From Deterministic to Probabilistic

- Why do probabilistic and where to start

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NSF NHERI Network

SimCenter

Goal: Develop an **open-source framework** and **extensible software tools** for researchers in **natural hazards engineering**

Transformational software that supports **uncertainty quantification (UQ), performance-based engineering, community resilience**

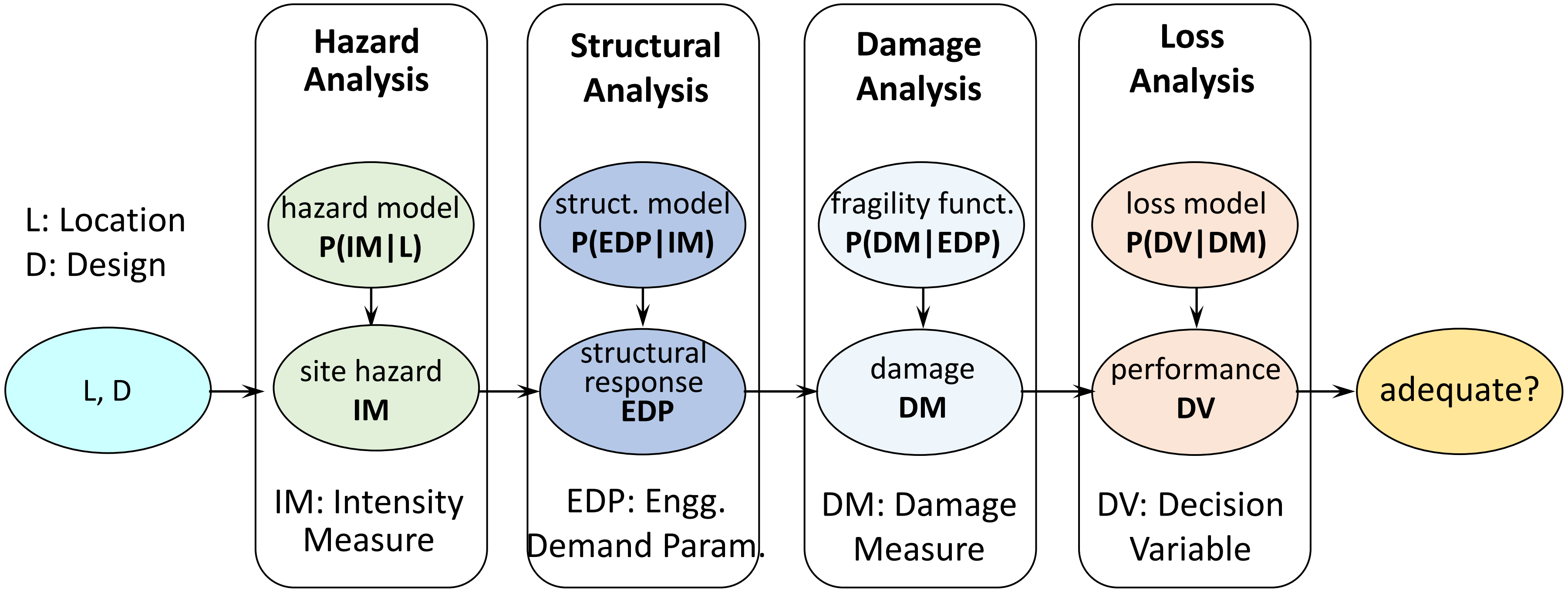
"There is **uncertainty inherent in all aspects of earthquake engineering** that **needs to be addressed** on an ongoing basis with transformative research, process and code development, and focused implementation programs."

- National Research Council 2011. *Grand Challenges in Earthquake Engineering Research: A Community Workshop Report*. Washington, DC: The National Academies Press. https://doi.org/10.17226/13167

SimCenter's scientific workflow

Why UQ workflow?

PBE Framework (Adapted from Porter 2003)

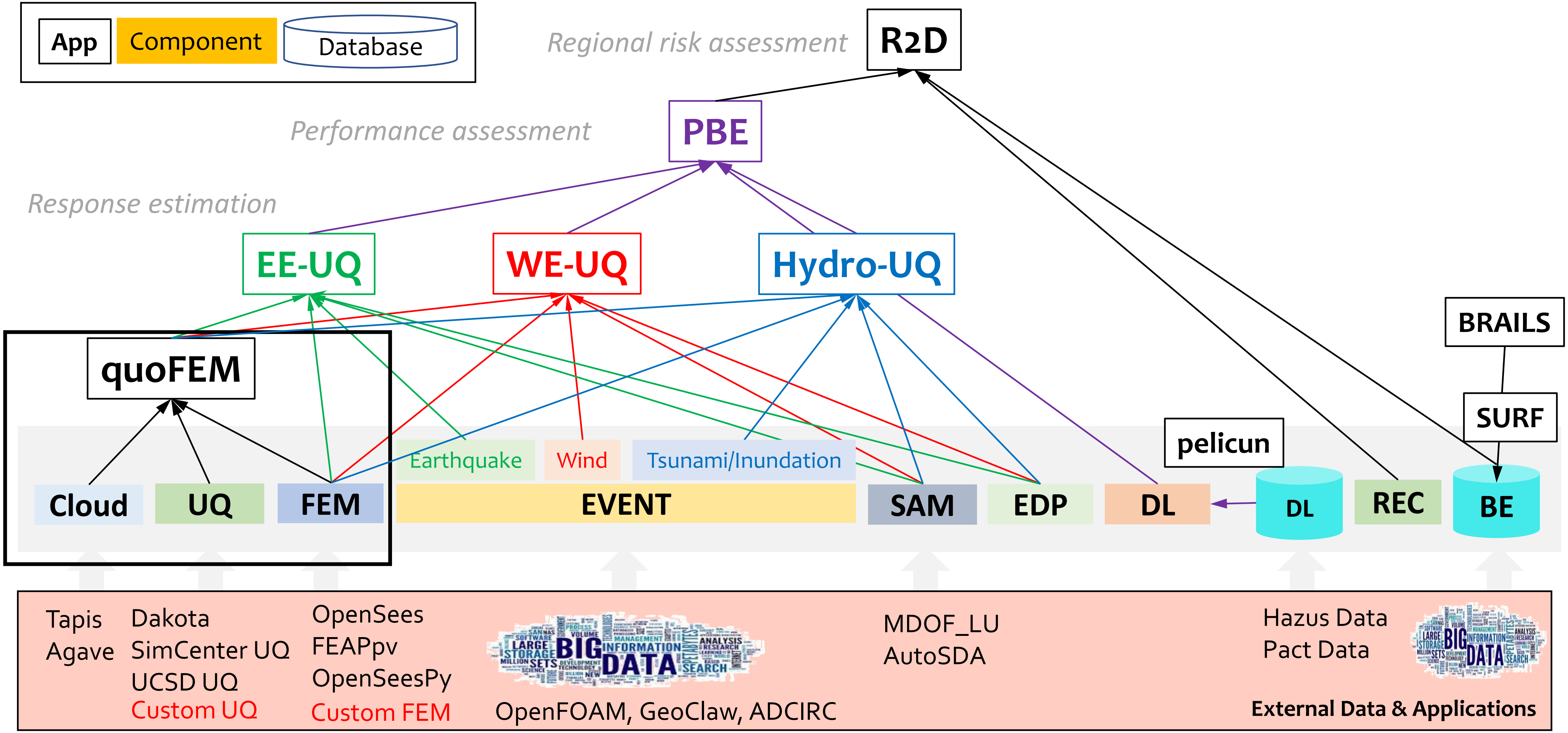


SimCenter's scientific workflow

Uncertainty from several sources, including:

