Automation of Engineering Analysis and Design Process in the Subsea Industry

A. Chakraborty, K. Mostafa, L. Garzon , B. Ozturk, S. Sawant
WG Kenny, Houston, USA
R. Watkins, K. Mix
Altair, Houston, USA

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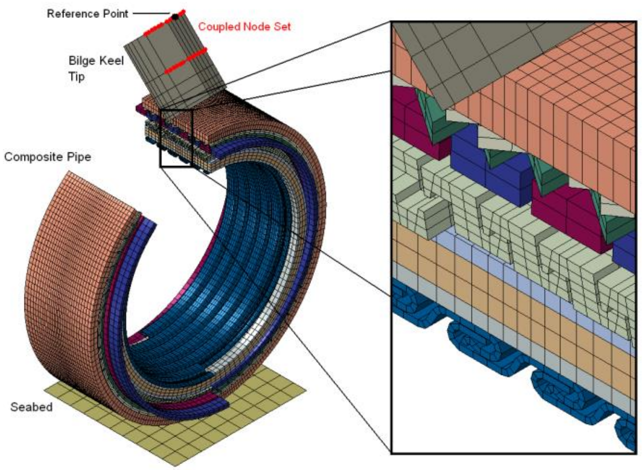
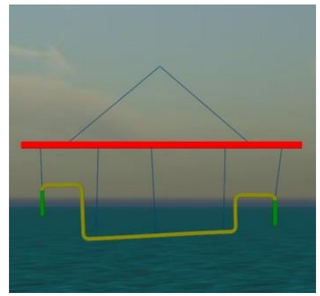
Outline

- Drivers Behind Study & Subsea Applications
- Design Automation
  - Introduction
  - Design Framework
  - Challenges
  - RBDO
  - Design Automation
- Reliability Based Analysis
  - Buckle Arrestor Design
  - Problem Statement
  - FE Model
  - RBDO Model
  - Results & Conclusions
  - Work in Progress

Drivers Behind Study & Subsea Applications

Examples





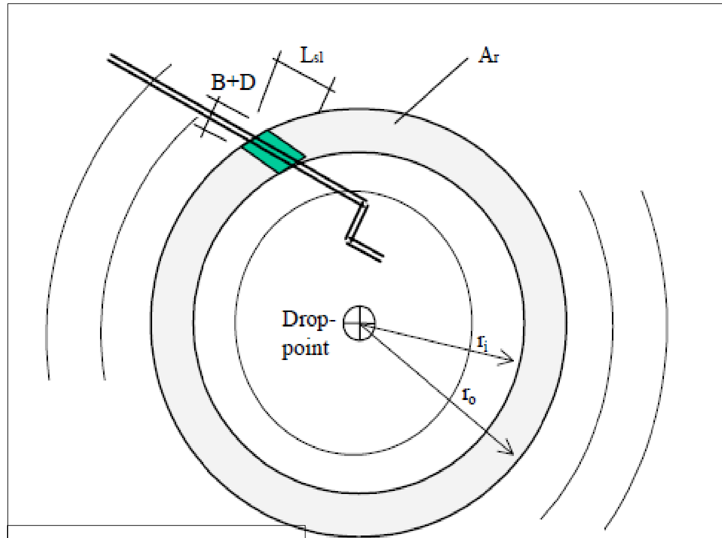


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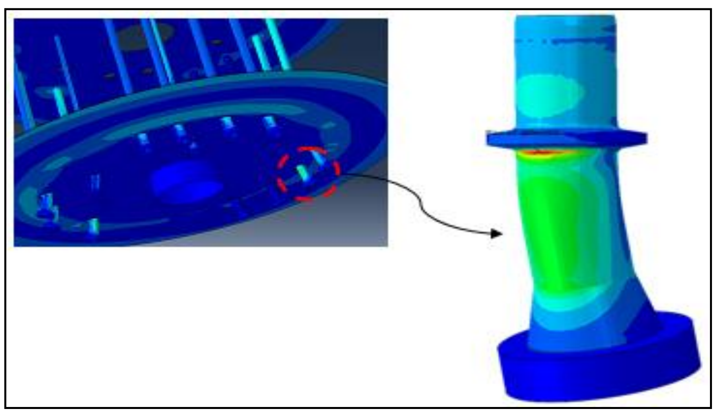
Figure 9 Probability of hit within a ring, defined by inner radius, r_i, and outer radius, r_o, from the drop point.



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Design Automation

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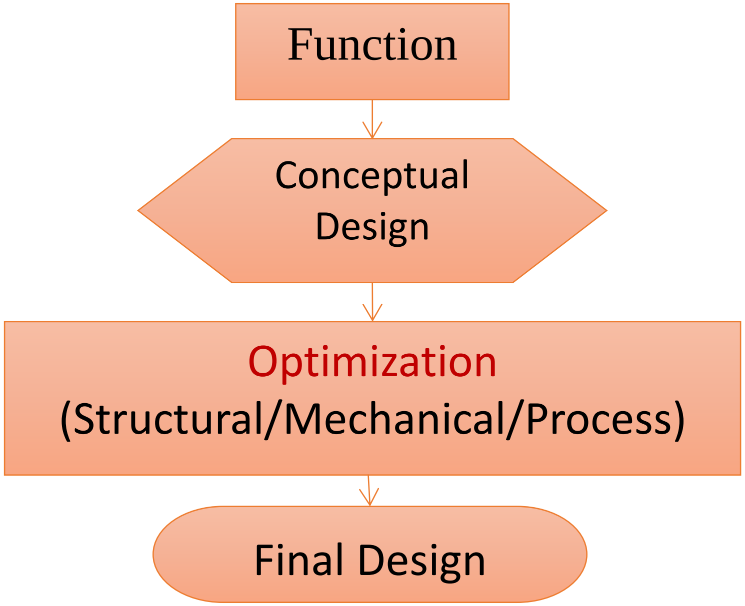
Introduction

Design Process



Optimization

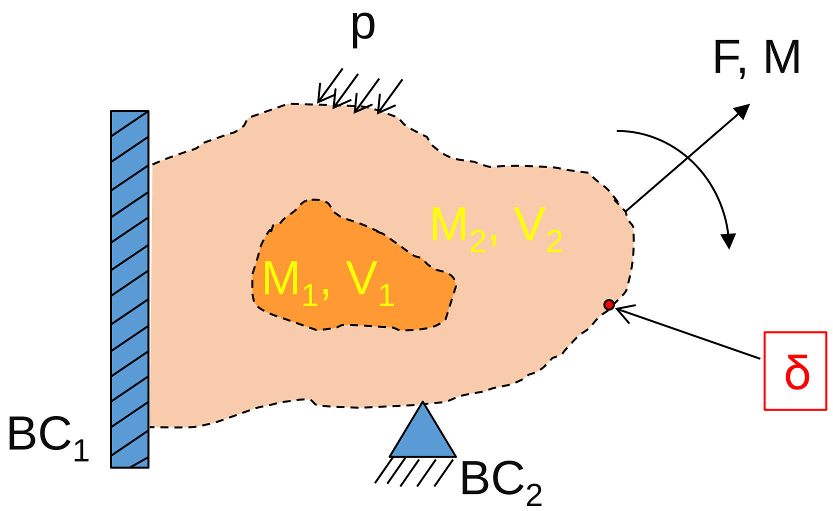
- Traditional (Non-mathematical, Iterative/Intuitive)
- Formulation Based (Mathematical)

Introduction (Cont.)

