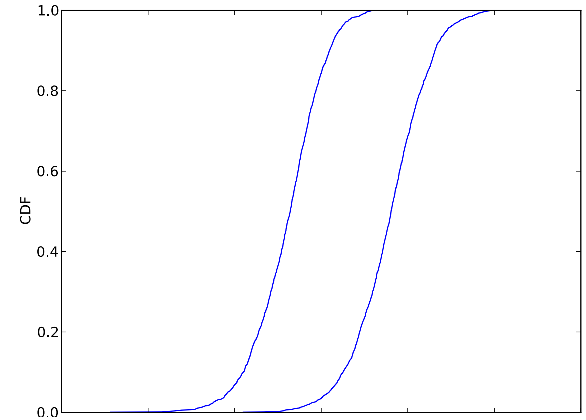
Model Fidelity/Uncertainty Models



Level: 0,1



Level: 2,3



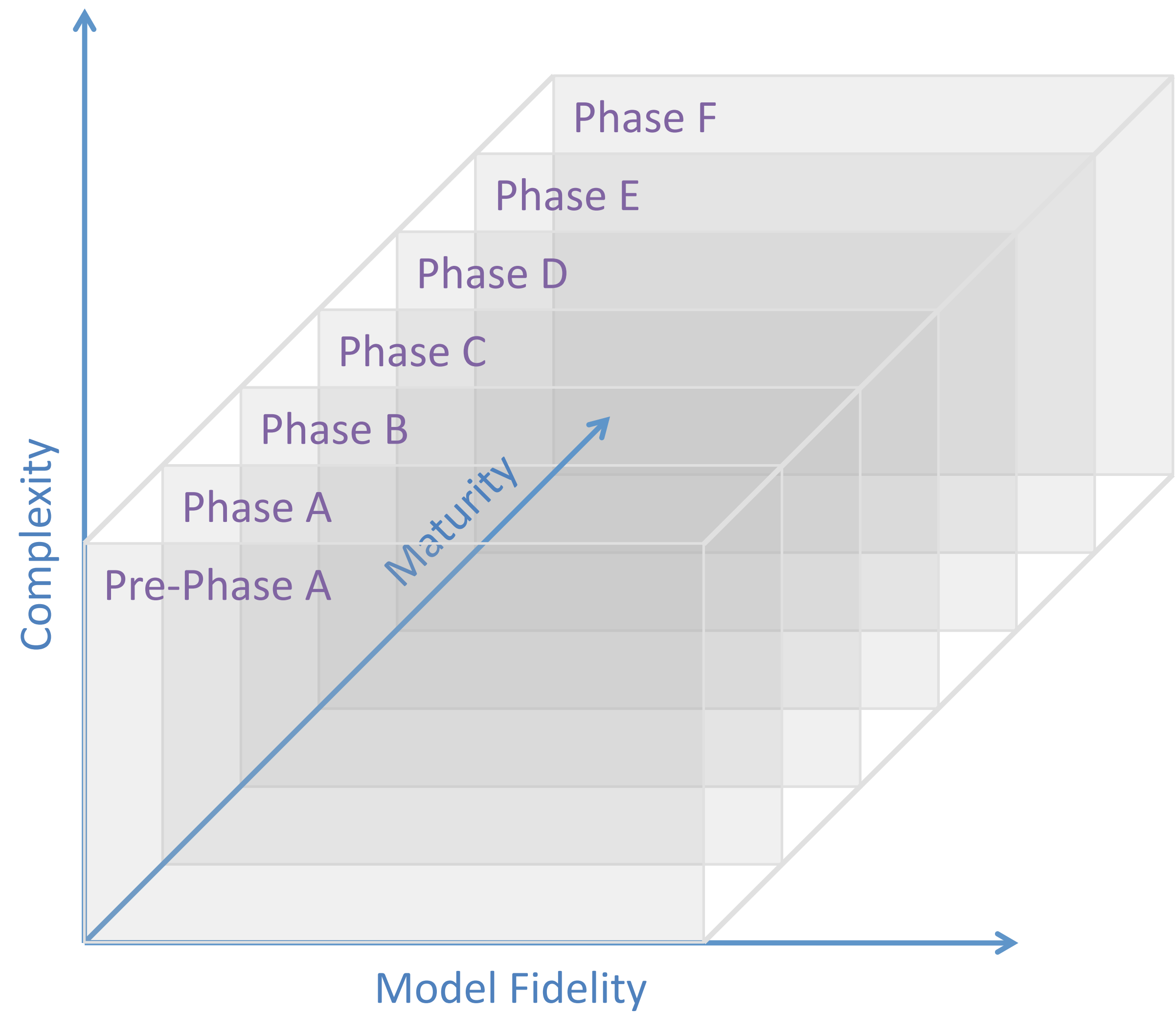
Level: 4,5

- Level 0: Hazard Detection and Failure Mode Identification
- Level 1: 'Worst Case' Approach
- Level 2: Quasi-Worst Cases and Plausible Upper Bounds
- Level 3: Best Estimates and Central Values
- Level 4: Probabilistic Risk Assessment, Single Risk Curve
- Level 5: Probabilistic Risk Assessment, Multiple Risk Curves

Model Fidelity

Paté-Cornell, M.E. (1996) "Uncertainties in Risk Analysis: Six Levels of Treatment." Reliability Engineering and System Safety. 54:95-111.