- Inherent variability
- Model parameter uncertainty
- Model form uncertainty

SimCenter Applications



Types of UQ

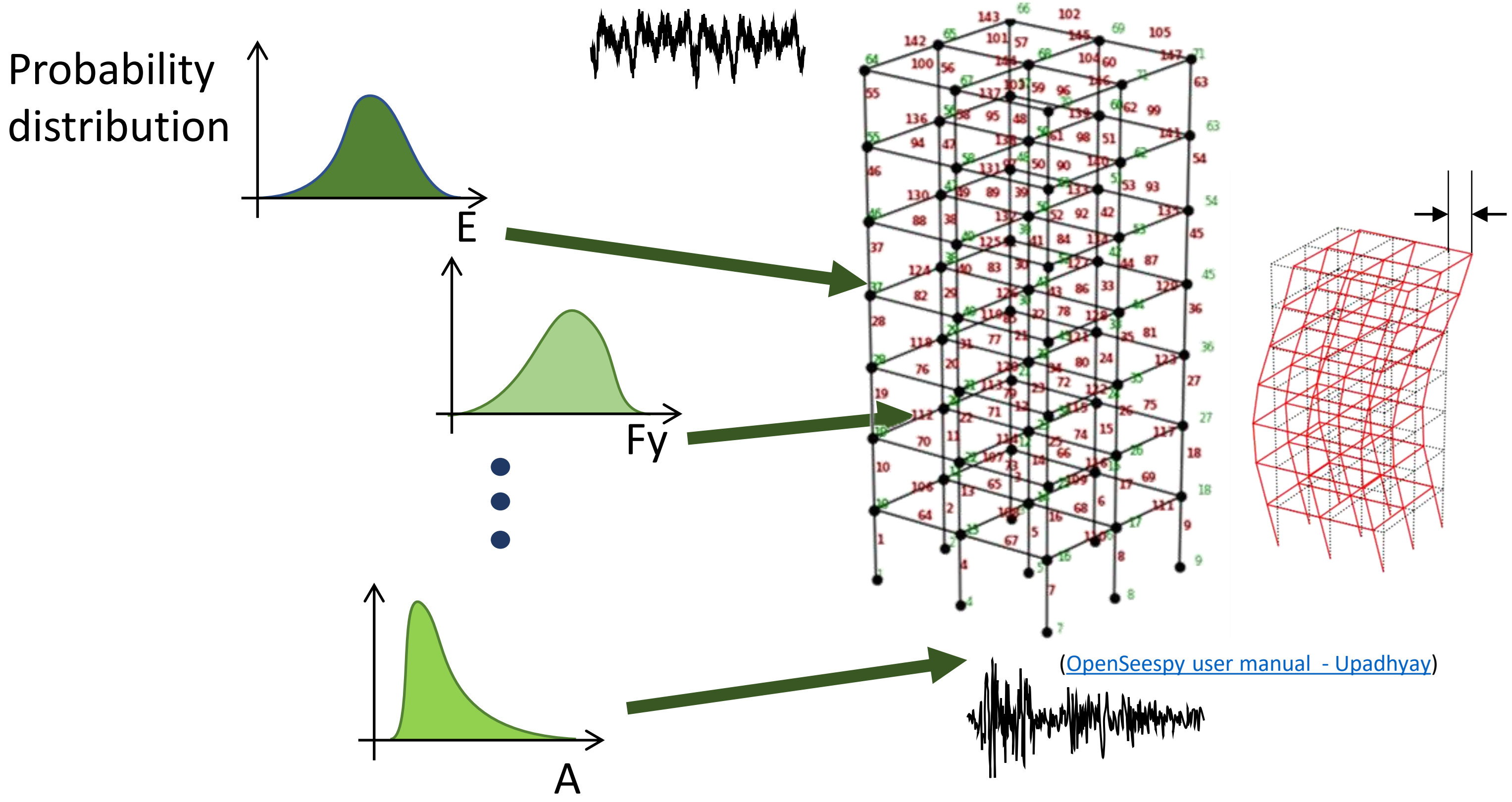
Forward Uncertainty Quantification

Inverse Uncertainty Quantification

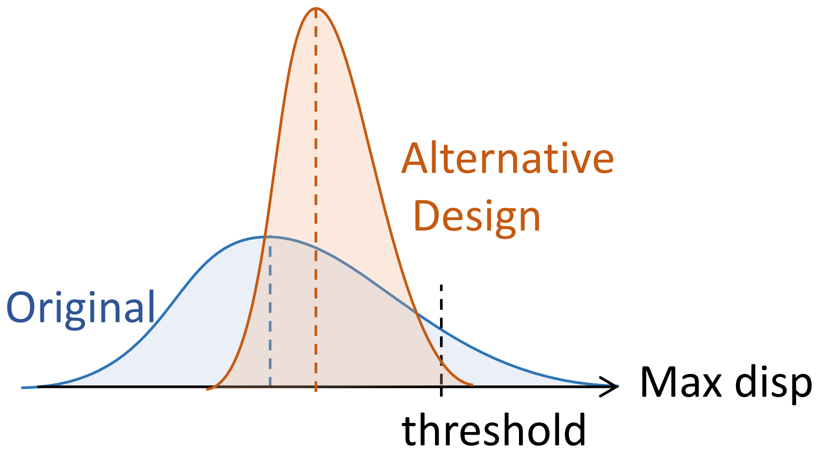
Forward UQ

- Propagation of uncertainty from inputs to outputs

Simulation Model



(OpenSeespy user manual - Upadhyay)

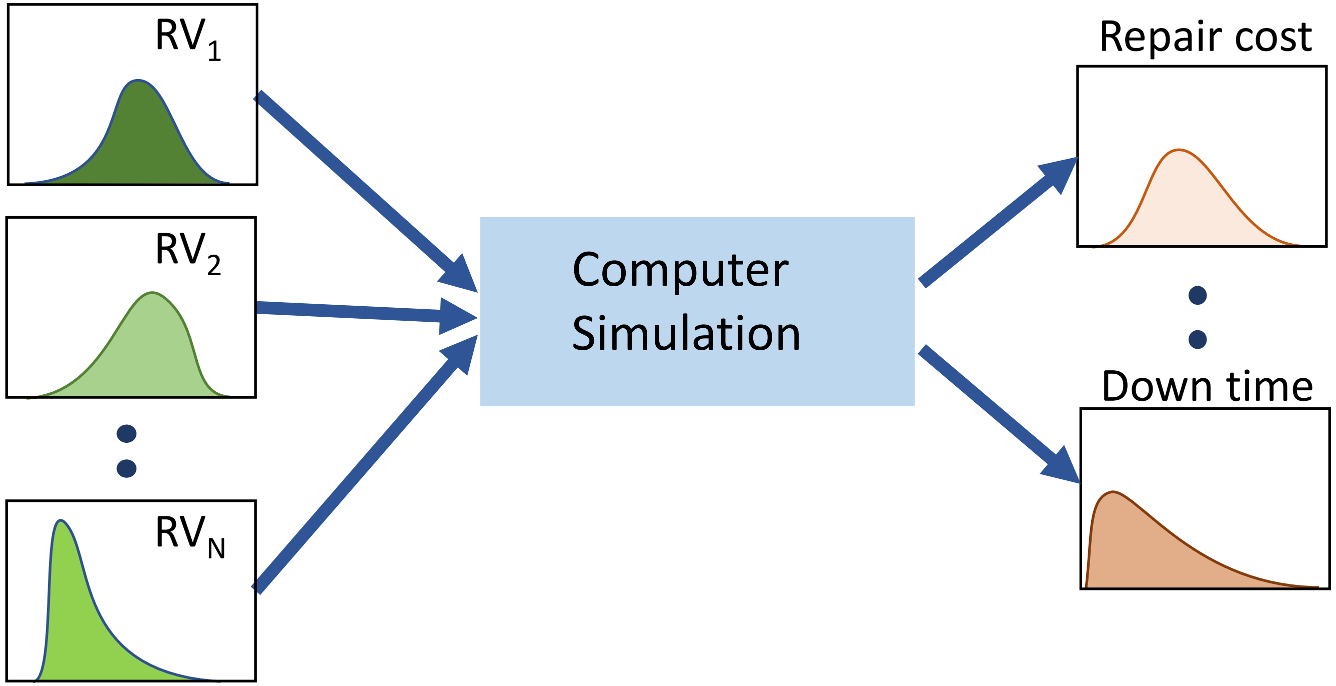


Which design would you select?

→ Uncertainty quantification
is essential in making decisions

Forward UQ

- Based on assumptions on inputs, predict the uncertainty in outputs



Mean expected down time
Standard deviation of repair cost

Forward sampling

Probability of significant damage

Reliability analysis

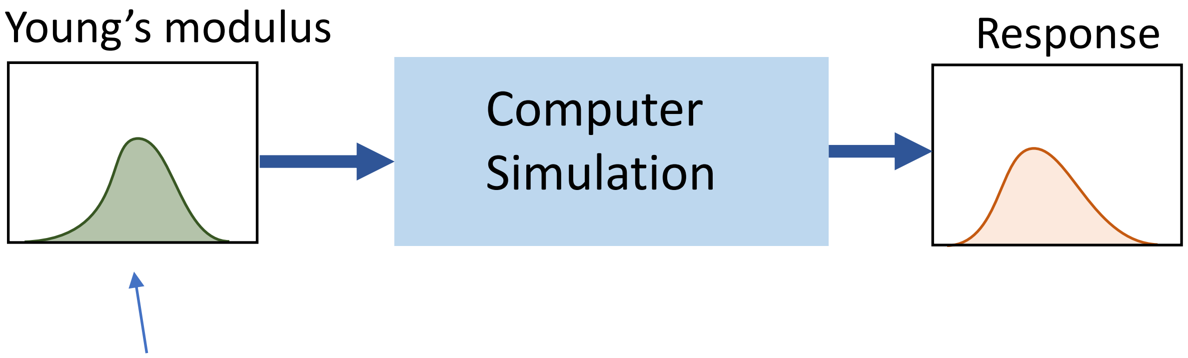
Importance of each parameter

…

Global sensitivity analysis

Forward UQ

- Let us first consider single RV / Response



How do we get the input distribution?