Optimization

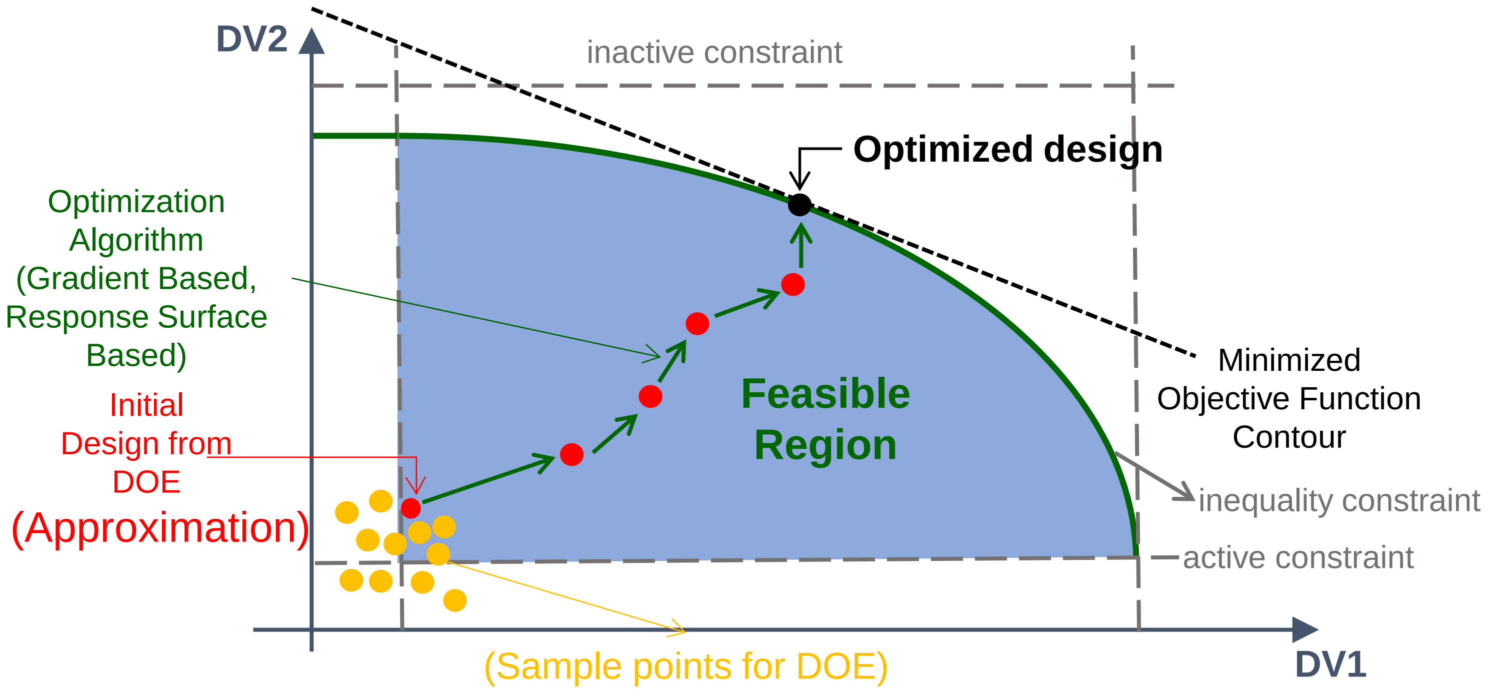
Mathematical Optimization

- Design Variables ($\bar{X}$)
- Objective Function ($g(\bar{X})$)
- Constraints ($k_i(\bar{X}) \leq 0$)
- Bounds ($a_i \leq x_i \leq b_i$)



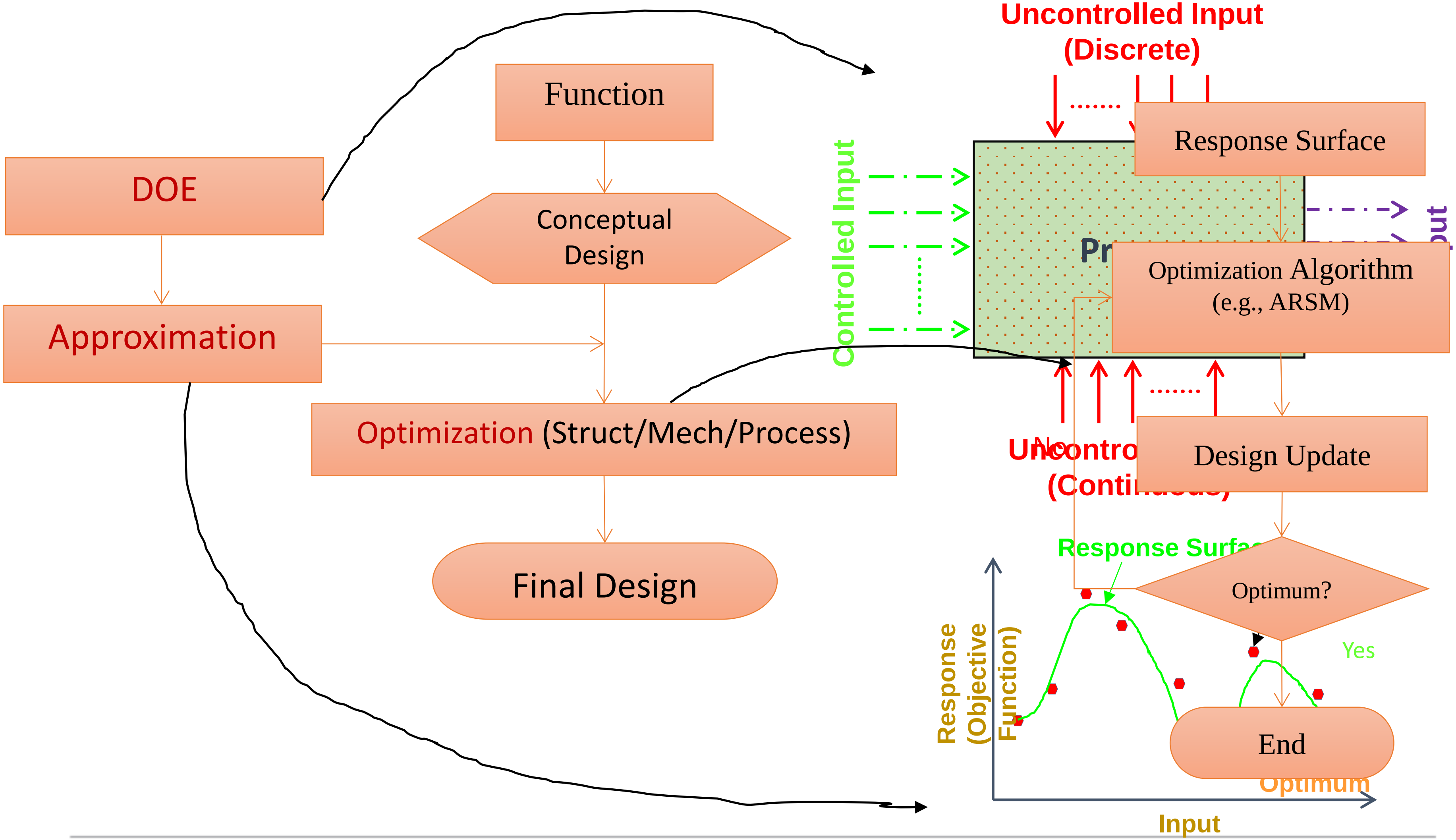
$$\text{Optimization}\begin{cases}\text{minimize } g(\bar{X})\\ \text{subject to } k_i(\bar{X}) \leq 0\\ \text{and } a_i \leq x_i \leq b_i\end{cases}$$