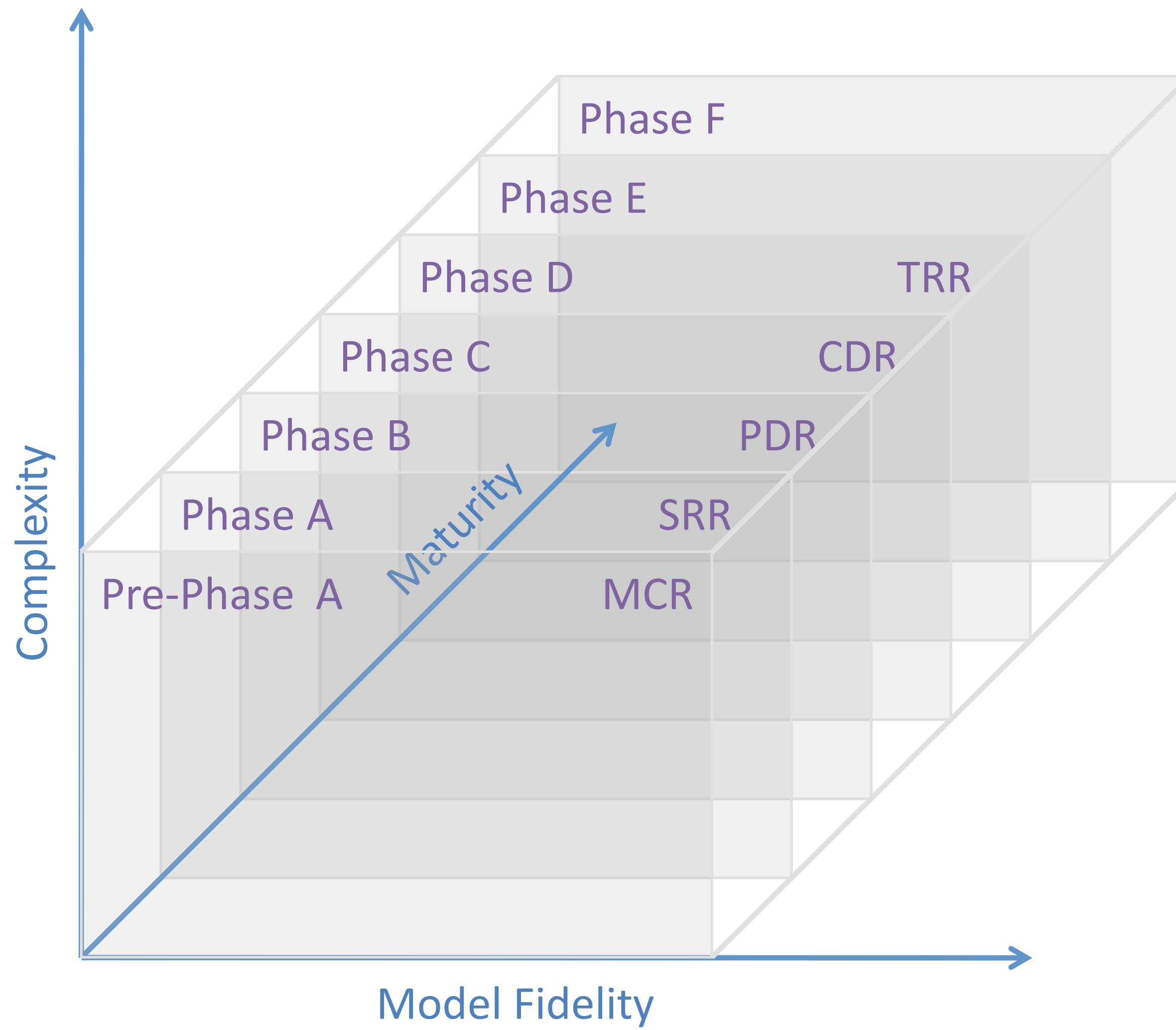
Mapping the NASA Design Life-Cycle



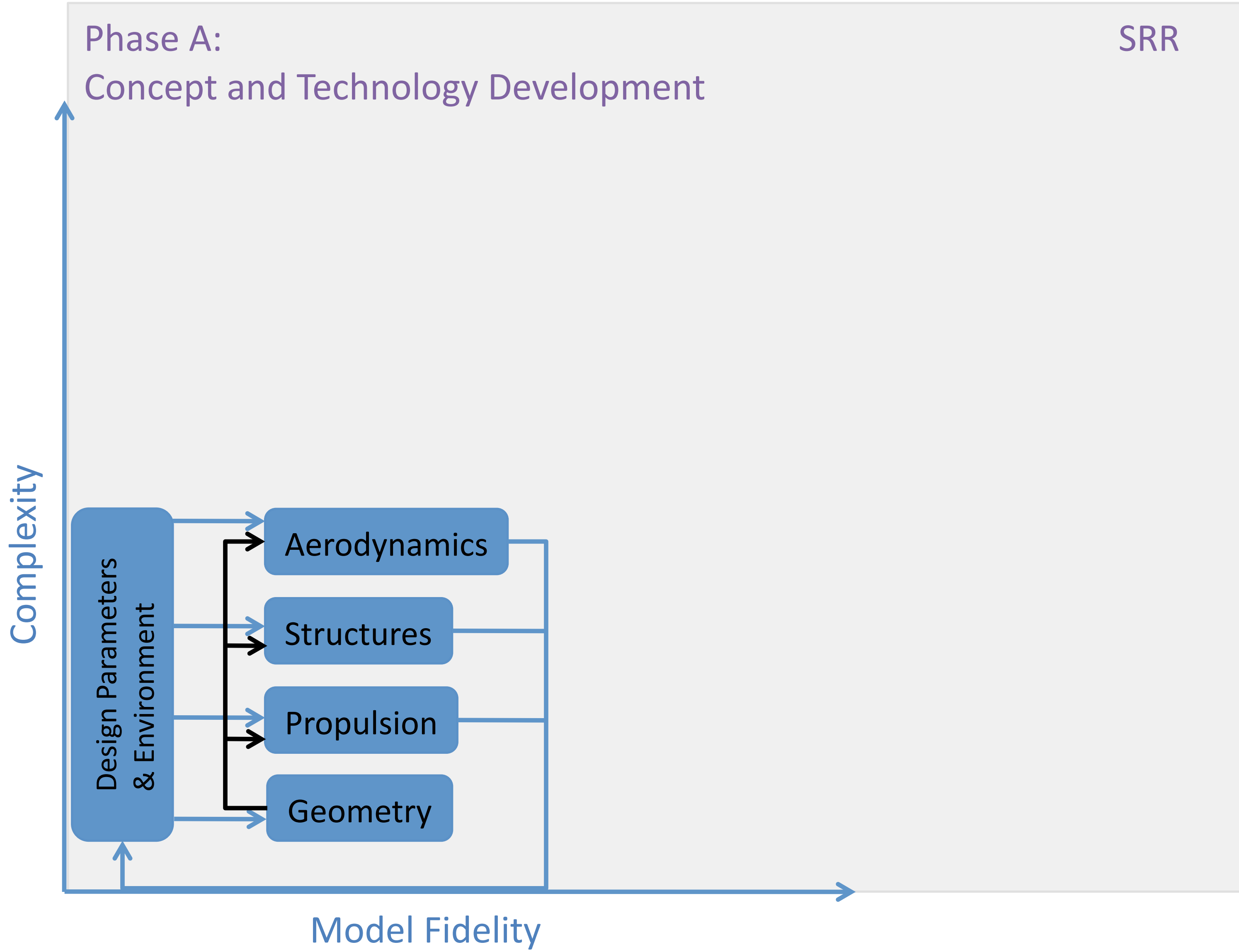
Mapping the NASA Design Life-Cycle

Reviews

- MCR – Mission Concept
- SRR – System Requirements
- PDR – Preliminary Design
- CDR – Critical Design
- TRR – Test Readiness



Mapping the Design Cycle



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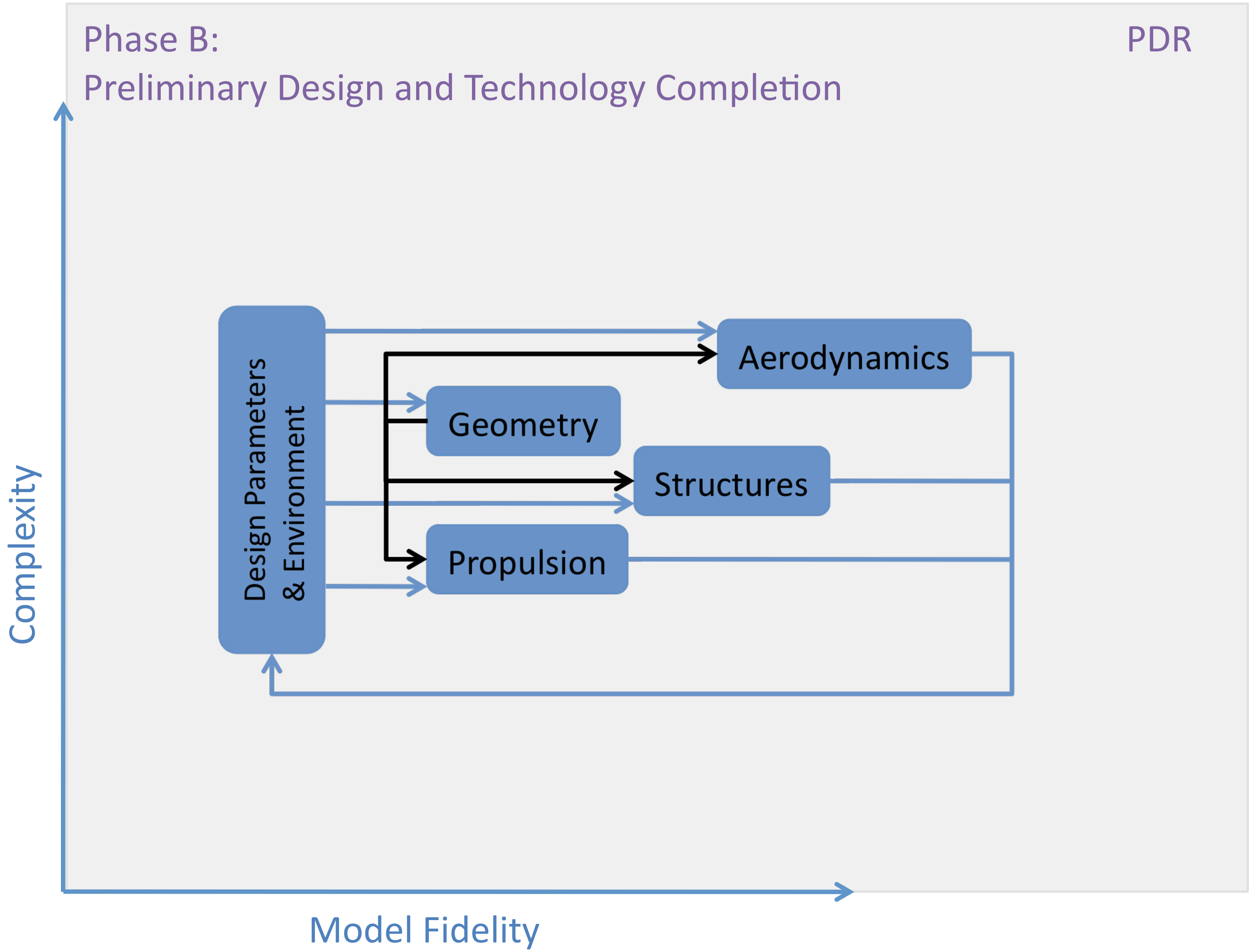
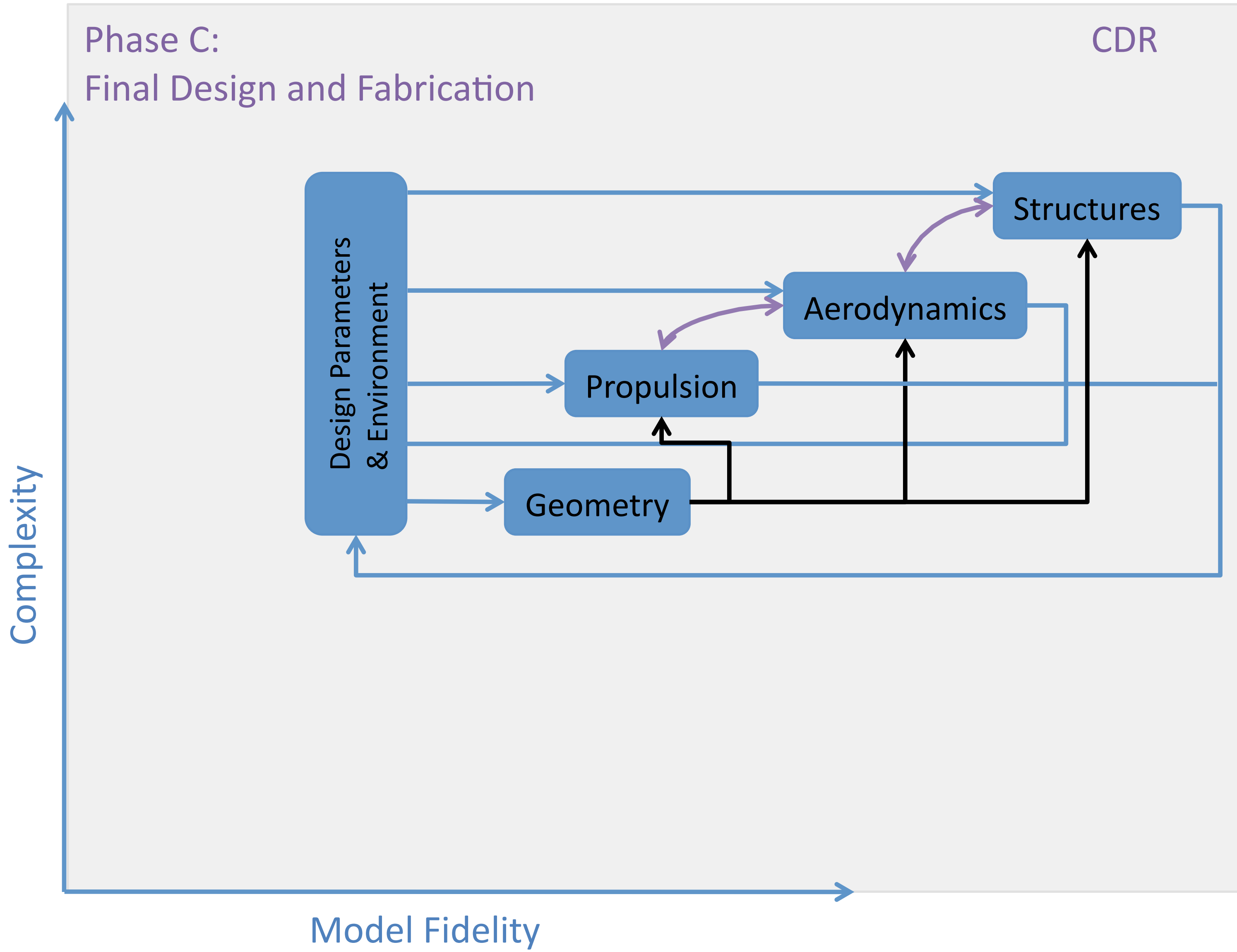