Mean expected down time
Standard deviation of repair cost

Forward sampling

Probability of significant damage

Reliability analysis

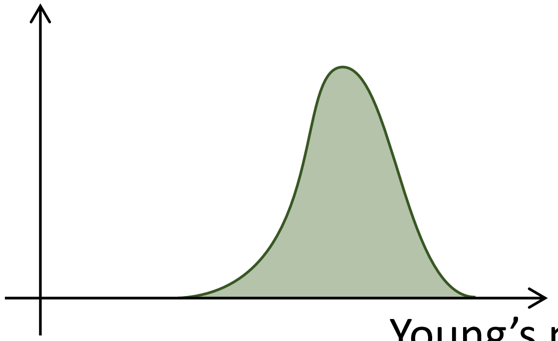
Importance of each parameter

Global sensitivity analysis

…

Probability distribution of RV

- Everything is **possible** but not everything is **probable**



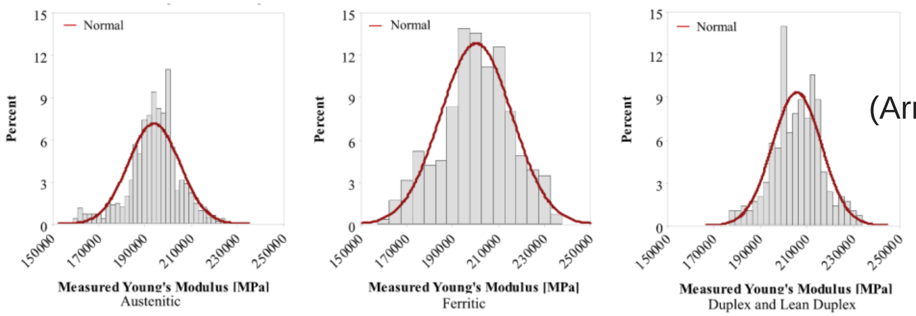
Engineering Judgement + Observation

- Based on underlying physics of quantity
- Select a simple distribution and apply reasonable limits

- Bayesian updating
  →inverse UQ

Examples

Known range of interest - Uniform distribution
Assumption - Gaussian with 10% variation
From reference



(Arrayago et al. 2020)

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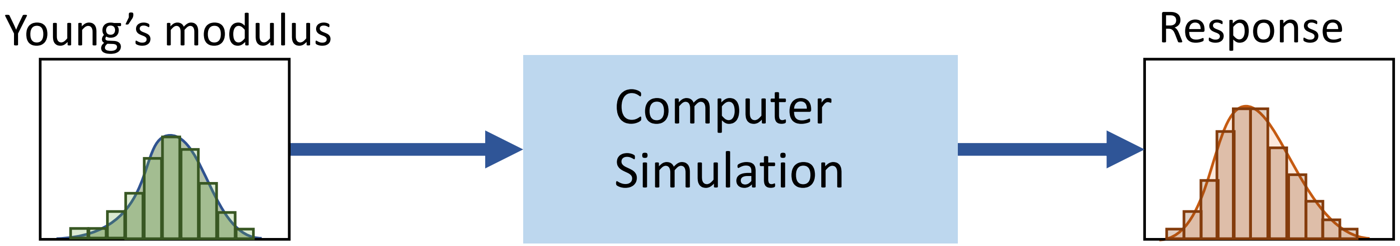
Forward Propagation

- Based on assumptions on inputs, predict the uncertainty in outputs

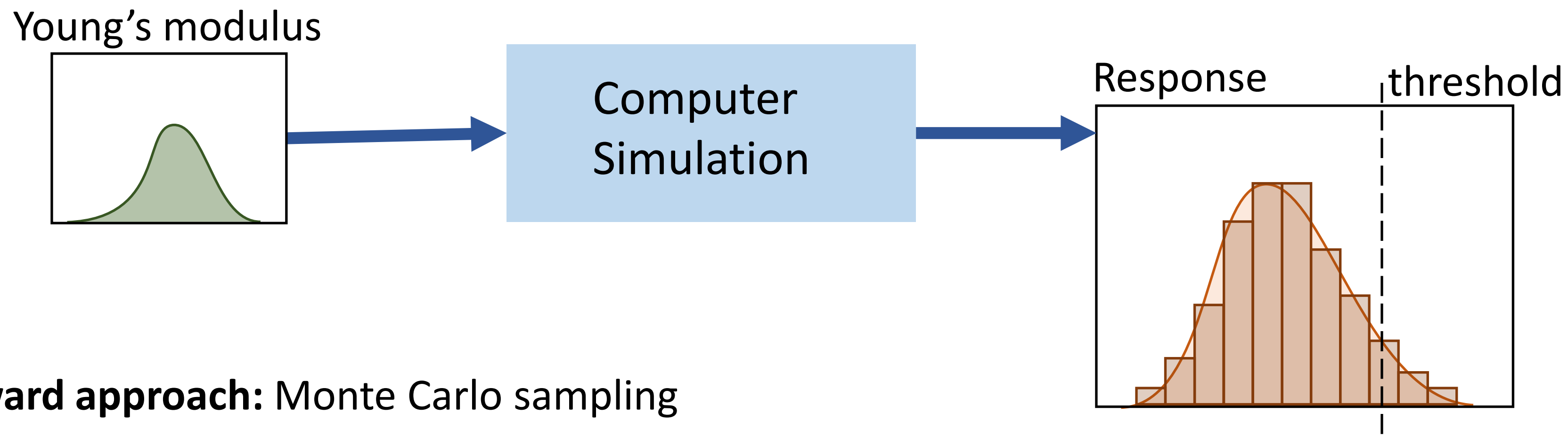


Mean
Standard deviation
Probability distribution

- **A straightforward approach** Monte Carlo sampling
- **Is the model numerically expensive?** Few simulations as much as possible
  - **- Better UQ algorithms**
    e.g. Latin hyper cube sampling
  - **- Approximation methods**
    e.g. Surrogate modeling
  - **- Combination of both**
    e.g. Multi-fidelity modeling

Reliability Analysis

- Probability of the response exceeding a threshold level
- Important for design decision



- **A straightforward approach:** Monte Carlo sampling
- **When the model is expensive & when failure probability is low**
  It is desirable to reduce the number of simulations

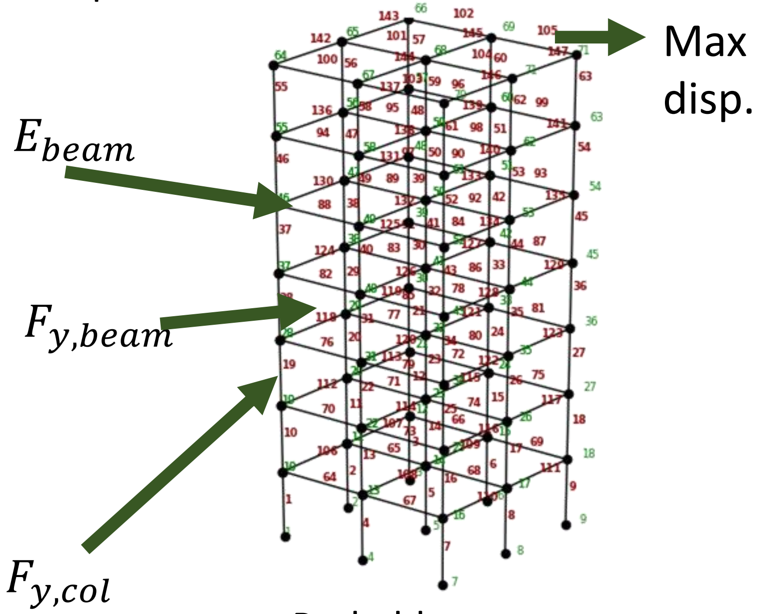
  P_f = 10% requires 1000 simulations
  P_f = 0.001% requires 1000000 simulations

$$c.o.v = \sqrt{\frac{NP_f}{1-P_f}} < 0.1$$

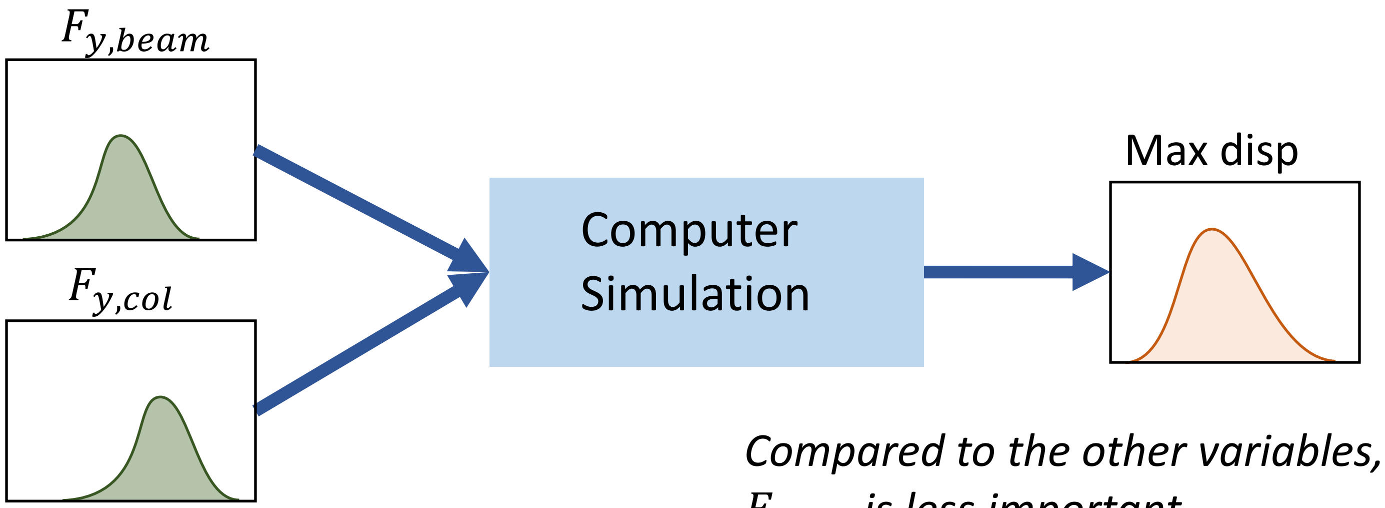
To reduce the number of simulations
- **Better UQ algorithms**
  Importance sampling, subset simulation
- **Approximation methods**
  Surrogate modeling, First-order approximations
- **Combination of both**