Introduction (Cont.)

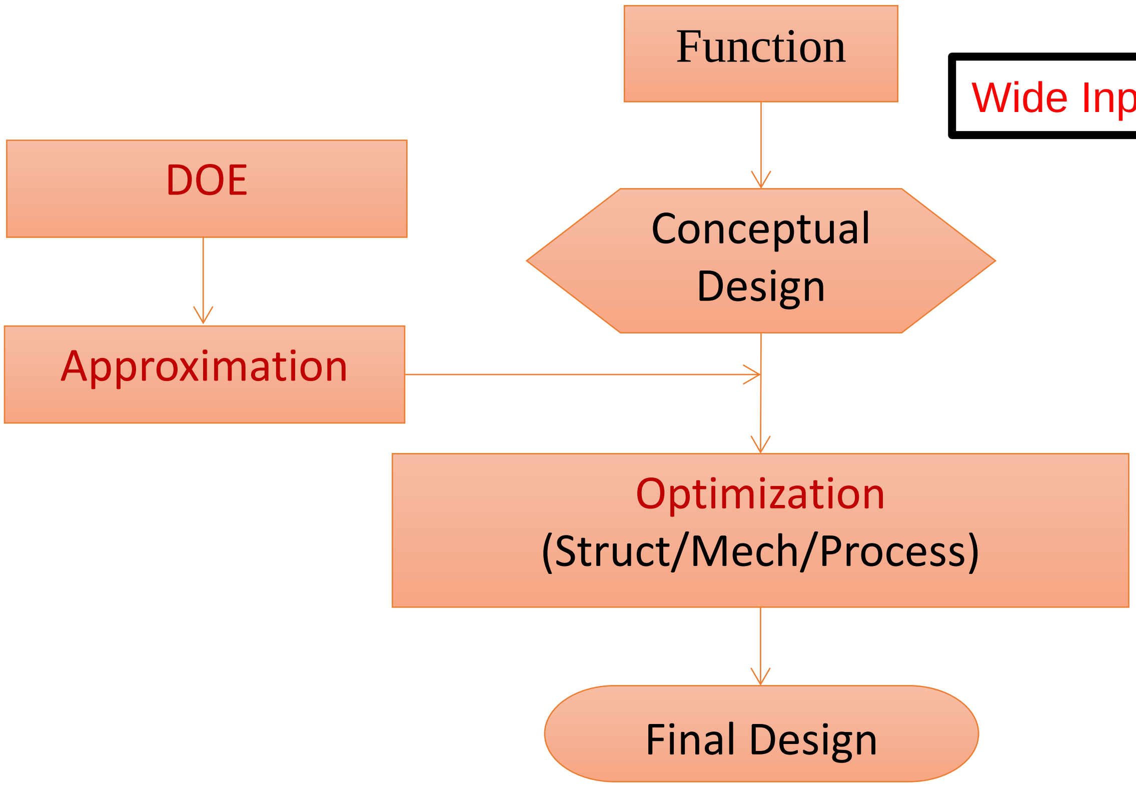


- Epistemic uncertainty at initial design stage is high - broader design space
- DOE sampling and optimization algorithm needs many simulations
- Each simulation may involve multiple analyses (software etc.)
- Difficult for manual book-keeping
- Aleatoric uncertainty can add significantly to the computation cost (RBDO)