Mapping the Design Cycle



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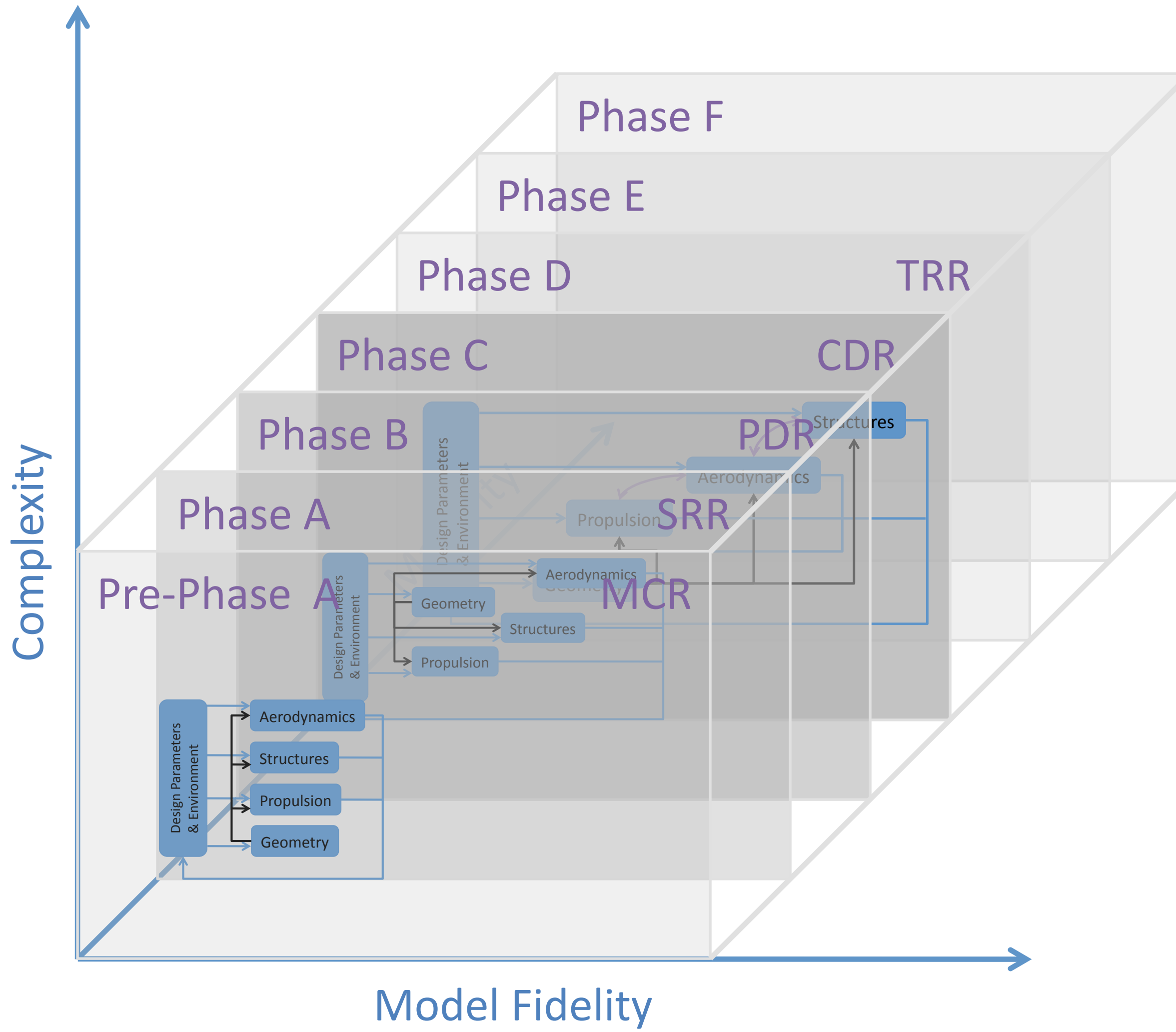
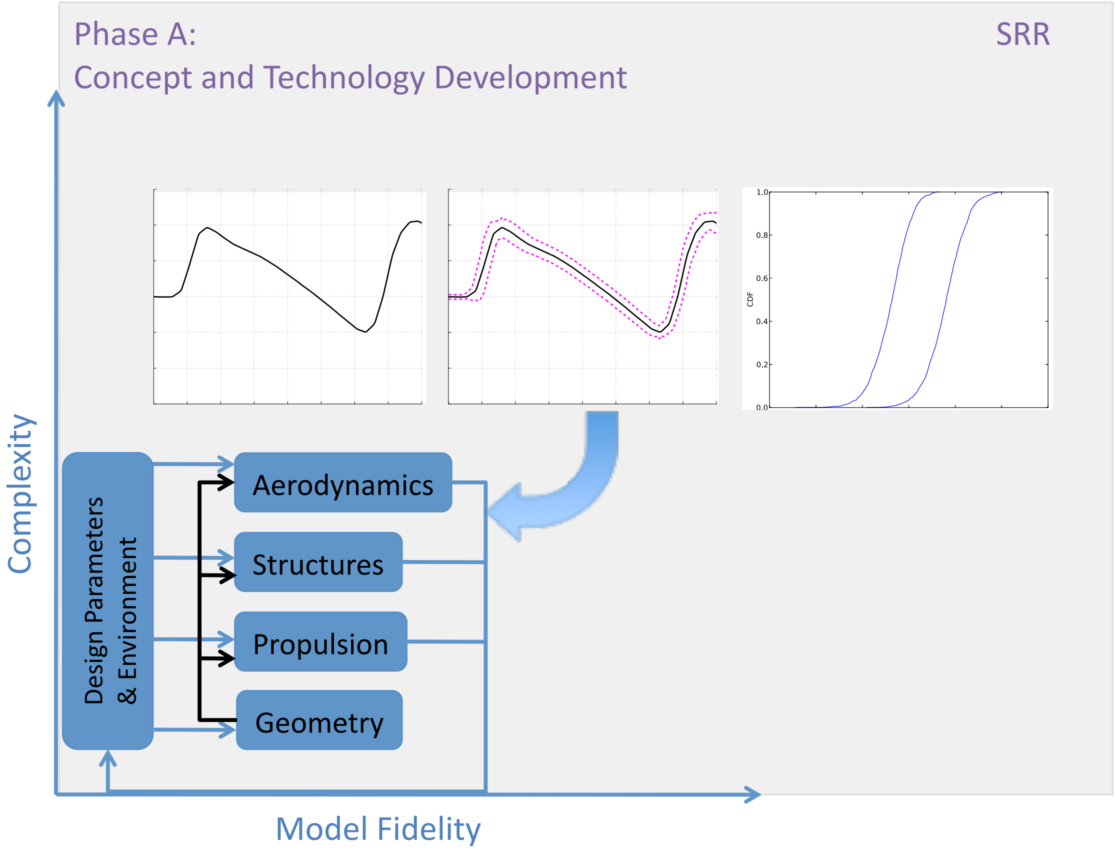


Uncertainty Quantification in the Design Cycle



- Typically discipline based
- Often enters in Phase B (before PDR)
- Early assessments tend to be engineering judgment based
- Ad-hoc
- Key component of risk

More representative uncertainty models → Better informed risk assessments

Uncertainty Classification

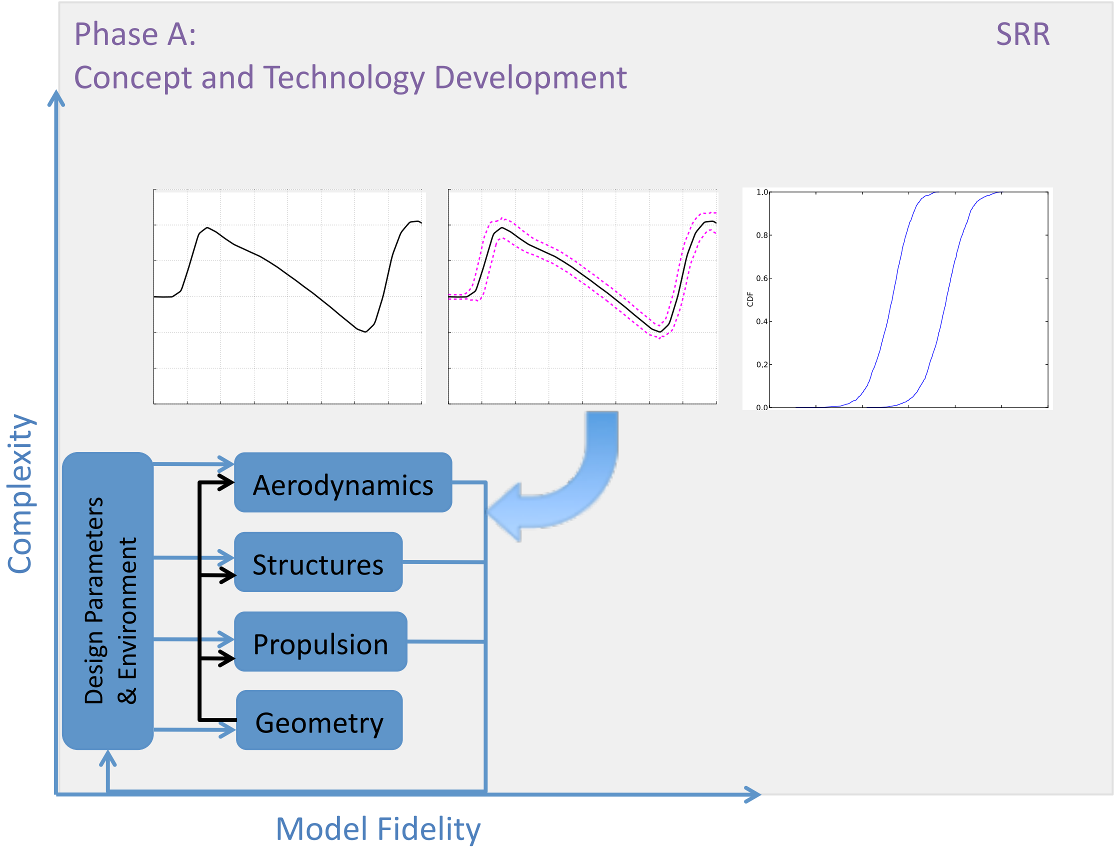
Aleatory Uncertainty is inherent variation associated with a parameter, physical system, or environment

- Also referred to as variability, stochastic uncertainty, **irreducible** uncertainty
- Is a characteristic of the **system** being analyzed
- Resources directed to **robust design**
- Examples:
  - Variability in geometric parameters due to manufacturing
  - Material properties, weather conditions