Global Sensitivity Analysis

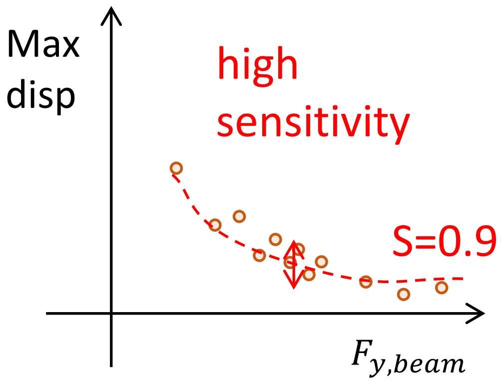
Are all the parameters equally impacting the response?

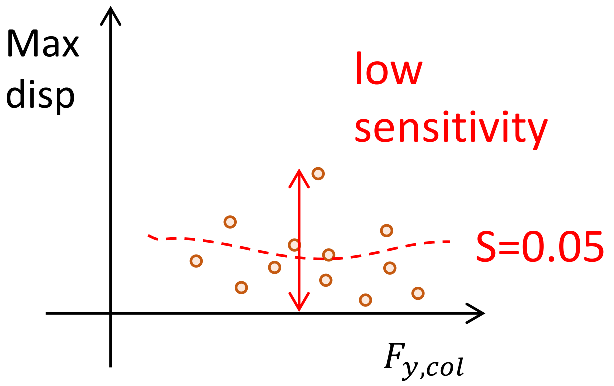


Probably not.
Then what are the variables that are **actually** influential?



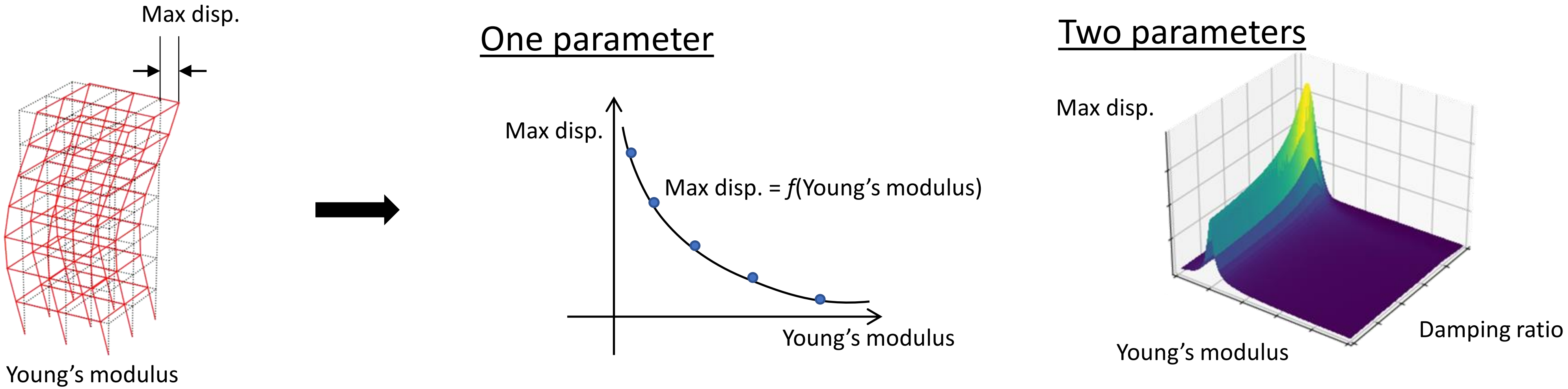
Compared to the other variables, $F_{y,col}$ is less important.
→ You might want to let $F_{y,col}$ be deterministic





Surrogate modeling

- Response surface representation



- Usually the curve (surface) is very flexible & general
  Neural networks, Gaussian process model, polynomial chaos…