Design Framework



Challenges

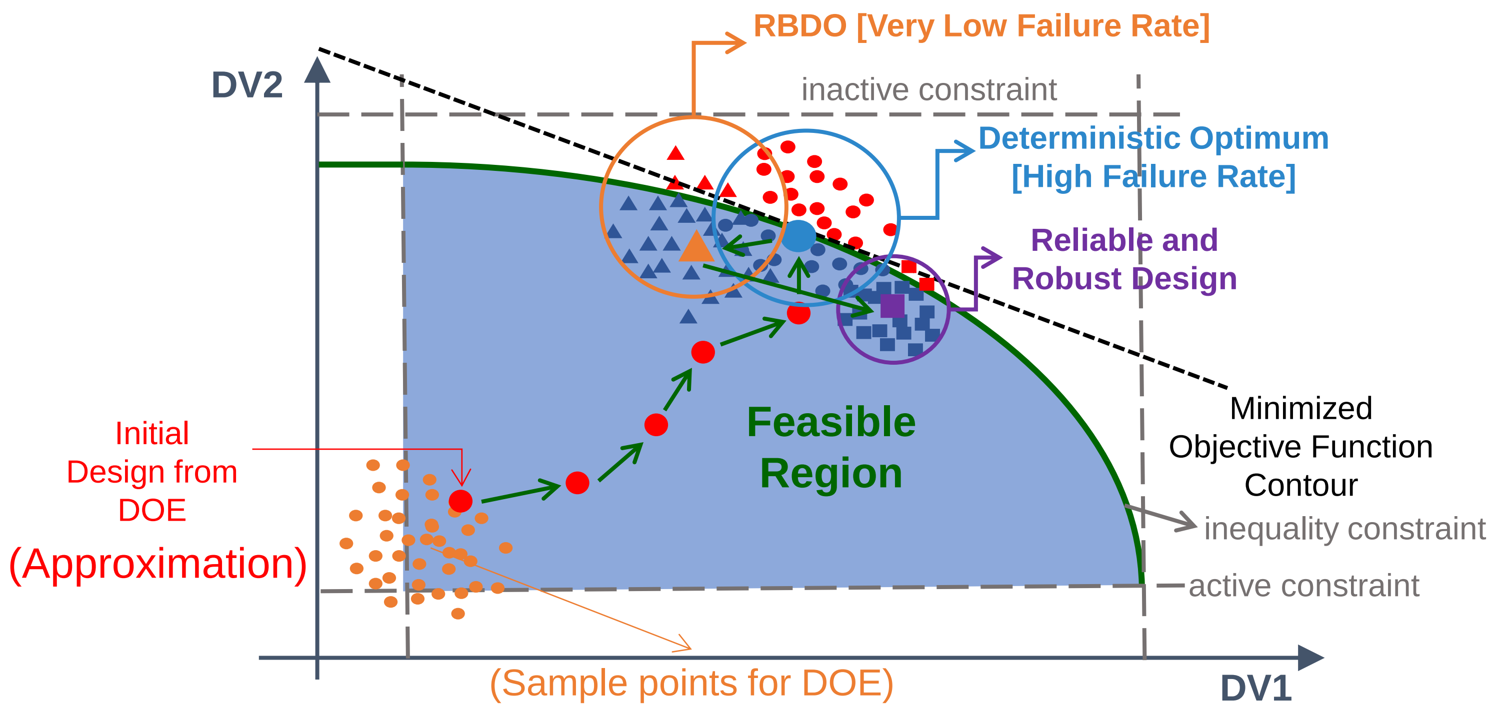


Wide Input Variability at Initial Design

Uncertainty??