Epistemic Uncertainty arises from imperfect knowledge or ignorance

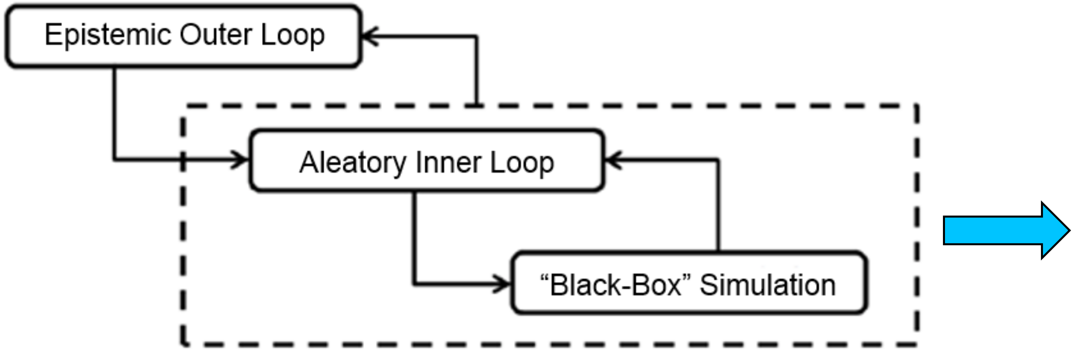
- Also referred to as subjective uncertainty, **reducible** uncertainty, or model-form uncertainty
- Is a characteristic of the state of knowledge of the **analysis team**
- Resources directed to better **understanding the problem**
- Examples
  - Insufficient experimental data to precisely characterize a probability distribution
  - Poor or limited understanding of physics phenomena or physics coupling

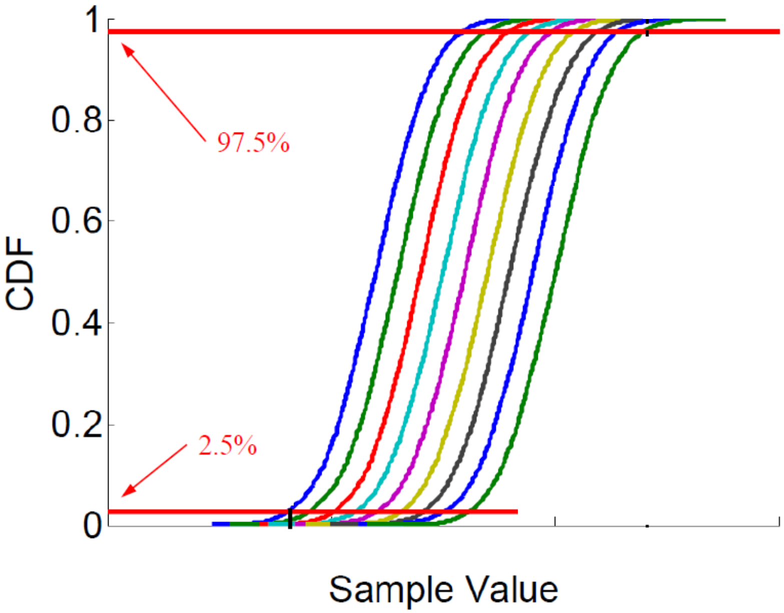
Uncertainty Integration



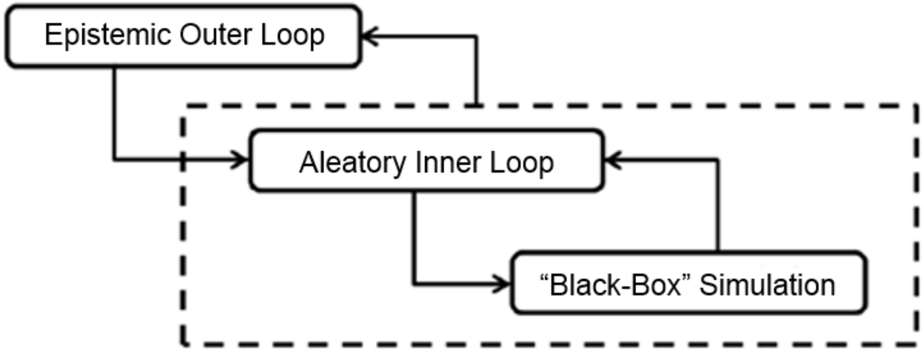
- Originates in discipline
- Critical means of communication in the discipline interface
- Development of discipline interface with appropriate exchanges of information

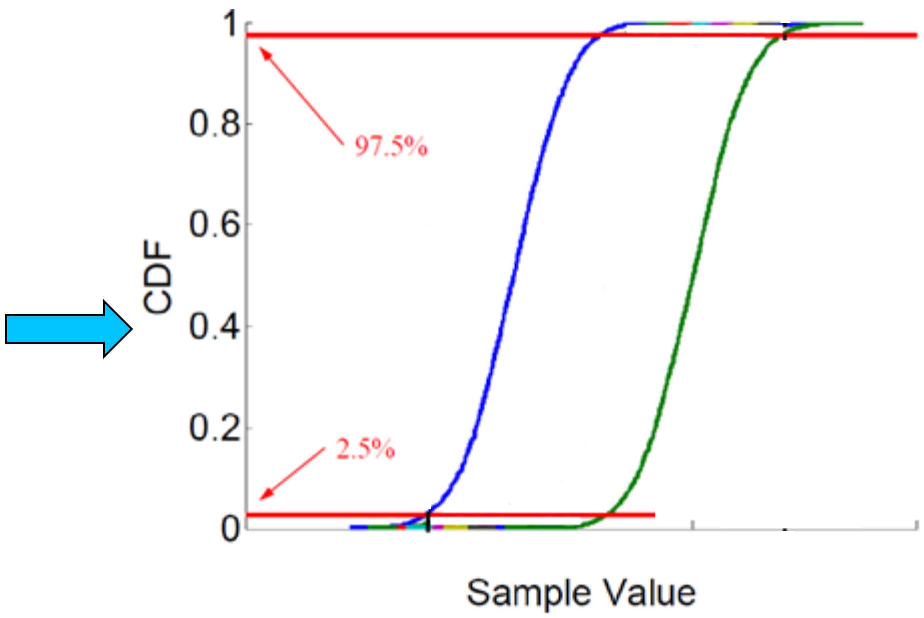
P-box Representation





P-box Representation





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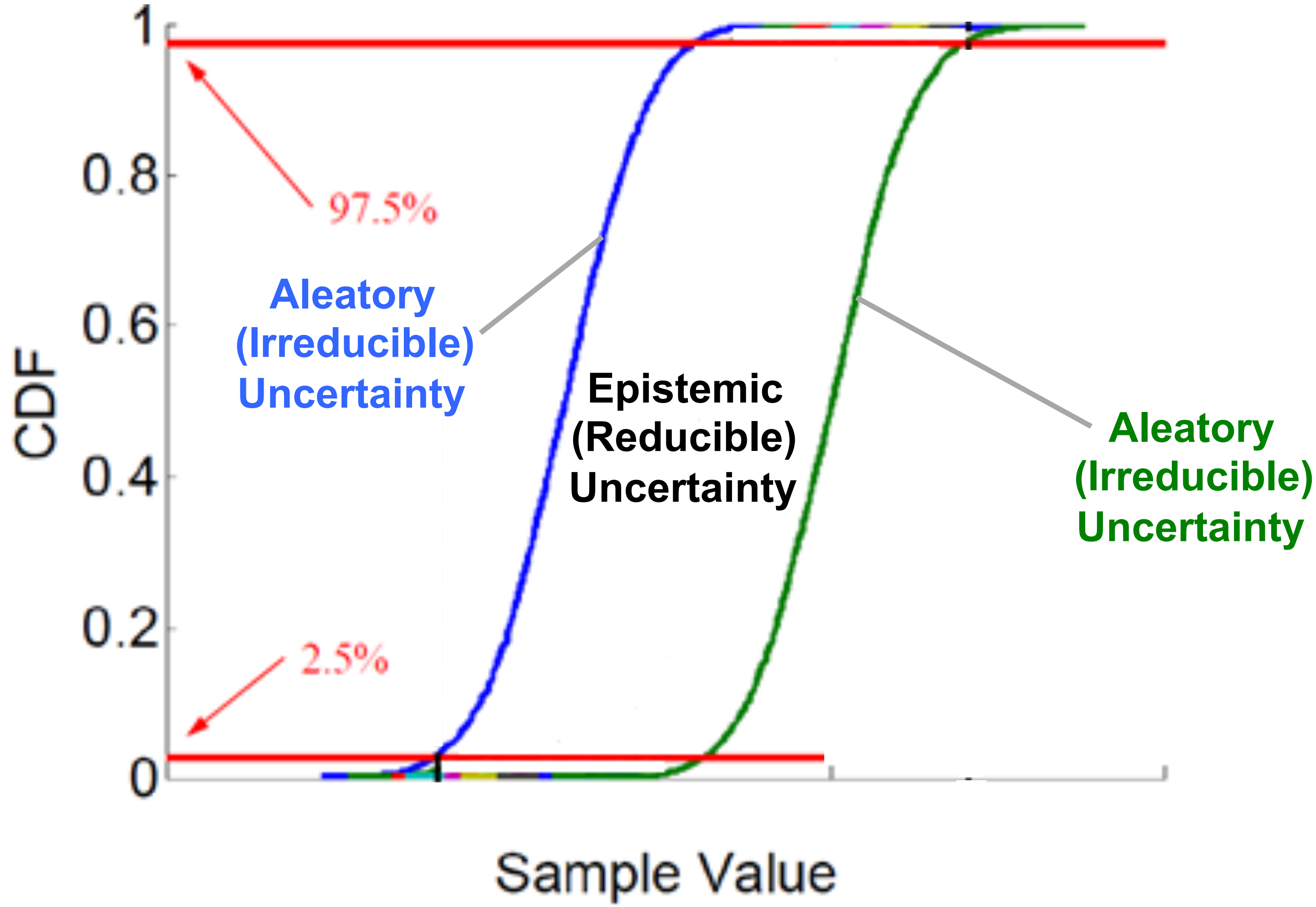
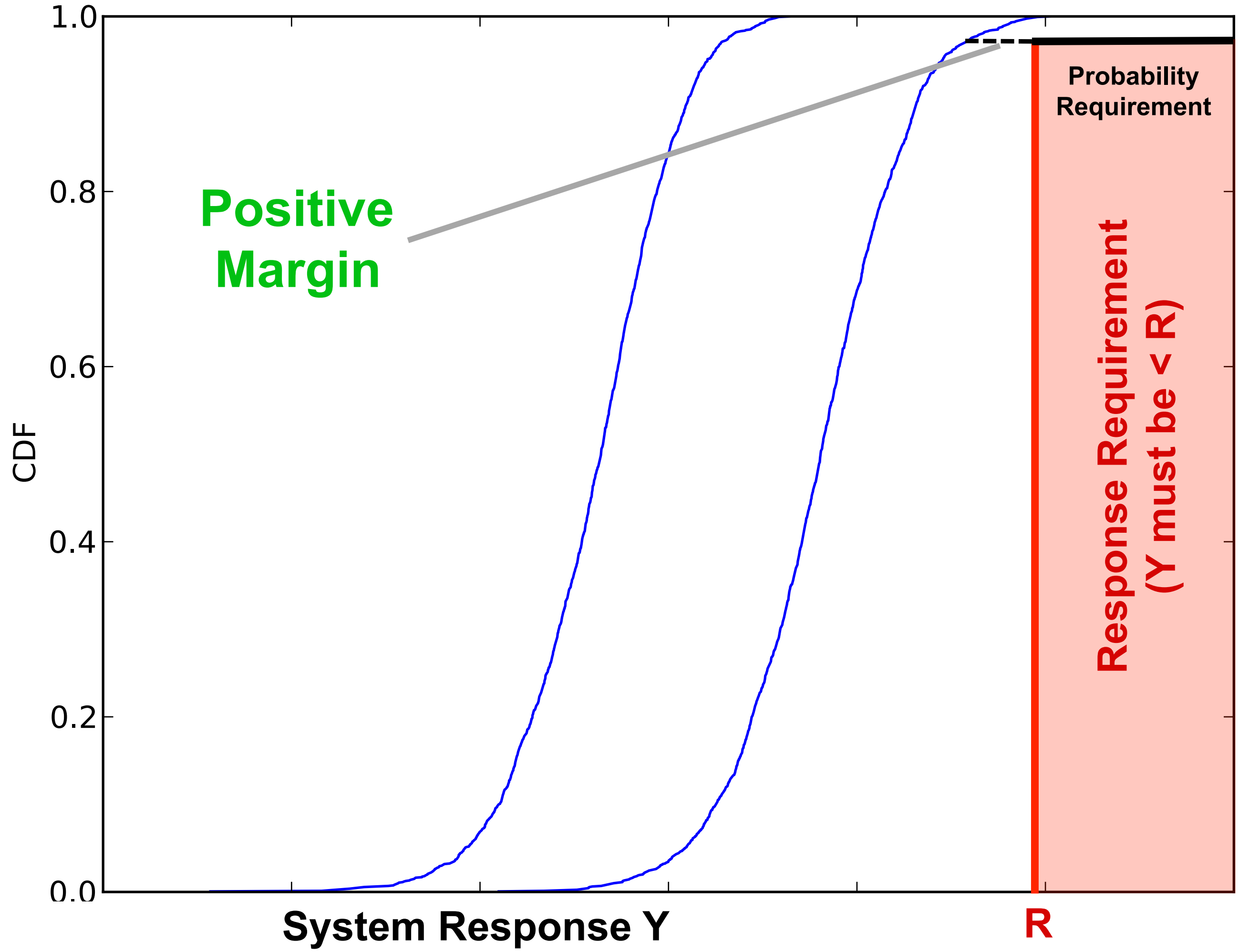