- **Design of experiments** are used to reduce the number of simulations

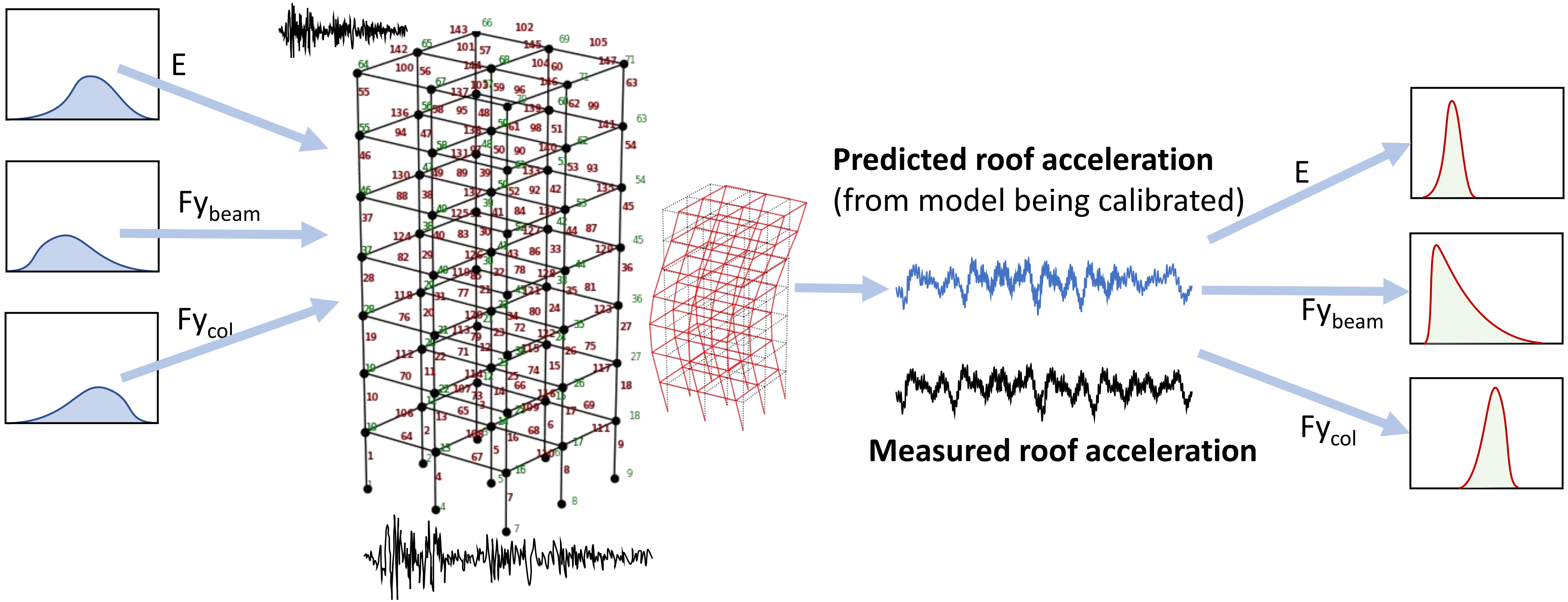
Types of UQ

Forward Uncertainty Quantification

Inverse Uncertainty Quantification

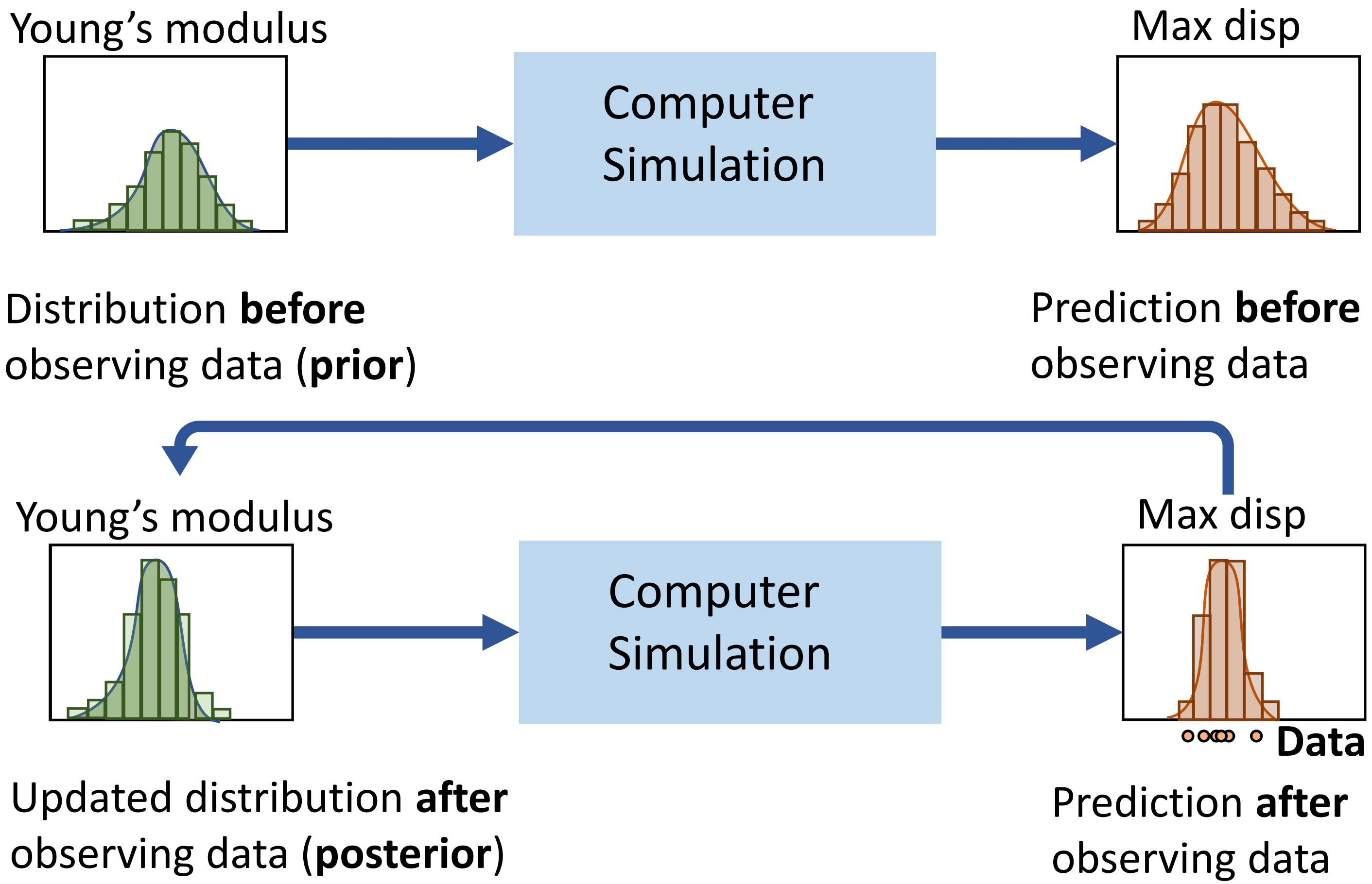
Inverse UQ

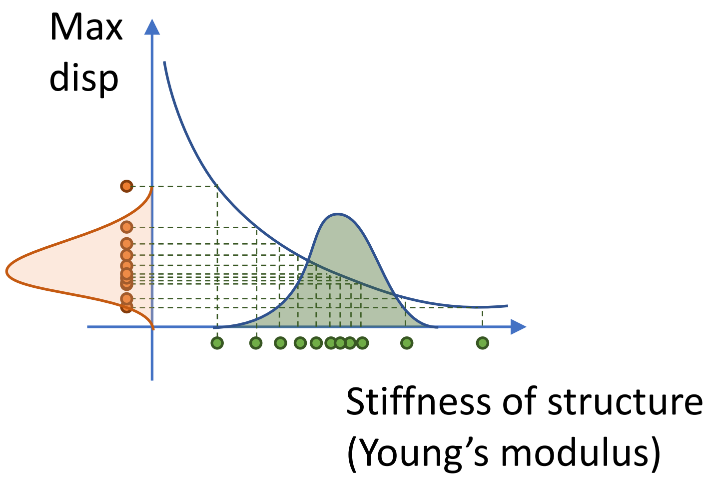
- Based on observed data, update the assumptions about the inputs and/or the model



Inverse UQ Methods – Bayesian calibration

- Based on observed data, update the distribution of the inputs to be consistent with the observations

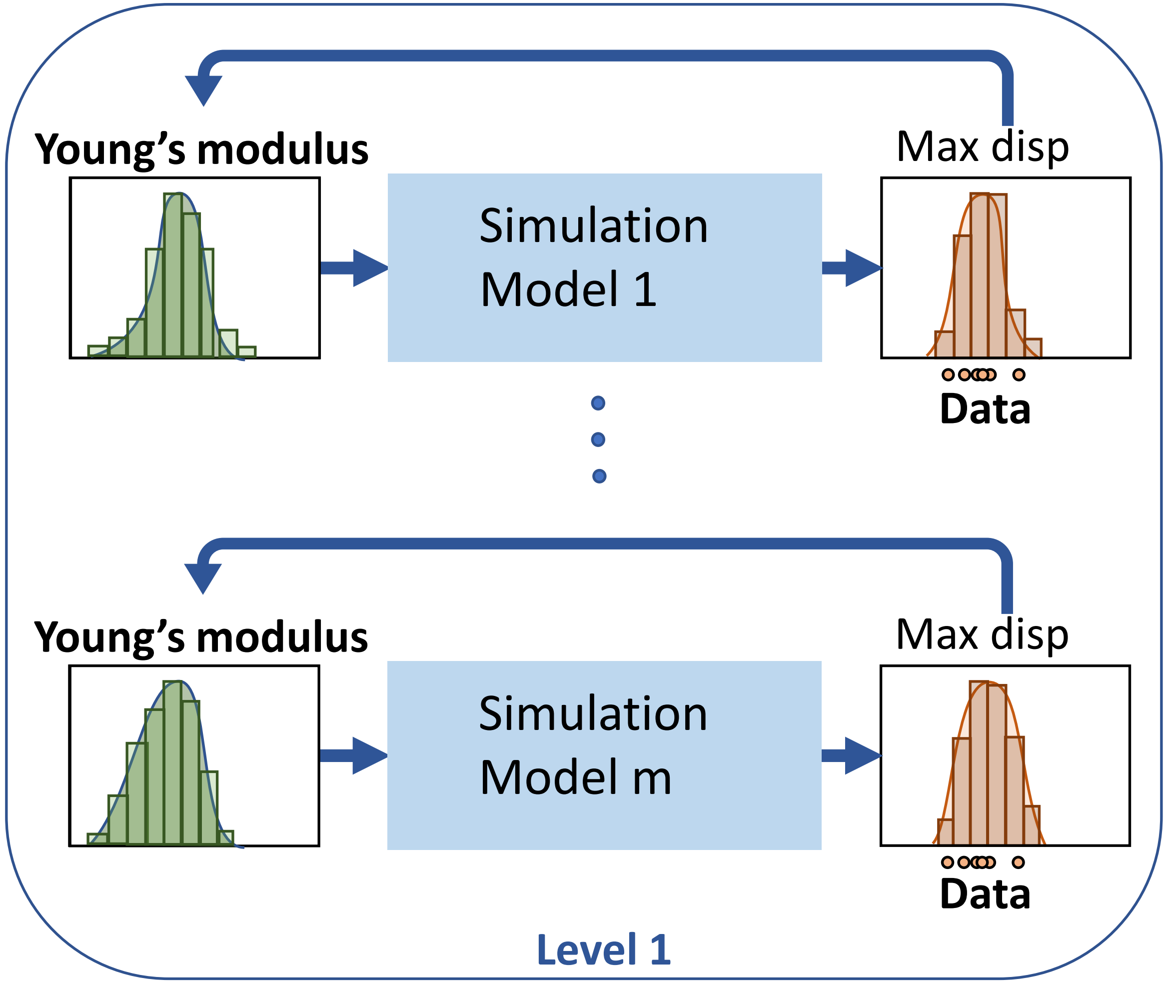




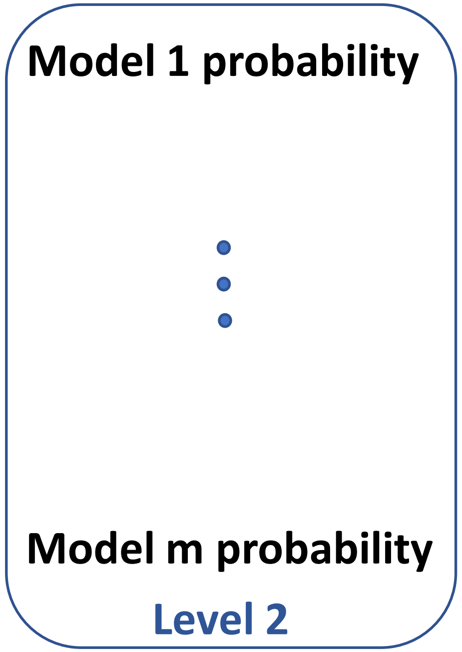
- Calibration of material model
- Calibration of reduced order model
- Post-event damage diagnosis and prognosis
- Digital twin of structure – real time updating
- Reliability updating

