Reducing Performance Variability and Improve Design Robustness through Simulation and Optimization

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Virtual Product Development via Physics-Based Simulation

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Why Virtual Product Development (VPD)?

- Manufacturers face demands for faster time-to-market, higher quality, and cost-effective design.
- The build–test–redesign–retest cycle can stretch the development schedule very long.
- The benefits of VPD are substantial, with reduced development costs, significantly fewer physical prototypes, and drastically shortened development schedules.
- Highly powerful CAE (FEA, CFD, MBD, Durability, Acoustics, etc.), CAD, CAM and Optimization Software make realization of VPD possible.
- Physics-based simulation will allow us to better understand the behavior of the system, while we can observe only the behavior of the system from physical testing.
- Physics-based simulation can be used for design optimization to ensure higher product reliability and quality, whereas it is very difficult to sequentially optimize using physical testing.

A Technology Needed for Development of VPD

- Firstly, to develop an effective VPD, the physics-based simulation models need to be validated so they can correctly represent the physical systems.
- Most simulations are performed on a single model with a few load conditions to obtain a single result. However, in the real world, input variables and feature of a simulation model and its environment have combinations of variability & uncertainty that must be considered to understand possible outcomes.
- Need tools enabling uncertainty quantification (UQ) to evaluate the effect of variability in the manufactured product as well as the variability in its operational environment.
- UQ gives engineers the ability to perform realistic tests of designs without relying upon the limited capabilities of physical prototypes.
- Need to identify variability factors that affect design performance and function. Material properties, loading conditions, manufacturing (thicknesses, dimensions), and other factors all vary randomly, affecting the performance and function of a design.

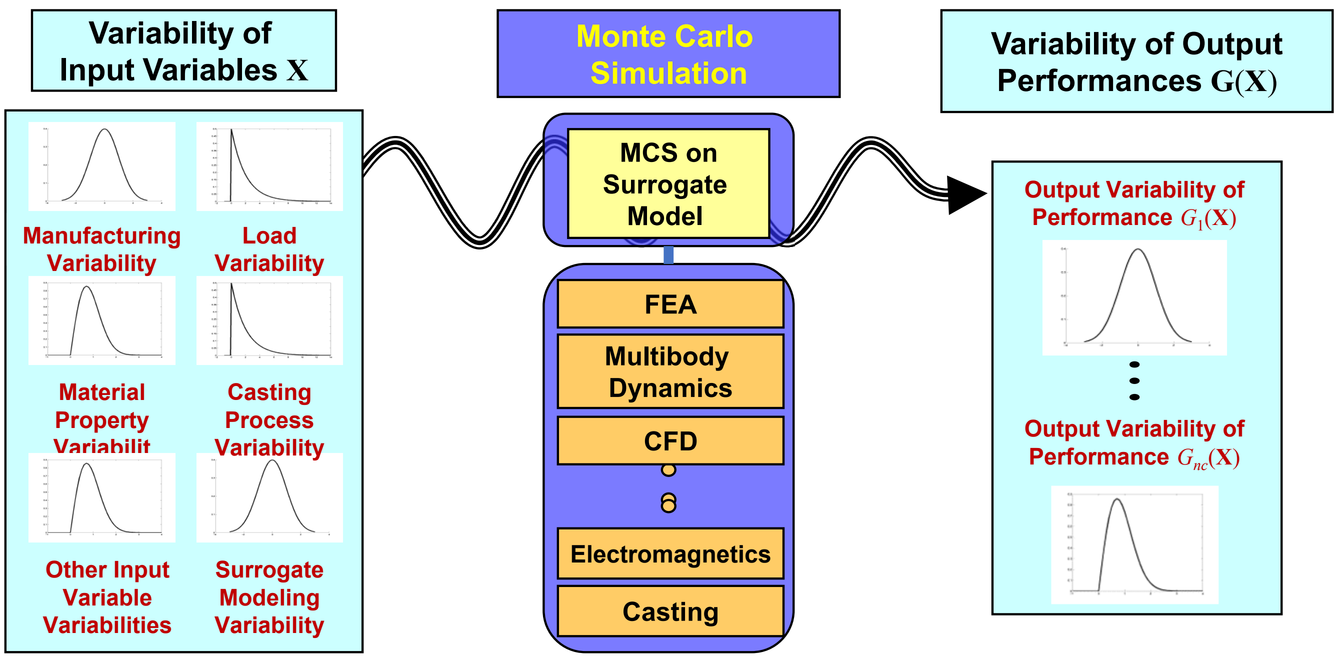
Variability vs Uncertainty

VARIABILITY (Aleatory)	***UNCERTAINTY (Epistemic)***
Refers to the inherent heterogeneity or diversity of data in an assessment. It is "a quantitative description of the range or spread of a set of values" (U.S. EPA, 2011), and is often expressed through statistical metrics such as variance, standard deviation, and interquartile ranges that reflect the variability of the data.	Refers to a lack of data or an incomplete understanding of the context of the risk assessment decision. It can be either qualitative or quantitative (U.S. EPA, 2011).
• Variability **cannot be reduced**, but it can be better characterized.	• Uncertainty **can be reduced** or eliminated with **more or better data**. • The model form uncertainty (error) **can be reduced** by carrying out **model improvement**.

- In our applications, there are three types of uncertainties: (1) uncertain input distribution models due to limited number of input test data, (2) biased simulation models and surrogate models due to assumptions and idealization, which needs to be validated against (3) limited number of output physical test data for validation.