Management of Risk and Resources

Passes Verification



Red Box indicates a "keep-out" zone defined by the probability and response requirements

Margin is the minimum horizontal distance between the p-box and the keep-out zone.

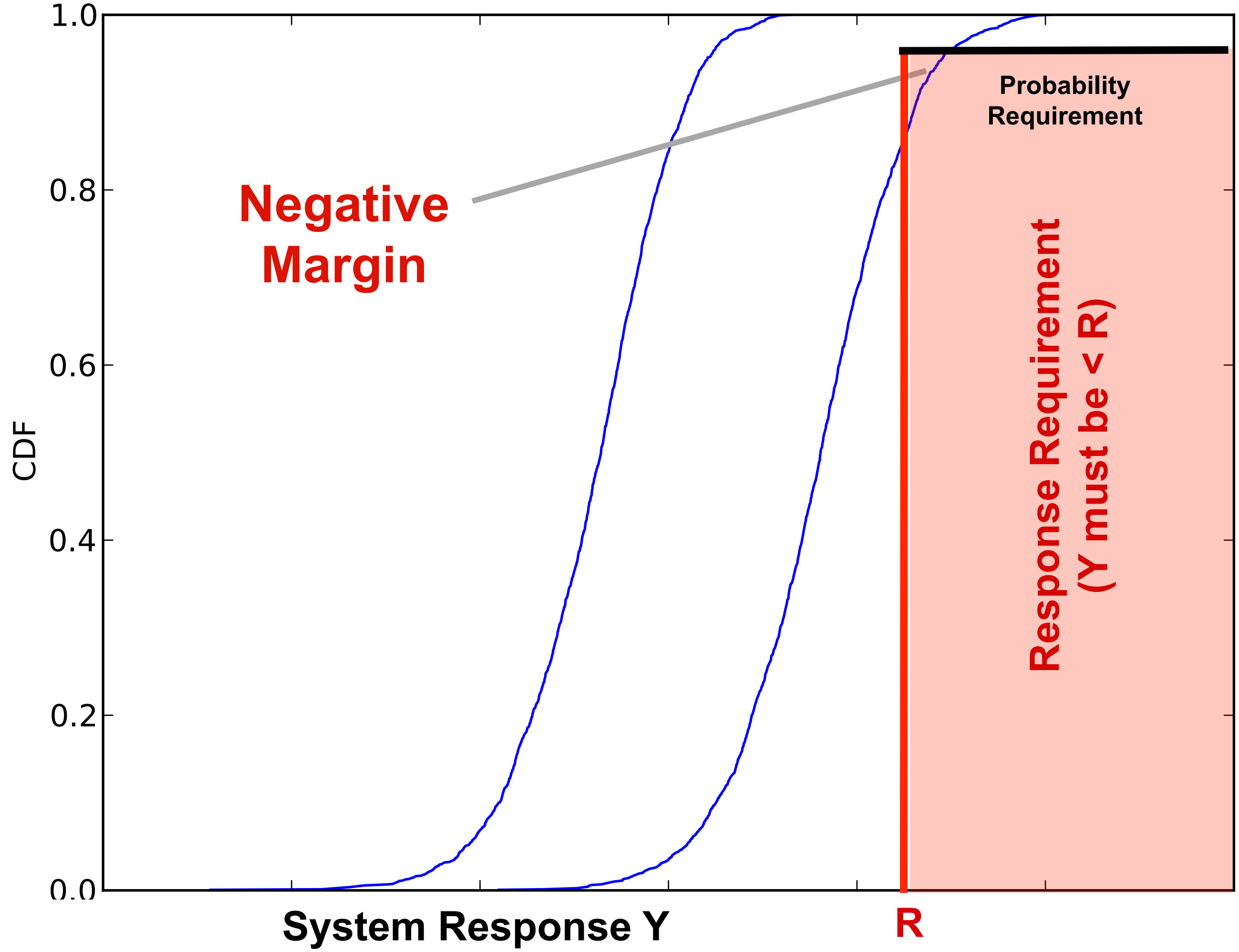
The p-box can also be represented with a complementary cumulative distribution (1-CDF)

Management of Risk and Resources

Fails Verification

P-box crosses into the keep-out zone

Indicative of possible negative margin in the system



Management of Risk and Resources

Fails Verification

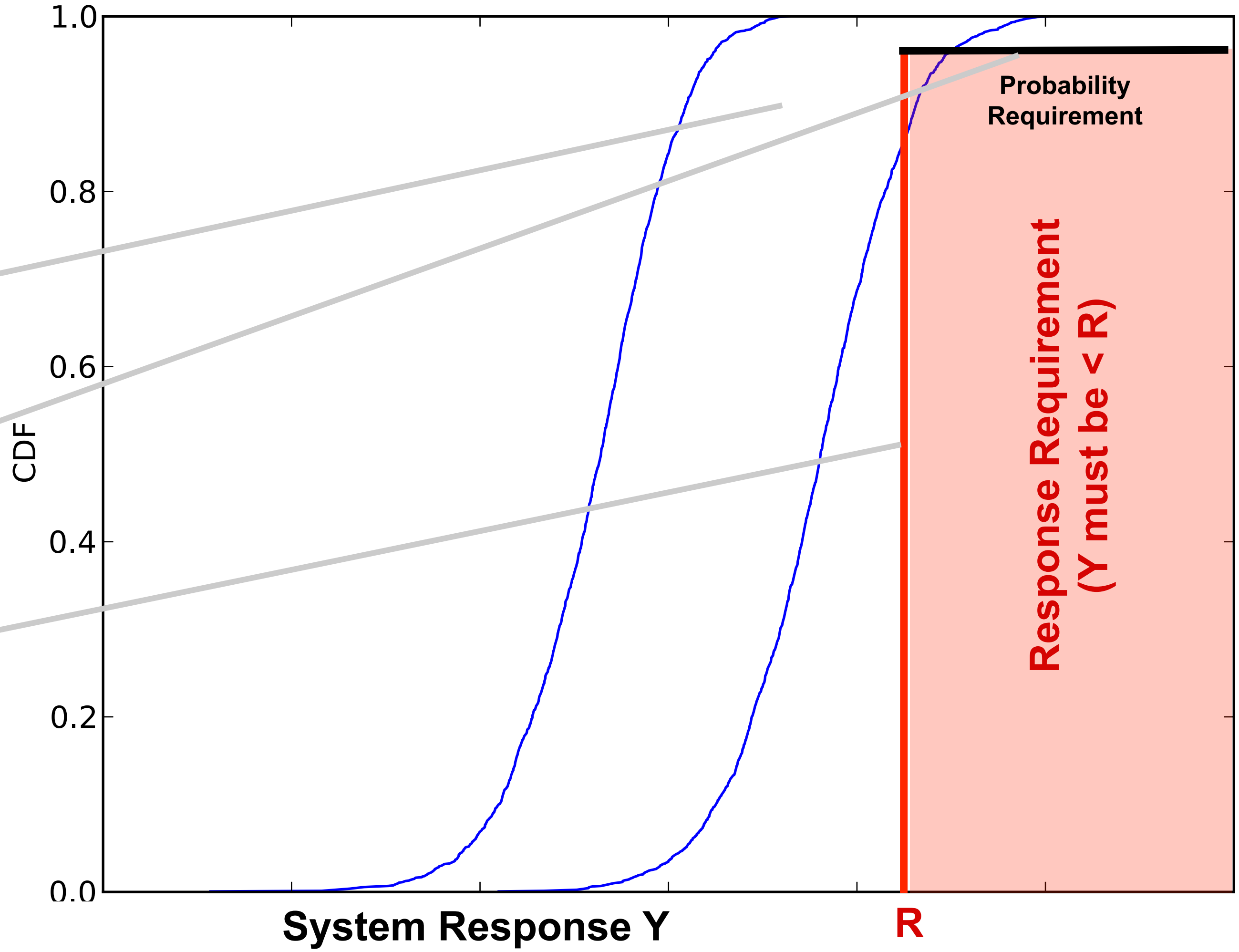
Options:

1.) Direct resources toward reduction of p-box

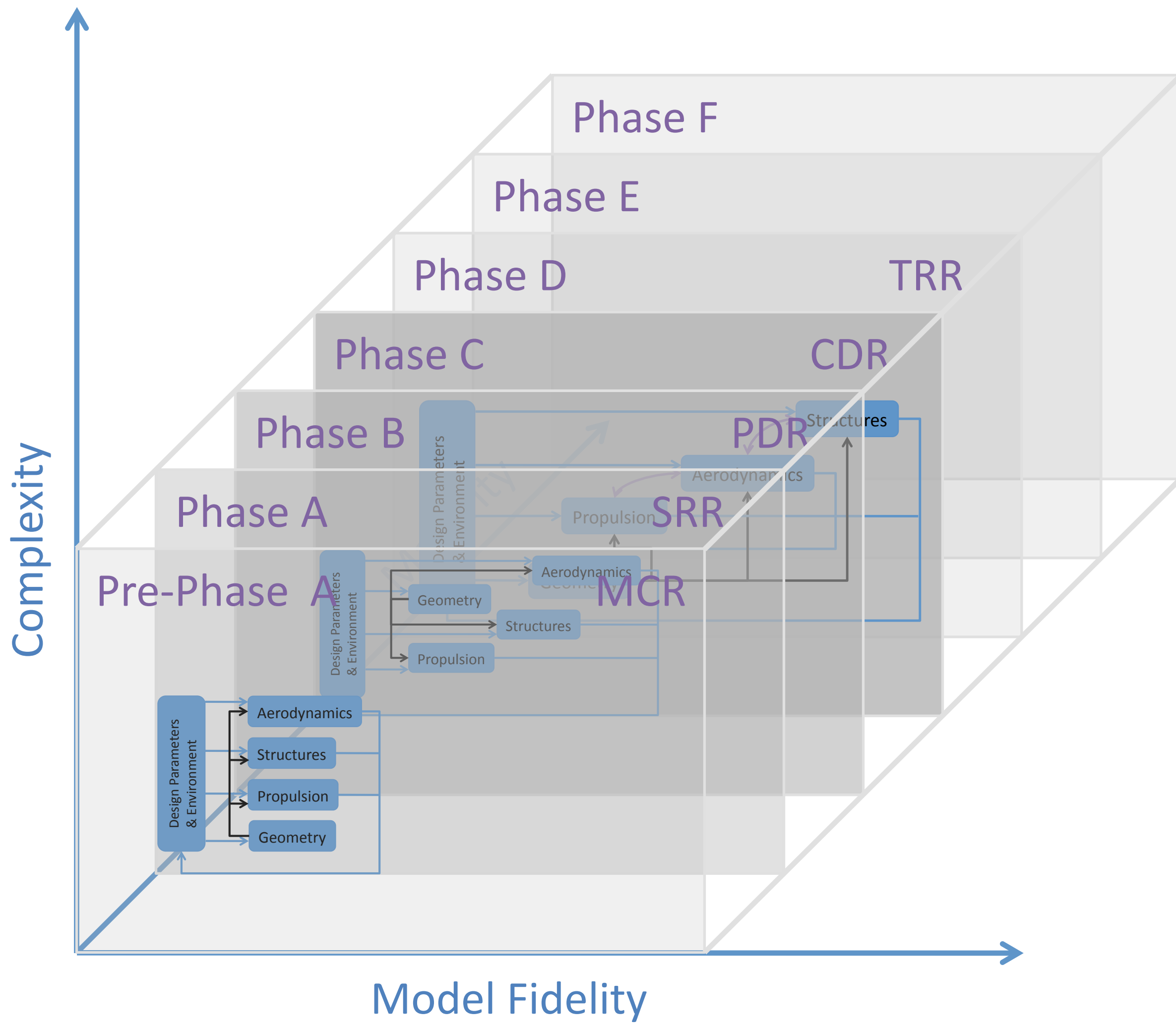
2.) Reevaluate/Accept lower probability requirement

3.) Reevaluate/Accept a less restrictive response requirement

4.) System/component architecture change (Redesign)

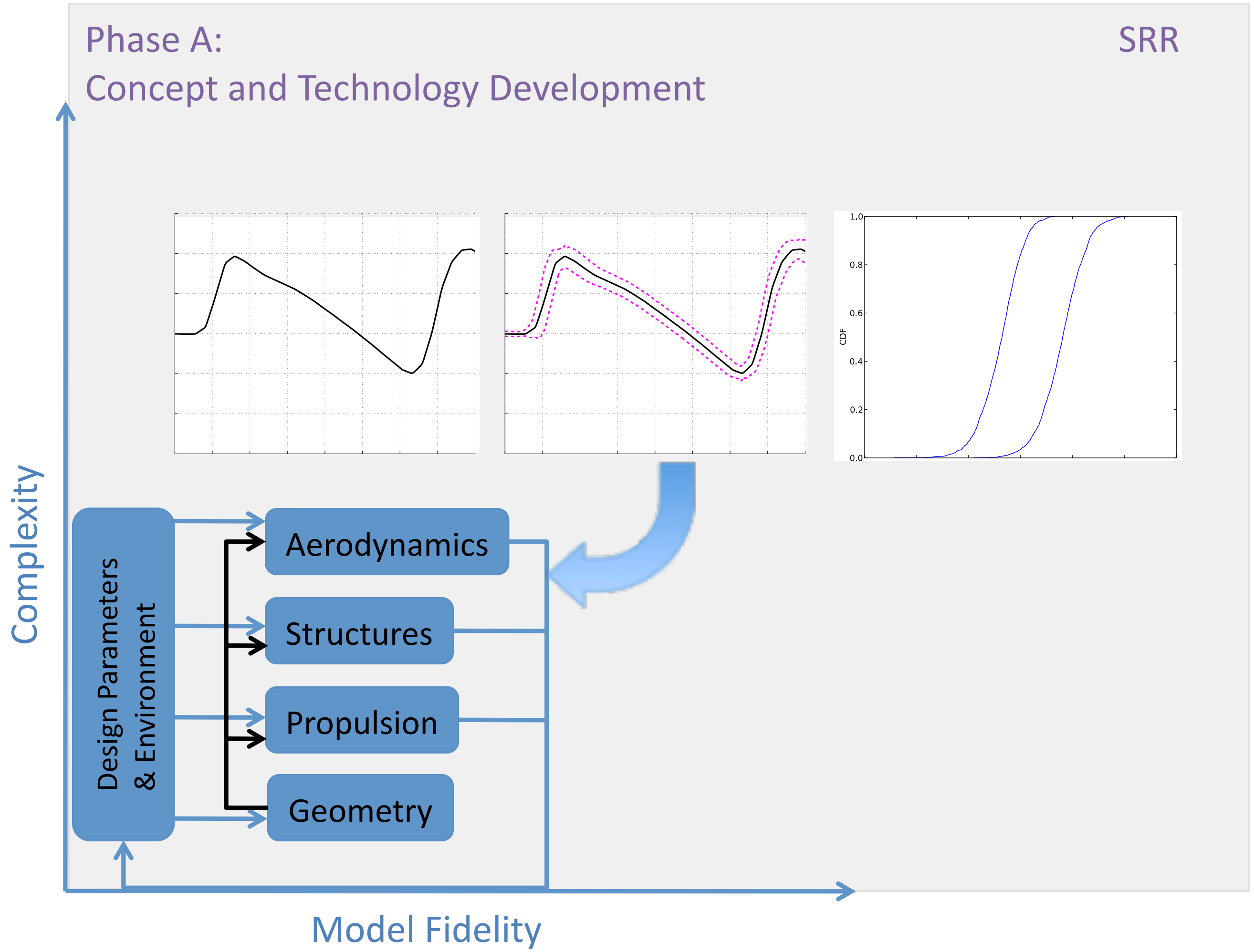


Management of Risk and Resources



- System level margin for uncertainty modeling
  - Maturity based probability requirements
  - Required epistemic uncertainty with maturity based burn-down plan
- Model fidelity selection
  - Maturity based requirements
  - Analysis models with some level of uncertainty quantification
  - Matching of model fidelity to requirements to save cost

Uncertainty Integration



Earlier, better, integrated UQ → Increased confidence in design

Final Remarks

Confidence can be built into design by using appropriate fidelity, integrated uncertainty early in the design cycle.

An improved understanding of risk helps to guide resource investment to save cost in the design as it matures.

Our experience is that integrated uncertainty quantification is not a trivial task!!

Questions?