Inverse UQ Methods – Model Class Selection / Averaging

- Based on observed data, update the probability of a set of plausible models



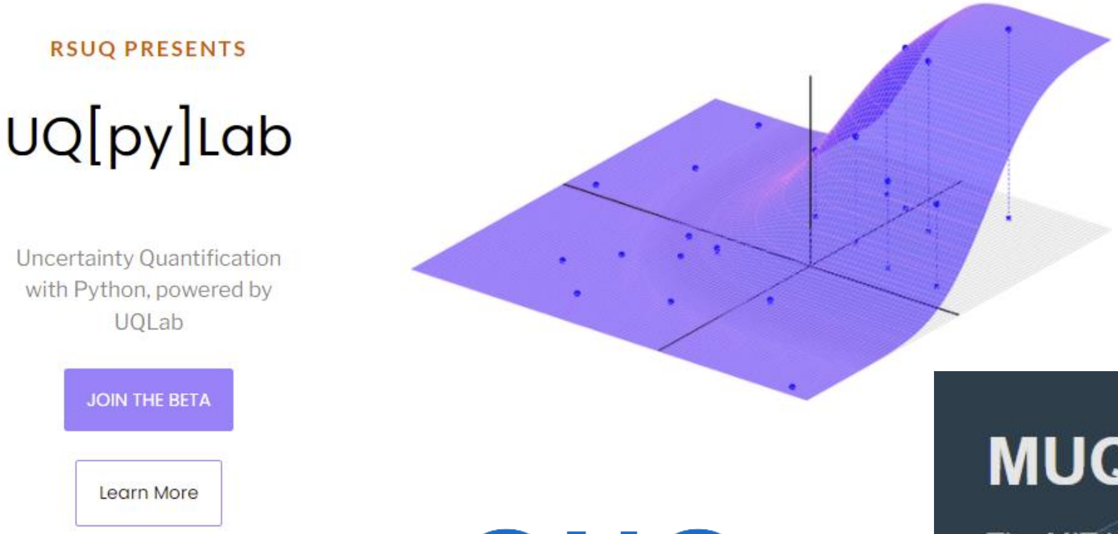
"**All models are wrong, but some are useful**"
– George E. P. Box



- **Model parsimony:** if two models fit the data equally well, the simpler model is assigned higher probability
- **Model class selection** – select the best model from the set and use for prediction
- **Model class averaging** – select all or the best few models, take weighted average of predictions from these models

Running UQ

- Toolbox/software packages for UQ analysis



UQpy

quoFEM

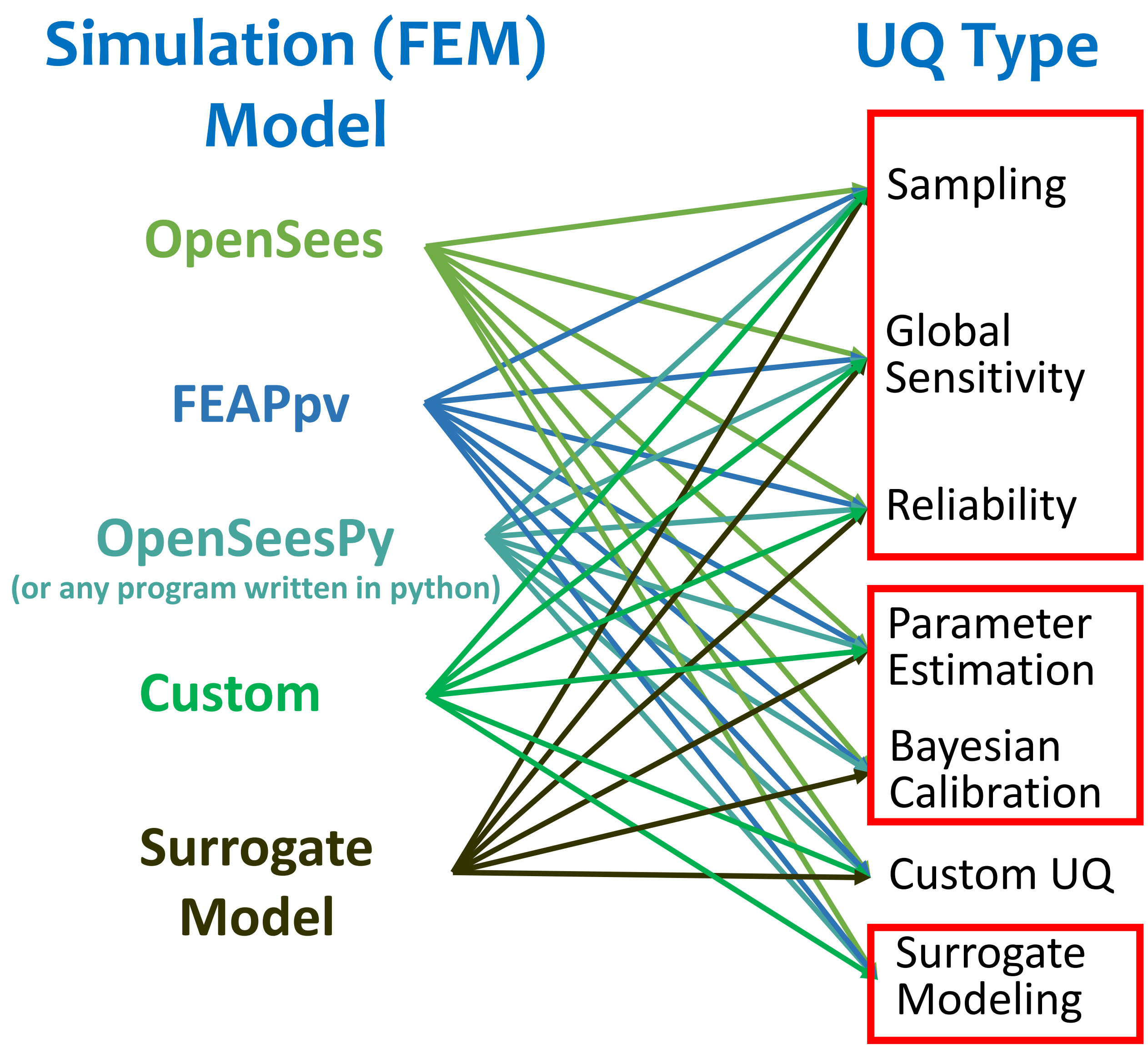
quoFEM

- A software tool with a user interface developed in SimCenter

"You bring the FEM model, we do the rest"

- Need more than what we have?
  - **Build your own quoFEM**
    Github page: https://github.com/NHERI-SimCenter/quoFEM
  - **Tell us what you need**
    SimCenter Forum: http://simcenter-messageboard.designsafe-ci.org/smf/index.php

quoFEM (v.2.4)



Algorithm

- Latin Hypercube Sampling
- Monte Carlo
- Gaussian Process Regression
- Polynomial Chaos Expansion