Multiple simulations for DOE, Optimization

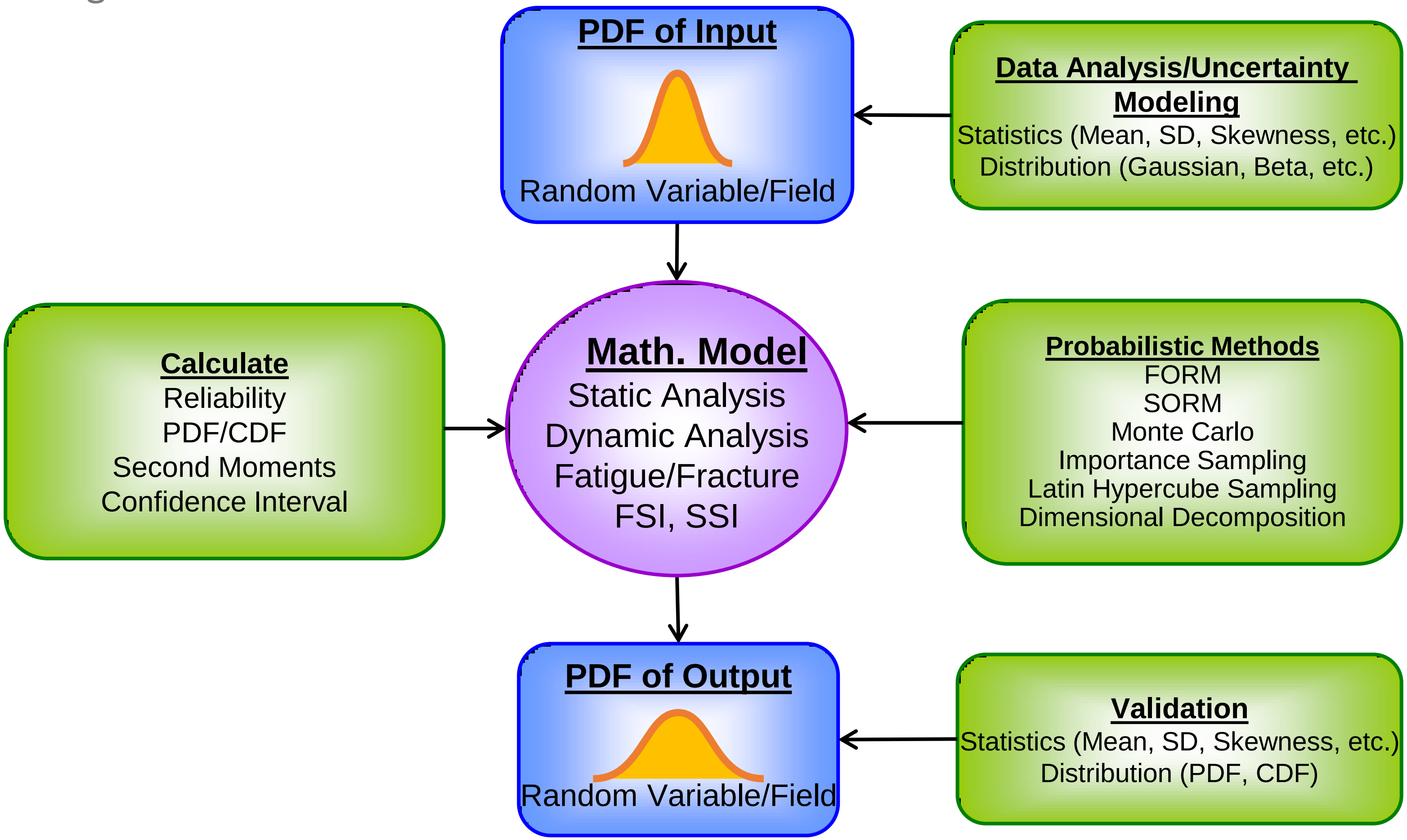
RBDO



Requires Design Process Automation

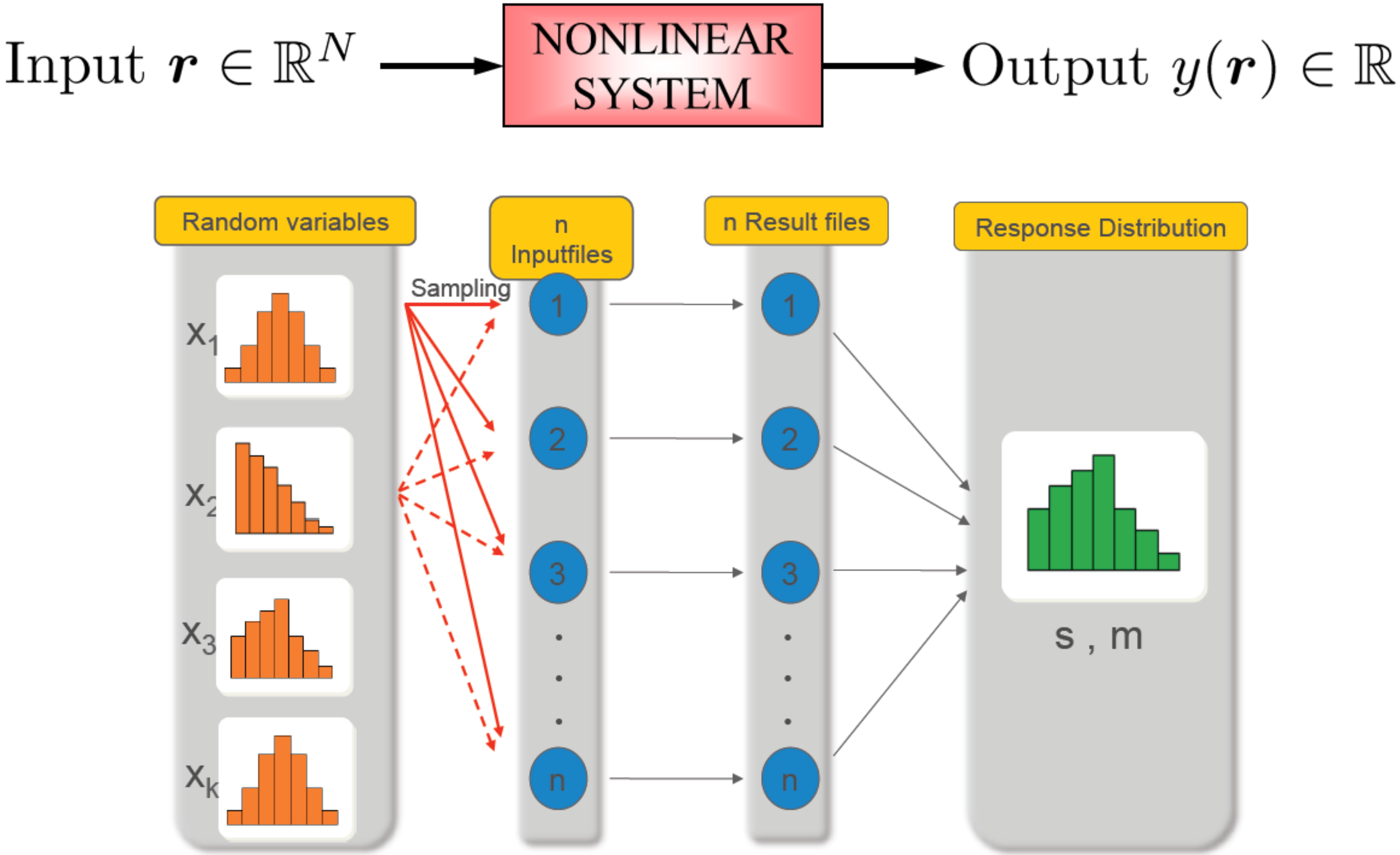
RBDO (Cont.)

Modeling Stochastic Problem

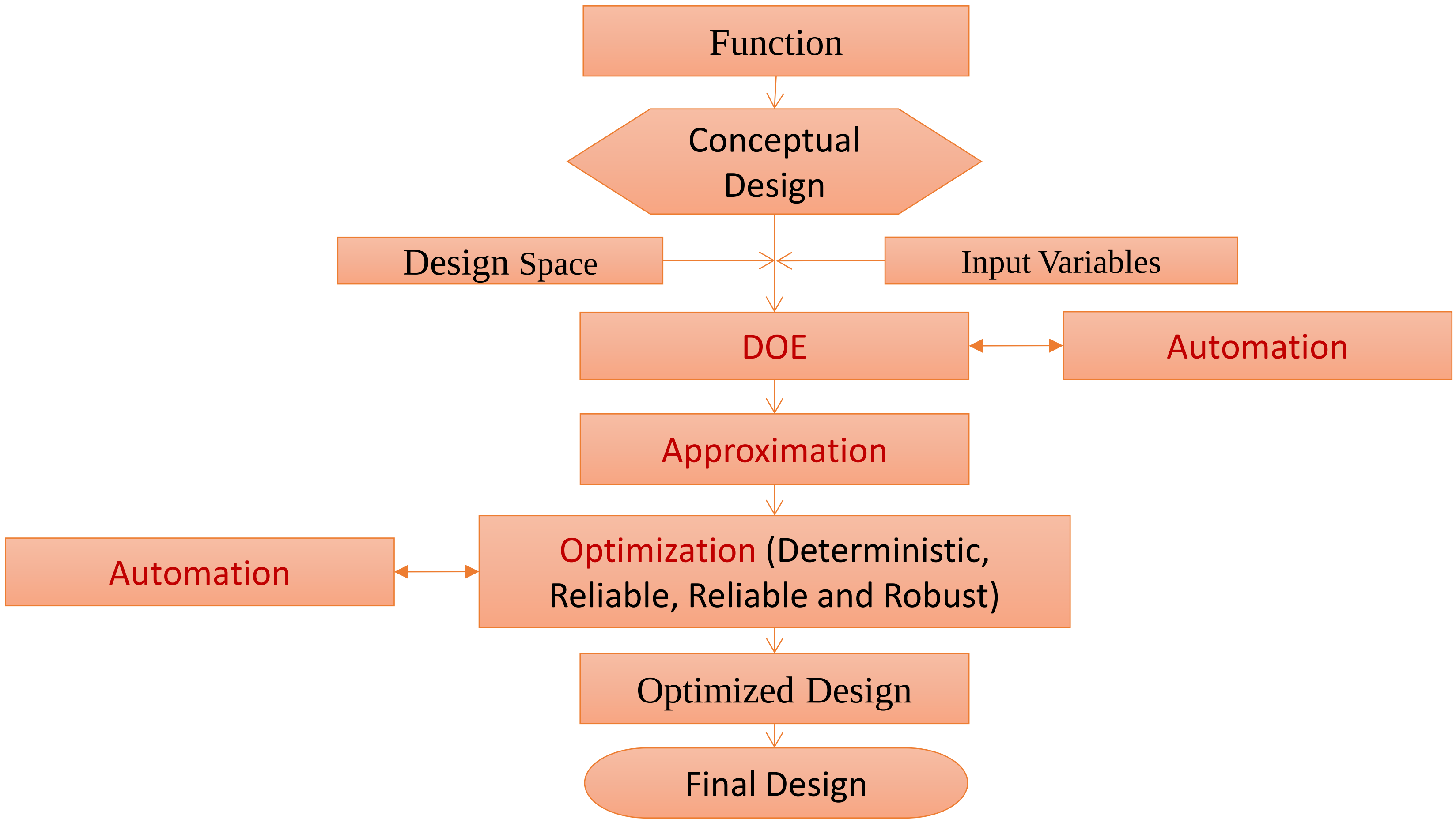


RBDO (Cont.)