Backup Slides

Model Problem Description

Ballistic Trajectory, Flat Ground, No Drag

v = initial velocity

θ = initial angle

d = strike distance

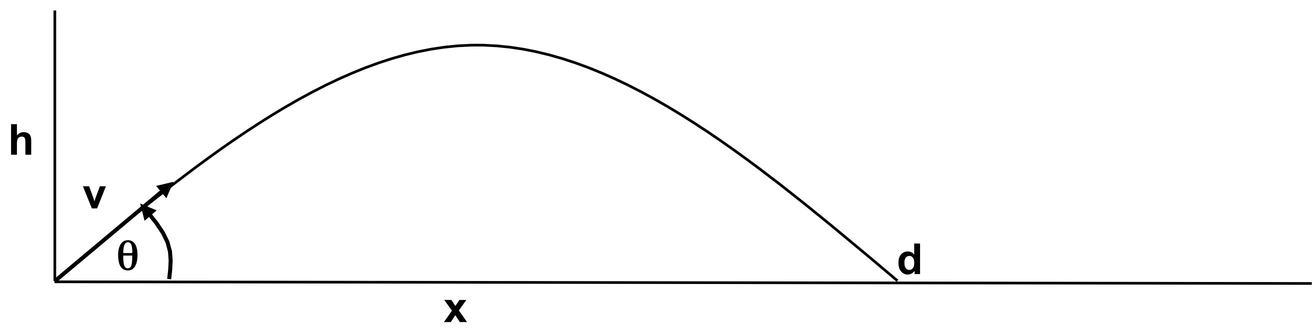
x = distance away from initial launch

h = height

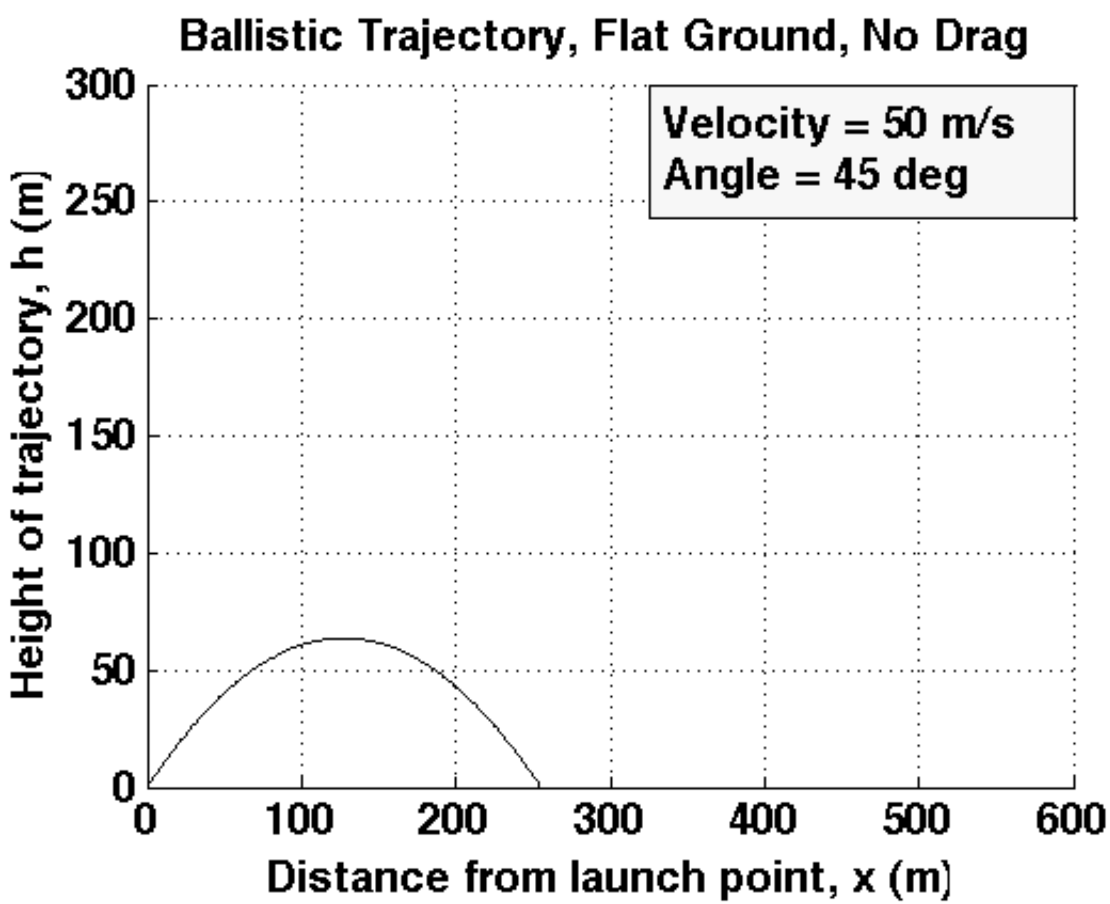
g = gravitational constant (9.81m/s²)