Uncertainty Quantification (UQ)

- To perform UQ using physical testing is not practically feasible.
- On the other hand, if we use physics-based simulation method, we need: (1) accurate input distribution models (2) accurate simulation & surrogate models and (3) accurate Monte Carlo simulations.



Uncertainty Quantification (UQ) and Calibration

- For accurate MCS, accurate surrogate model is critically important.
- Surrogate modeling is a special case of supervised machine learning applied in the area of engineering simulation. Instead of training on a pre-fixed dataset, it uses active learning via sequential surrogate modeling, to enrich the training data as training progresses and improves accuracy.
- UQ helps design engineers model uncertainty and pinpoint the most influential variables by carrying out variable screening.
- Calibration is especially valuable for reduced order or simplified simulation models, where instead of fully physics-based detailed model, a substituted part/subsystem is used. As this is not a physics-based part/subsystem, no test data would be available to characterize input uncertainty for the part/subsystem.

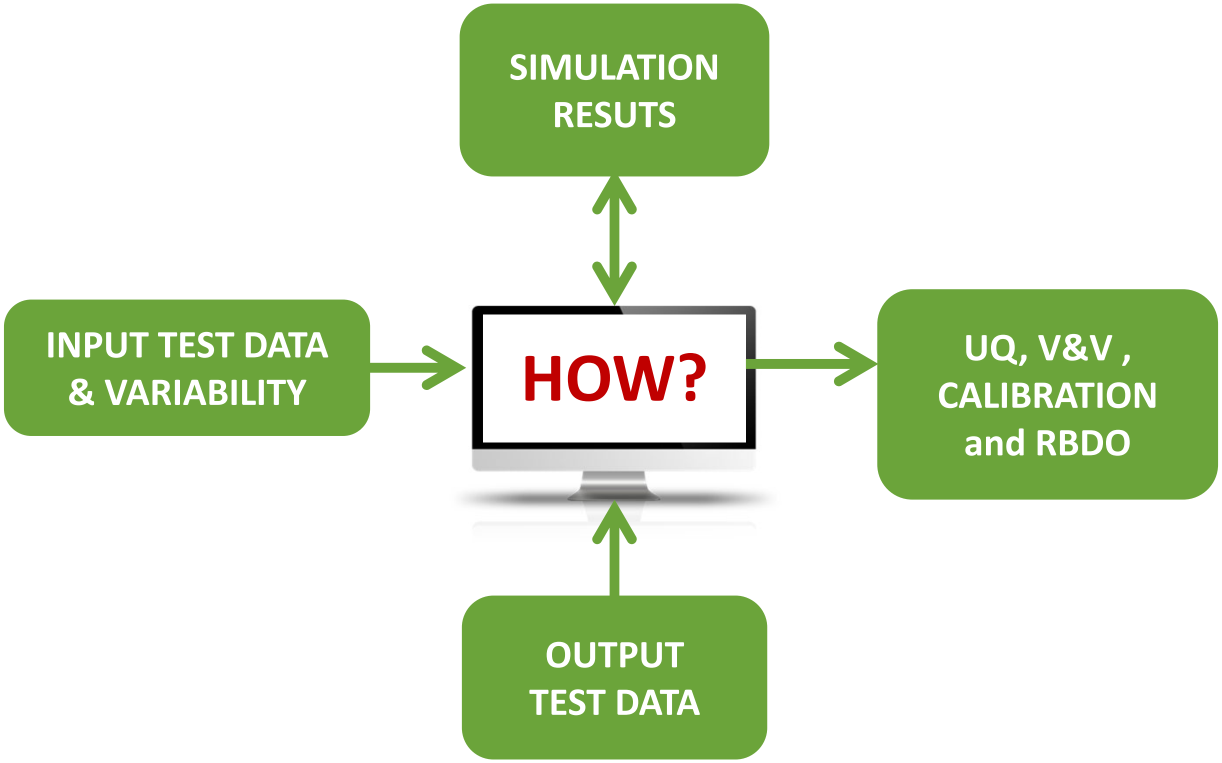
Validation of Simulation Models (V&V)

- Validating how well a physics-based simulation represents physical reality is critical for using simulation results by decision makers.
- Validation should be based on statistical tests of agreement between the behavior of the simulation model and physical system.
- It is essential to note that physical and virtual prototyping should not compete each other; they should be complementary. Validation should motivate close collaboration between testing expert and simulation expert.
- Need to establish quantitative model validation requirements to specify the degree to which each element (component, parameter) of the model is to be validated.
- Due to three types of uncertainties, we need to use a confidence interval to assess simulation model agreement and specify a confidence level.

Reliability-Based Design Optimization (RBDO)

- Need to enable optimized design with reliability. Product reliability is important to the manufacturer for reduction of warranty cost, product quality, and customer satisfaction.
- Traditional design methods often handle uncertainty in models via safety factors. But this method have often led to overdesign with no measure of the reliability levels in the product.
- Reliability is a function of irreducible uncertainty (*i.e.*, variability).
- Imperfections in input distribution models due to limited number of test data, simulation models, and surrogate models are reducible uncertainty. To deal with reducible uncertainty, confidence-based reliability prediction needs to be used in RBDO.

How to Do UQ, V&V, Calibration & RBDO for VPD?



Thank You

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