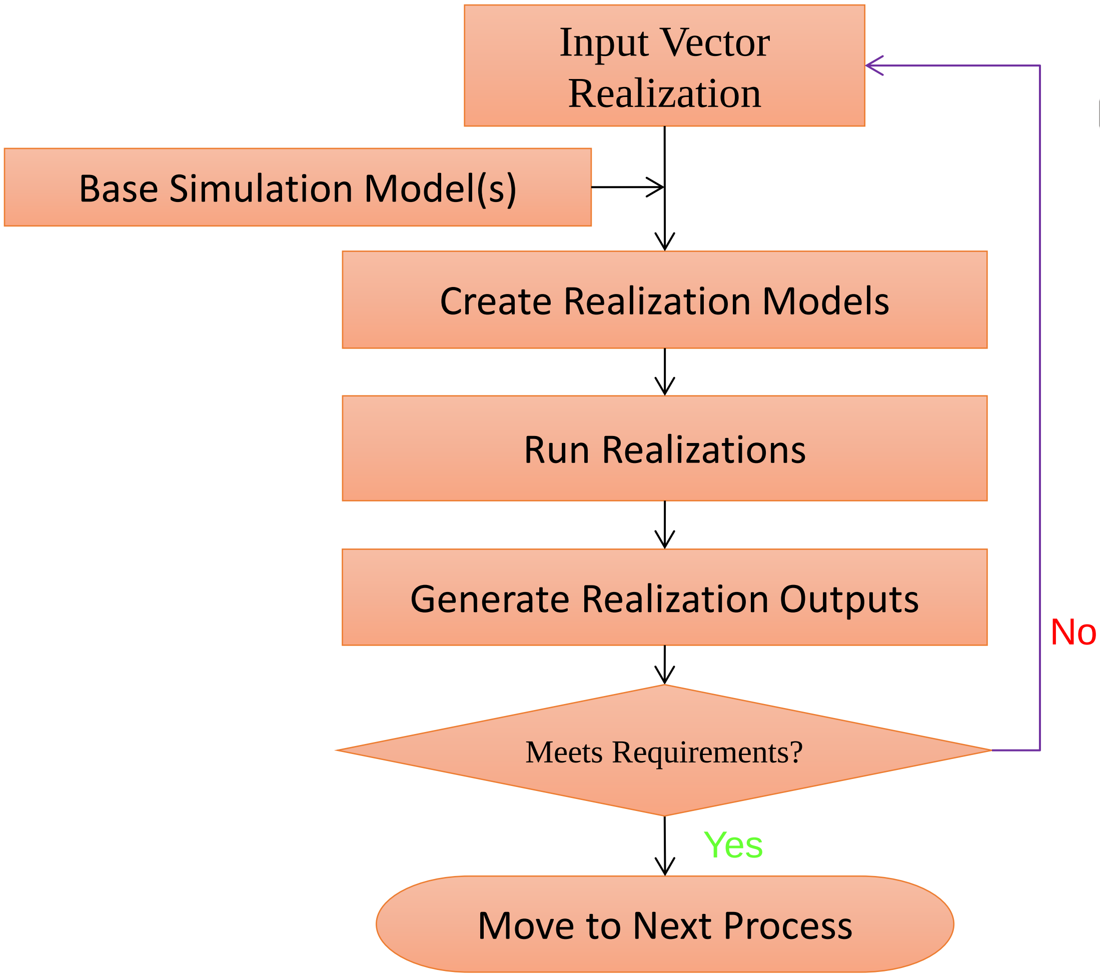
Meta Modeling

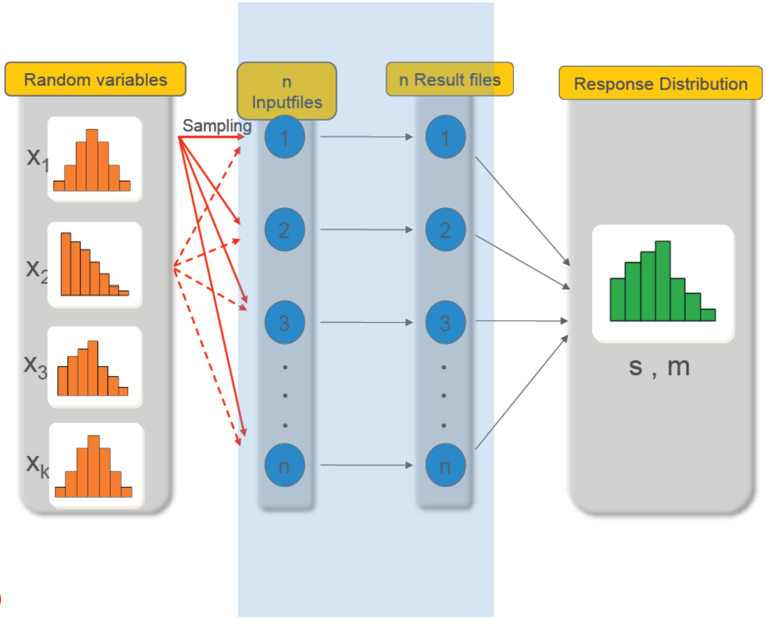


Design Automation



Design Automation (Cont.)





Each may include multiple analyses

Reliability Based Analysis

Subsea Applications

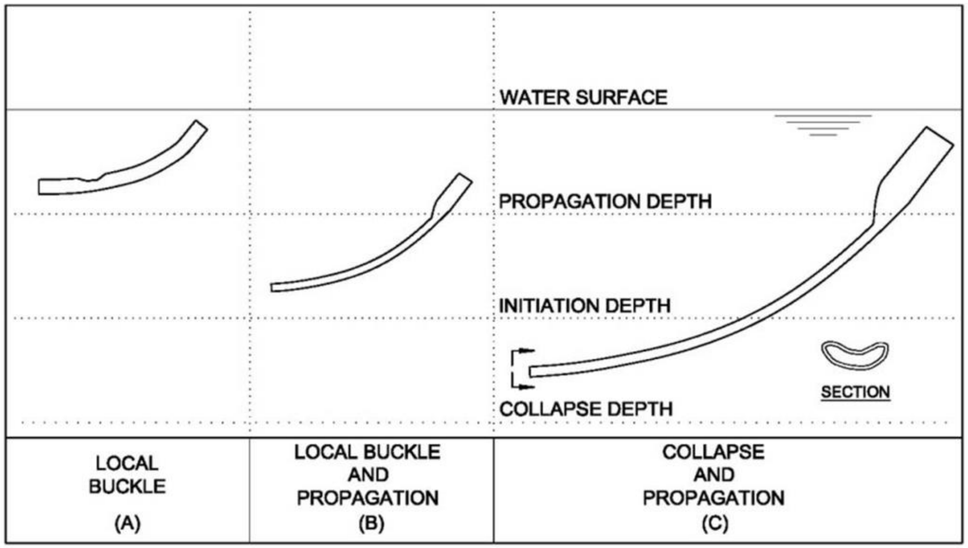
- Input may change significantly between initial and final design stages
- Many parameters with complex effect on response
- Highly complex interactions (SSI, FSI, ECA)
- Aleatoric and epistemic randomness in input parameters
- Simulation is computationally expensive (non-linear, iterative)
- FOS Based design may be infeasible