- Quasi-Monte Carlo
- Probability-model-based approximation

- Local Reliability (FORM, SORM,..)
- Global Reliability
- Importance Sampling

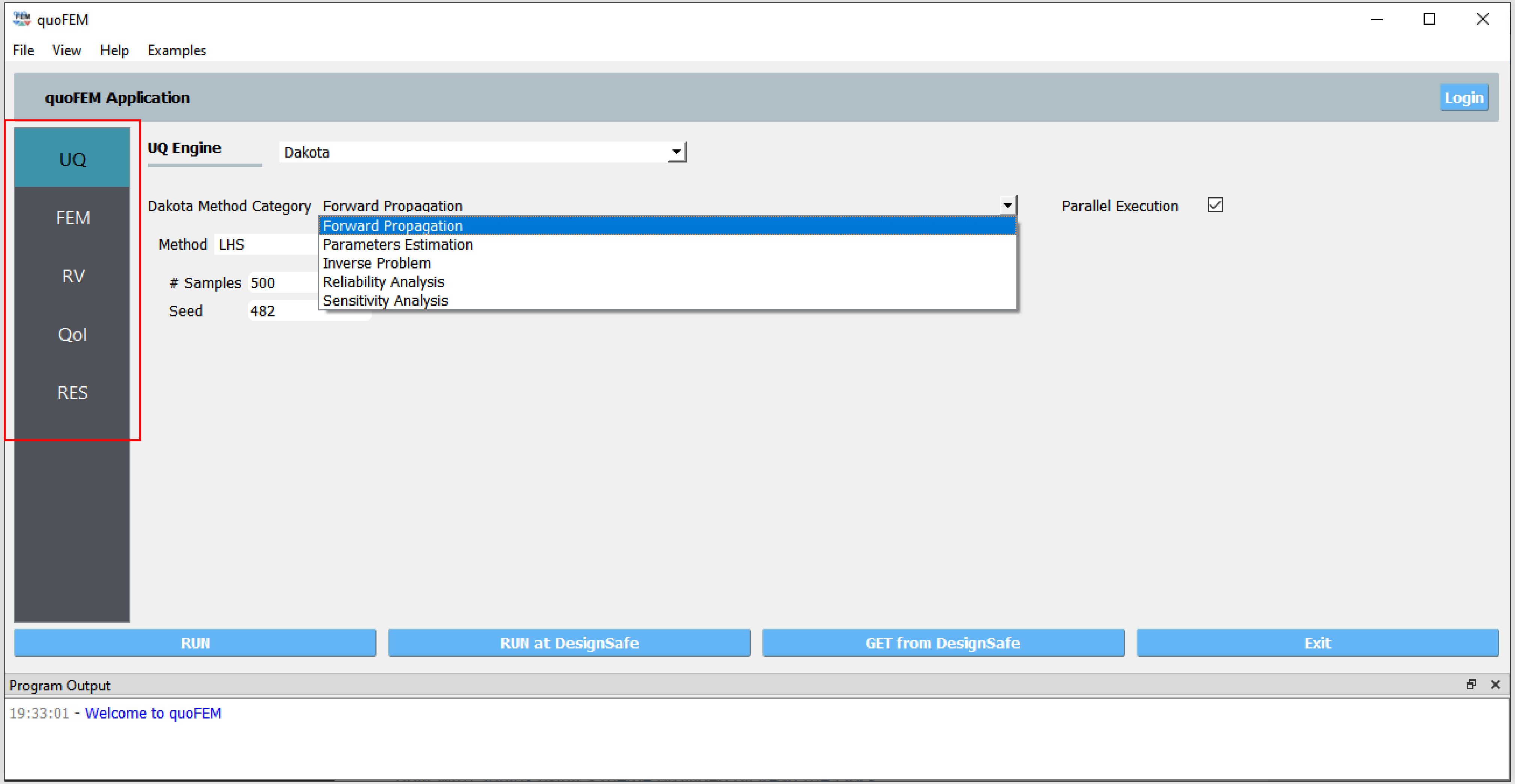
- OPT++GaussNewton
- NL2SOL

- DREAM
- TMCMC

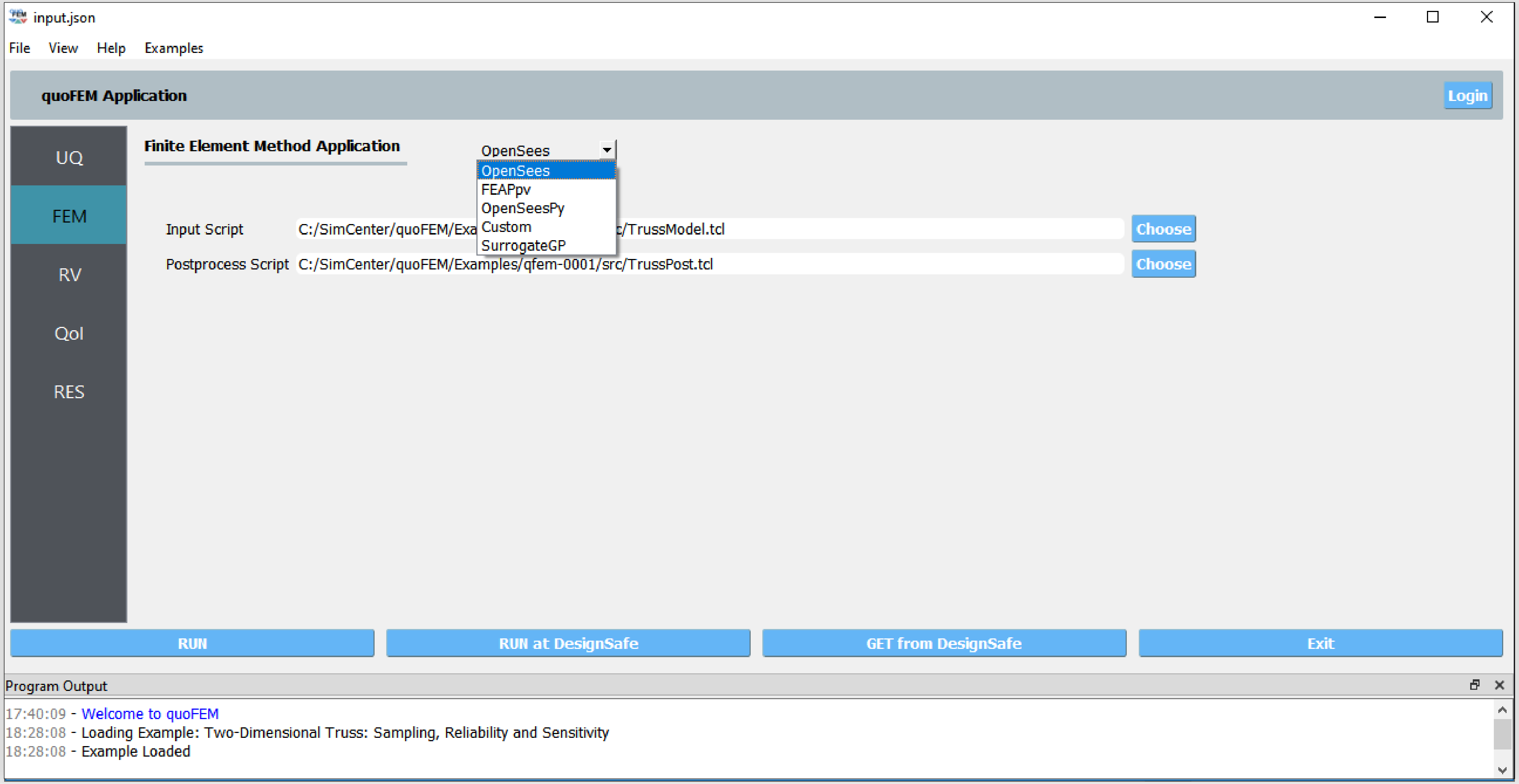
- Custom UQ algorithm

- Gaussian process surrogate modeling
- Gaussian process multi-fidelity modeling

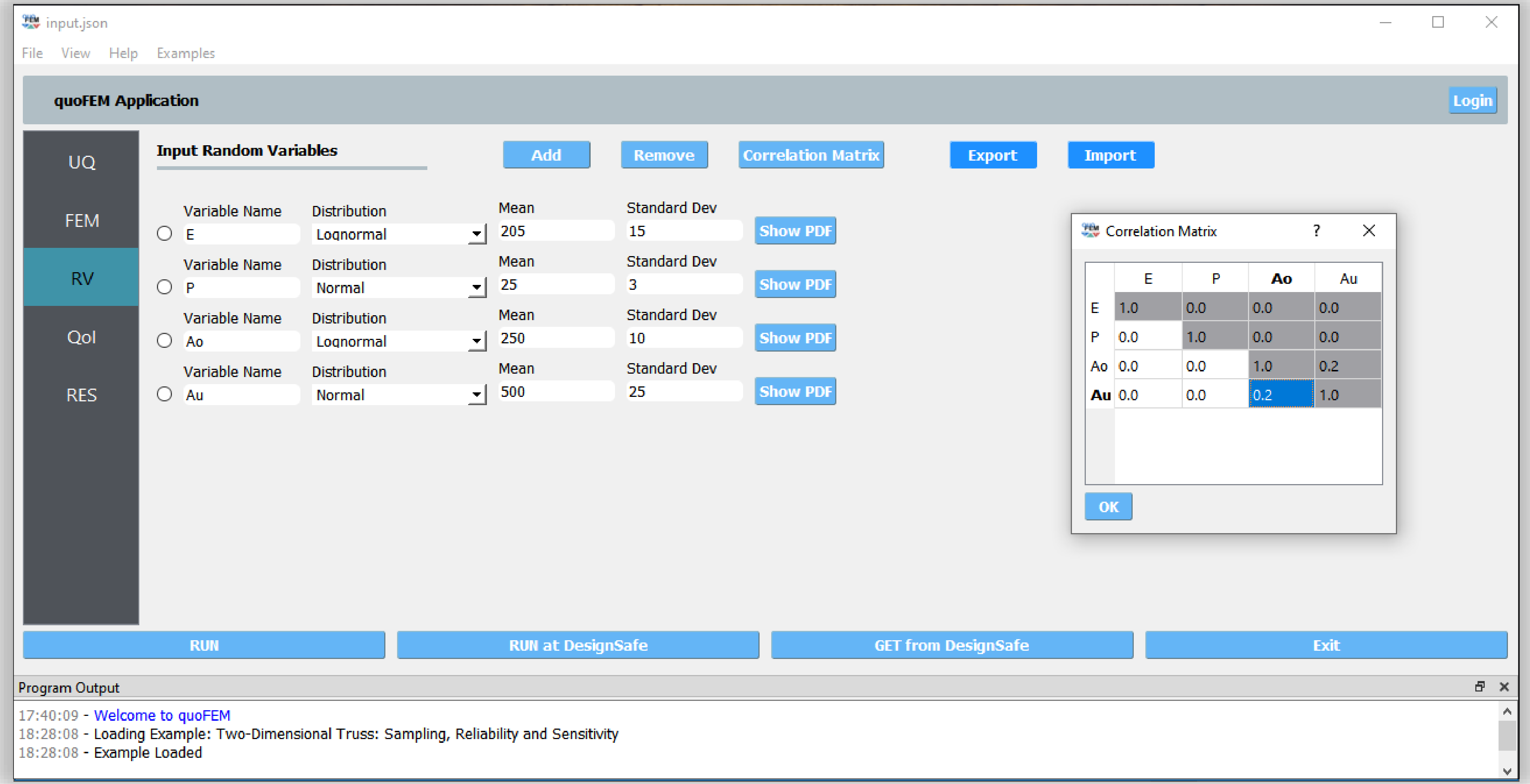
quoFEM User Interface



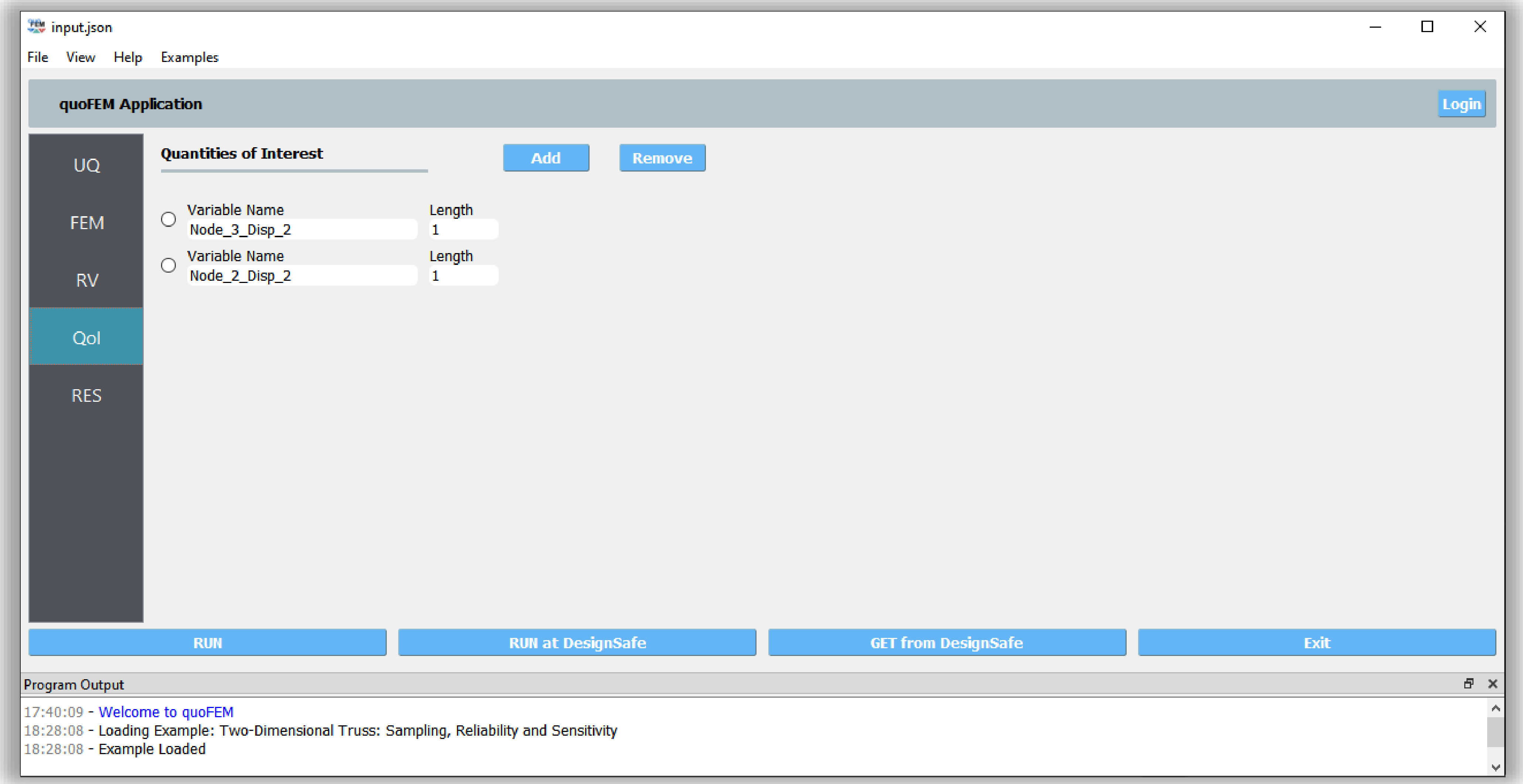
quoFEM User Interface