$$d = \frac{v^2 \sin(2\theta)}{g}$$

$$h = x\tan(\theta) - \frac{gx^2}{2v^2\cos^2(\theta)}$$

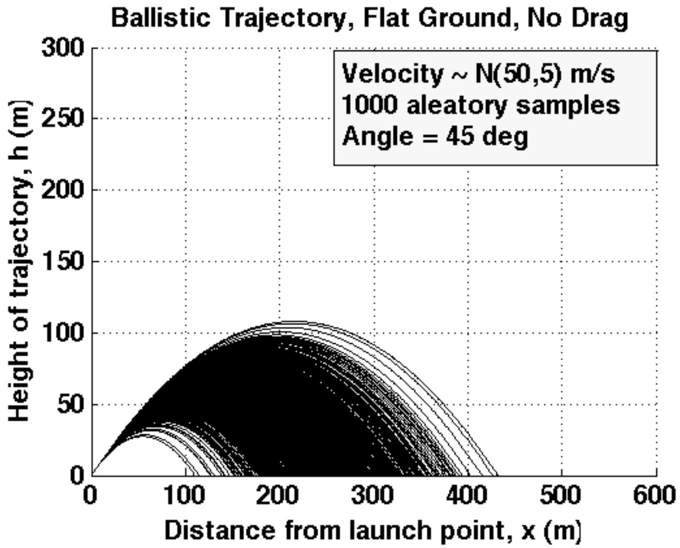


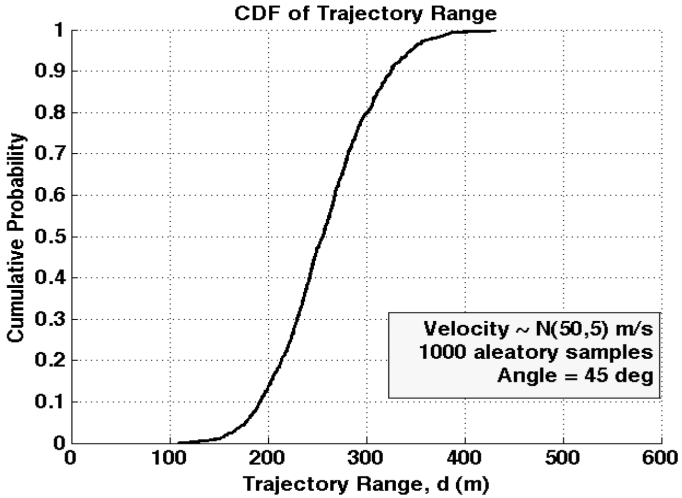
Deterministic Solution



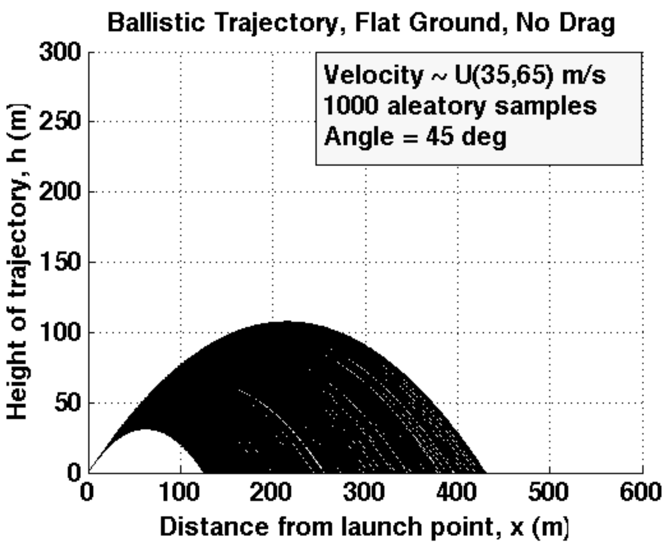
Aleatory Dispersion of Velocity

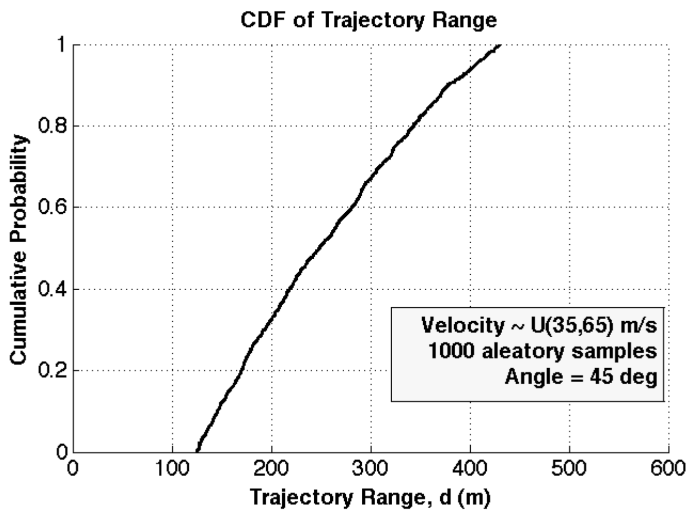
Normal





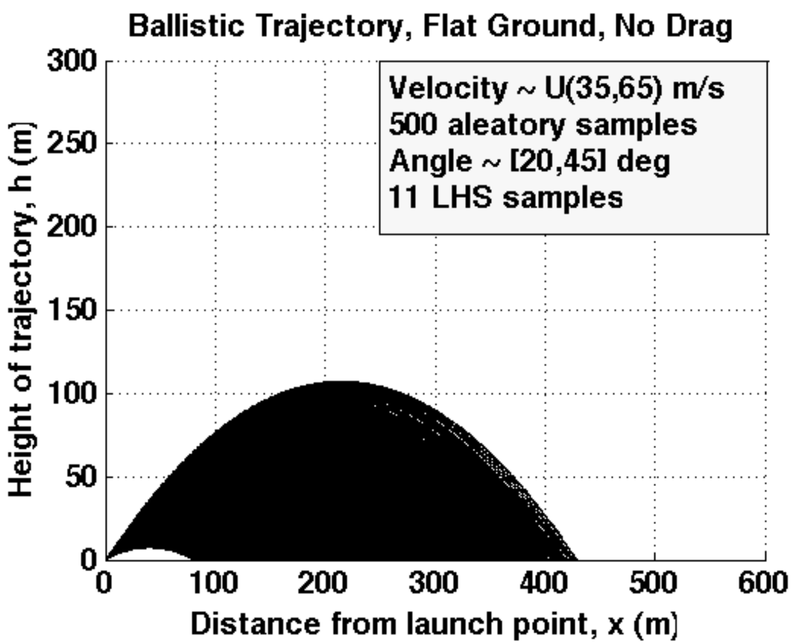
Uniform

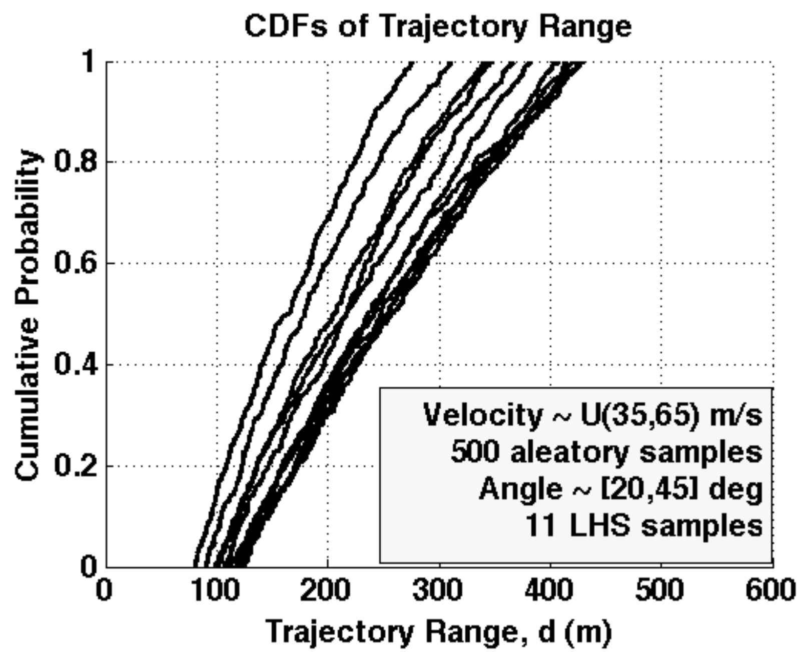




Epistemic Treatment of Initial Angle

Velocity treated as aleatory with Uniform distribution
Initial angle treated epistemically (no distribution modeled, weakest statement)



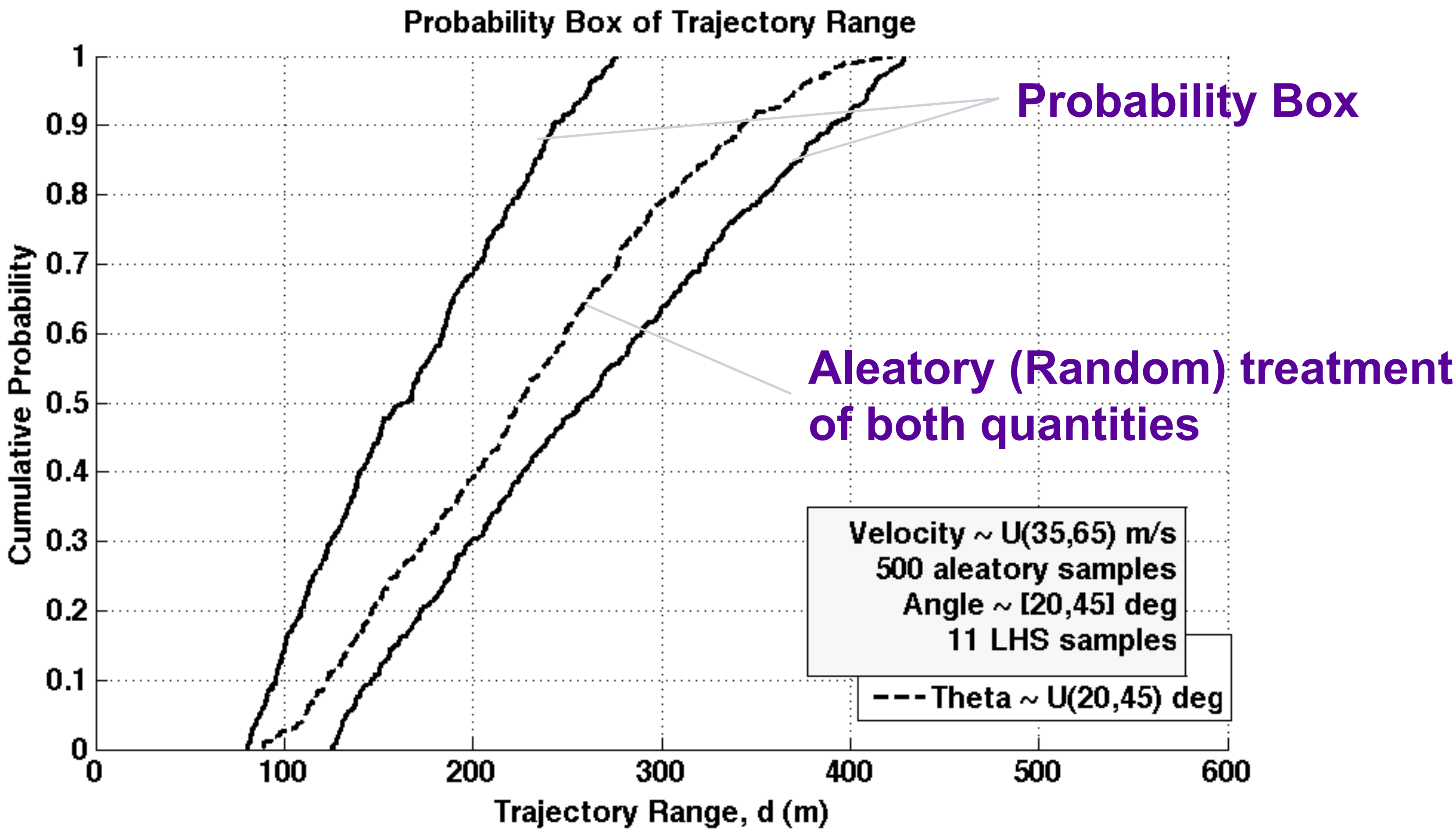


Epistemic treatment of angle results in a family of CDFs for velocity. One for each selection of angle.

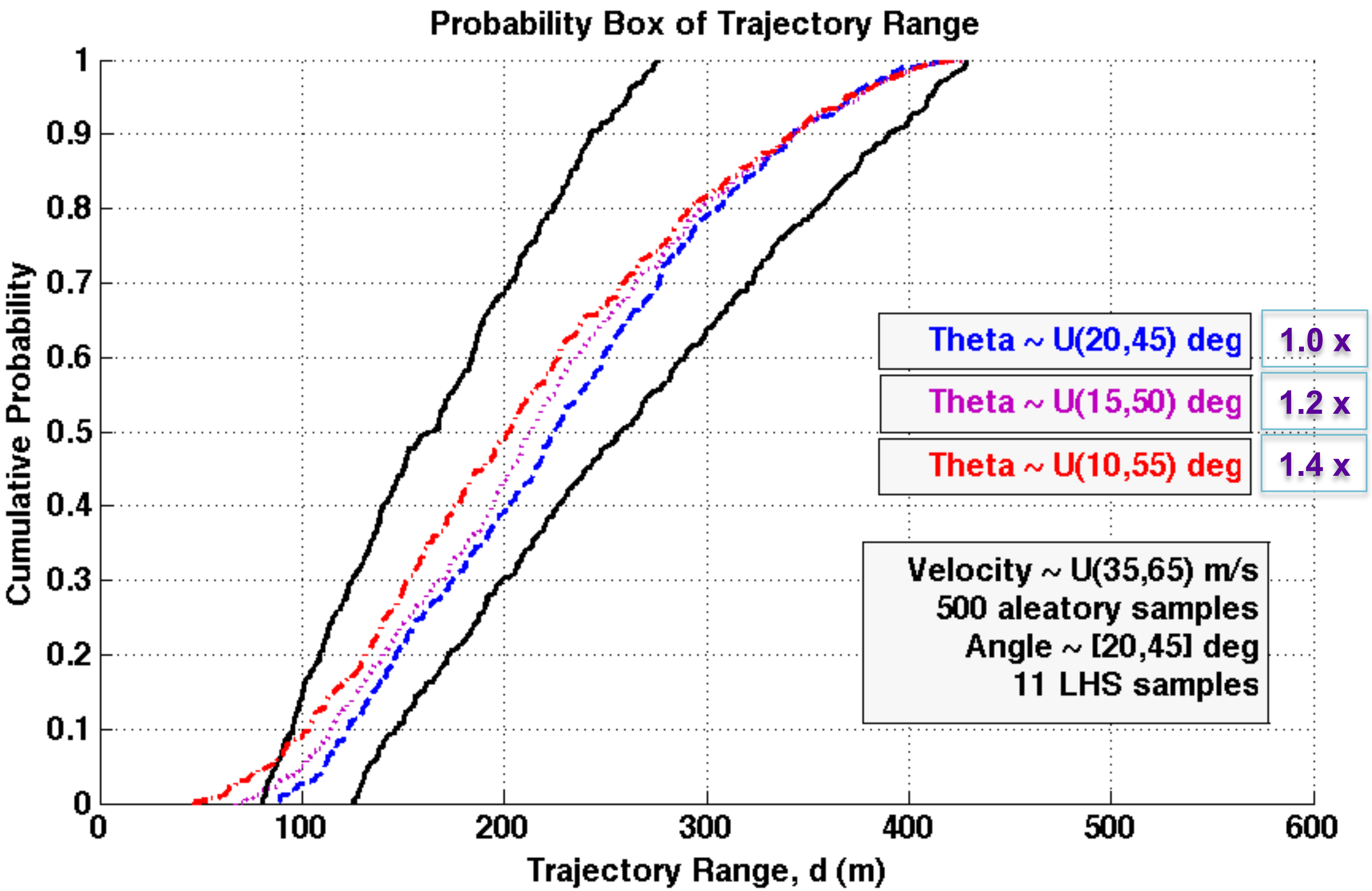
LHS = Latin Hypercube Sampling

Probability-box vs Aleatory only

Taking the Min and Max of the CDFs Results in a P-box for the Response



Can't I just use bigger uncertainties?



Just increasing an incorrectly classified uncertainty does *not* yield a more conservative result. *This is counterintuitive!!*

Guidance on Uncertainty Informed Decisions

Aleatory dominated predictions (negligible epistemic uncertainty)

- More experimental data and better simulation data
  - Will only support the current distribution used
  - Not reduce the uncertainty
- Resources directed to robust design

Epistemic dominated predictions (negligible aleatory uncertainty)

- More experimental data and better simulation data
  - Can lead to better understanding
  - Should reduce uncertainty
- Resources directed to better understanding the problem

Mixed aleatory and epistemic predictions

- Use sensitivity analyses to determine resource allocation based on programmatic risk tolerance

Segregating aleatory and epistemic uncertainty is not a worst-on-worst analysis. It is a true representation of both random variation and lack of knowledge.