↓

- DOE captures complex interactions and effects
- Optimized design at initial stage – Minimal change during final design
- Including reliable and robust design – Increased safety during operation

Buckle Arrestor Design

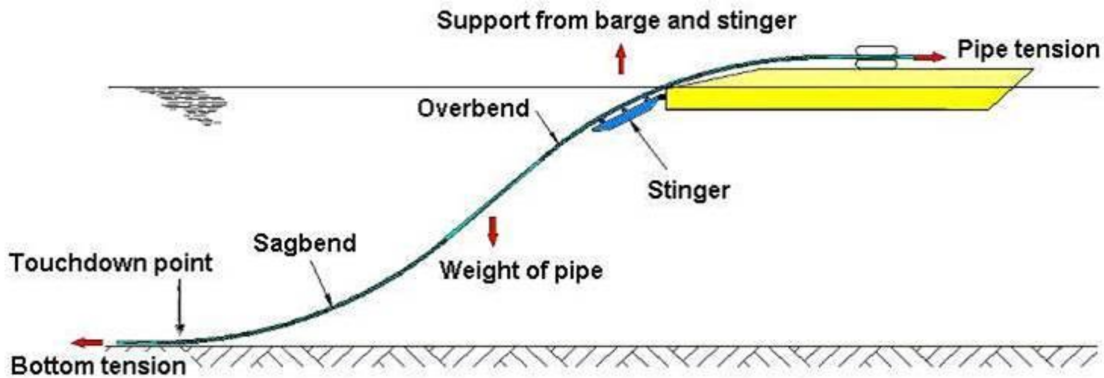
- Locally Damaged Pipe (Due to Plastic Buckling under High Hydrostatic Pressure and Bending)



<u>WT Design against Collapse not the Propagation</u>

- Collapse Propagation Pressure << Collapse Pressure
- Buckle Arrestor is Designed to Prevent
  - Collapse Propagation of Locally Damaged Pipe

Buckle Arrestor Design (Cont.)



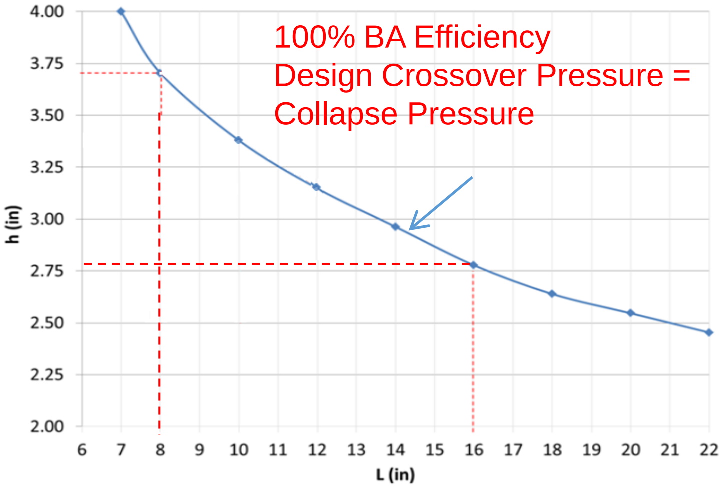
- Challenge is the Lay-Tension Requirement
  - For Ultra Deepwater (>5000 ft), Length of Catenary Line is Very Long ⟹ Very High Tension
- Catenary Length can be Reduced by Decreasing Stinger Radius
  - Smaller Stinger Radius ⟹ More Vertical Stinger angle ⟹ Less Tension
- However, Smaller Stinger Radius will Create High Strain During Installation
- Challenge is to Reduce High Strain at Knee by BA Design Modification
- Equally Important is to Reduce Stress at BA/Pipe Weld

Design BA to Minimize Stress/Strain During Installation Using Least Amount of Material & Higher Allowable Weld Flaw

Problem Statement

Why BA & Why Reliability?

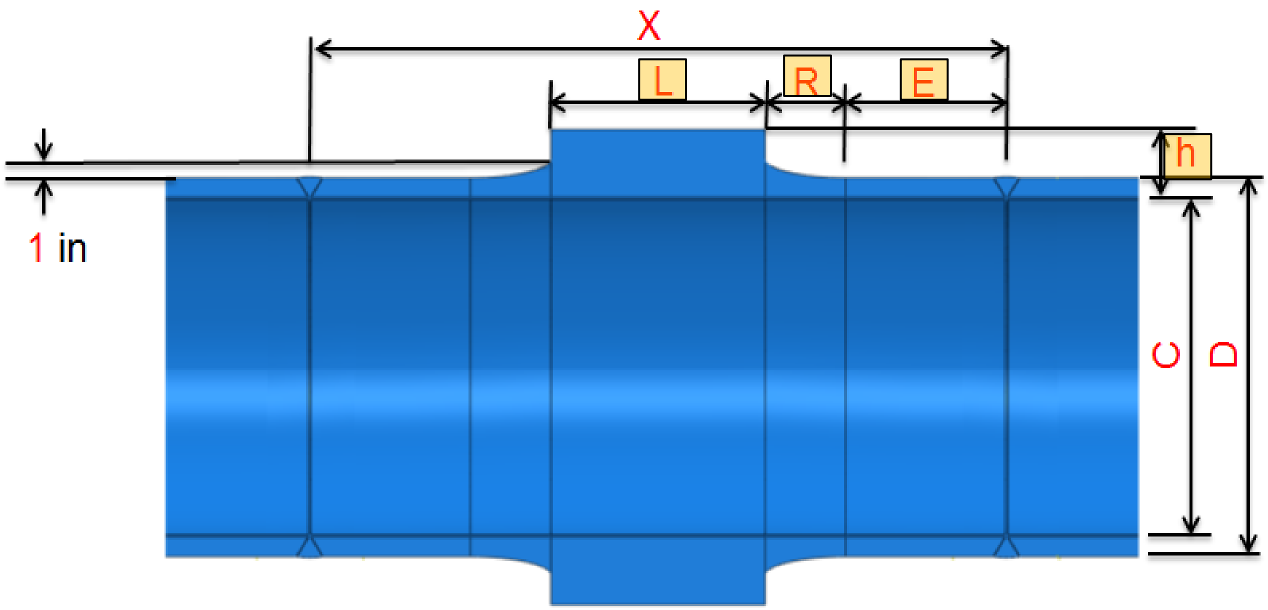
- High Strain at BA knee at installation (BA is designed for collapse pressure < crossover pressure)



  - Not all points on the curve is ok for knee strain and weld stress to be within functional limit– need design evaluation
- Used for installation check – unless variability is very small (not a realistic scenario) design can be marginal
- Loads, materials can be variable (weld mismatch, etc.)