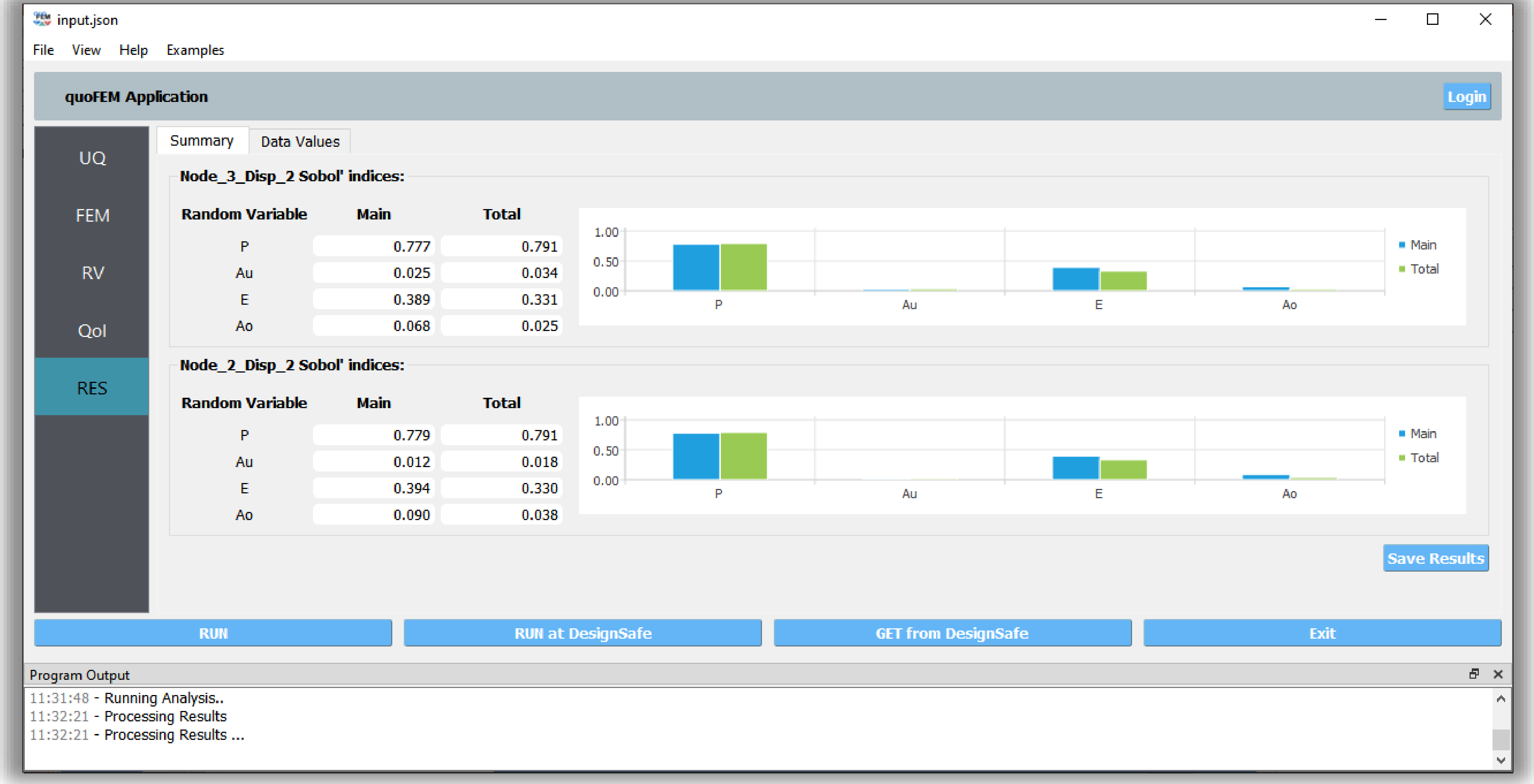
quoFEM User Interface



quoFEM User Interface



quoFEM User Interface

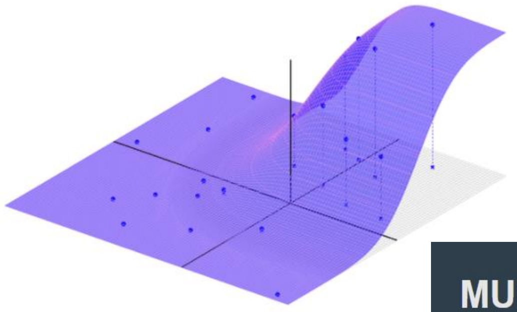


Conclusion

"An estimate without a standard error is practically meaningless." (Jeffreys 1967)

- Deterministic result is just one of many **possible** outcomes
- In order to make decisions, we need to also know how **probable** the outcome is

- There are tools available out there to help you apply UQ methods



Thank you for your attention!