Problem Statement (Cont.)

Initial Design Dimensions



Design Variables

h (in)	R (in)	C (in)	D (in)	E (in)	L (in)	X (in)
3.25	4	16	19	8	12	38

Problem Statement (Cont.)

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Loads, Materials (Mean Values)

❖Pipe & BA Material Properties

- Yield Strength: 65.3 ksi
- Ultimate/Yield Ratio: 1.15

❖Weld Material Properties

- Yield Strength: 70.3 ksi
- Ultimate/Yield Ratio: 1.15

Bi-linear Stress-Strain Curve is Used

Tension (kip)	Bending Moment (kip-ft)
820	686

Problem Statement (Cont.)

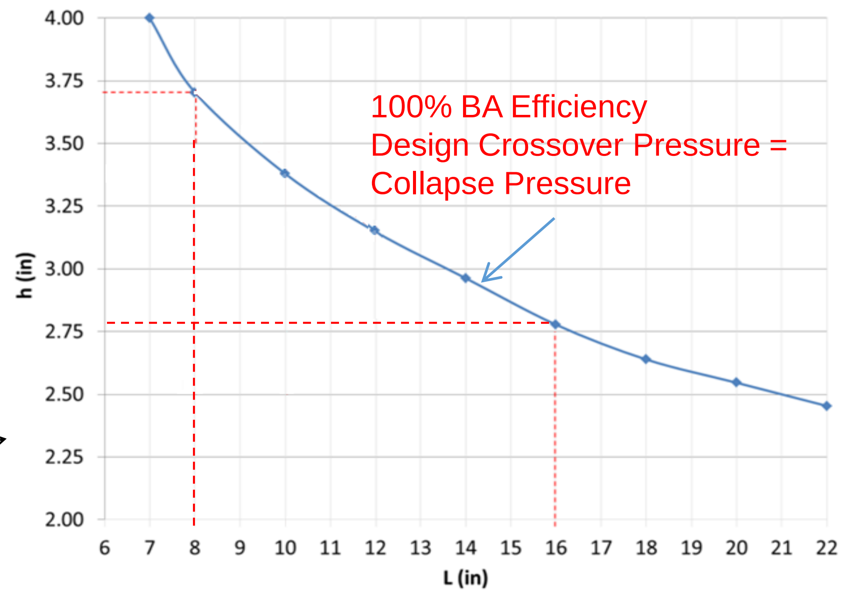
Optimization

Objective:

- **Minimize BA Volume g(E, R, L, h)**
- **Allowable Flaw Size**

Design Variables (Deterministic):

- 8" ≤ E ≥ 12"
- 8" ≤ L ≥ 16"
- 1" ≤ R ≥ 4"



Constraint (Probabilistic):

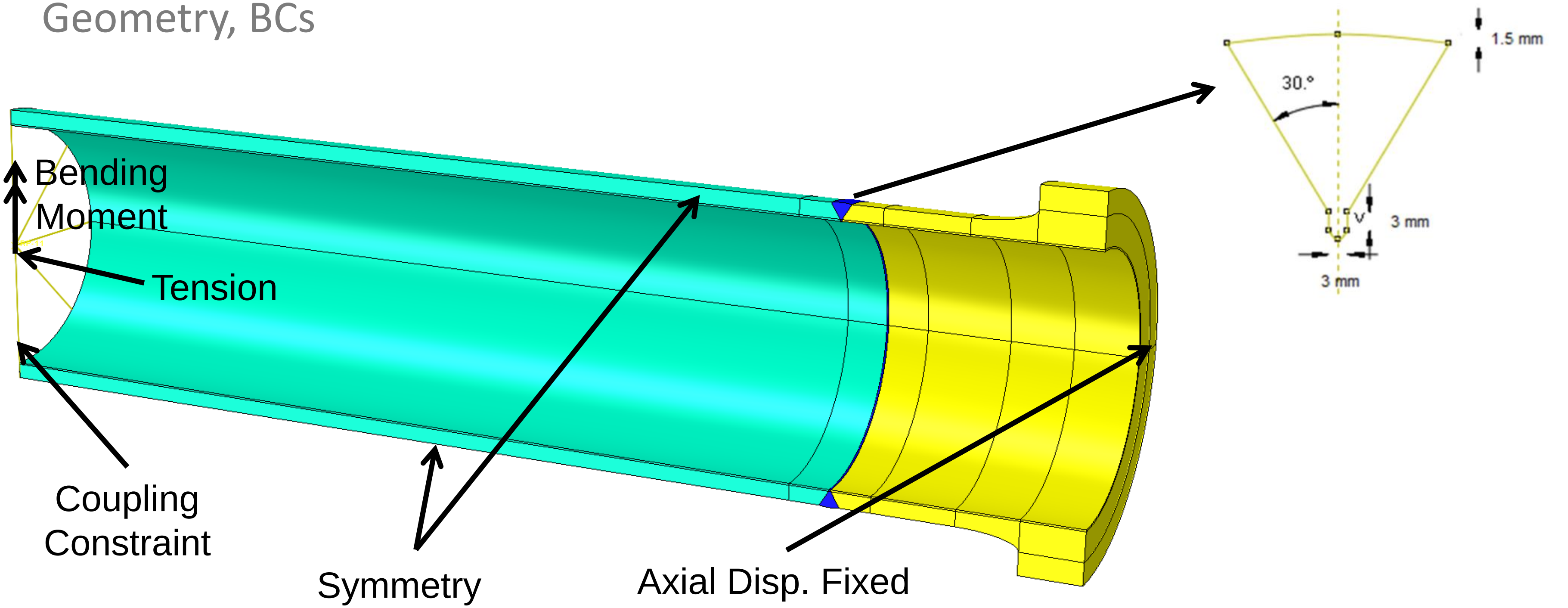
- P(Longitudinal Strain at BA Knee <= 0.005) = 0.95
- P(Longitudinal Stress at Weld <= 73 ksi) = 0.95

Random Variables:

- RV = {Pipe, BA, and Weld Material Yield Strength & Ultimate/Yield Ratio, Tension, Bending Moment}
  Normally Distributed with Mean & COV

FE Model

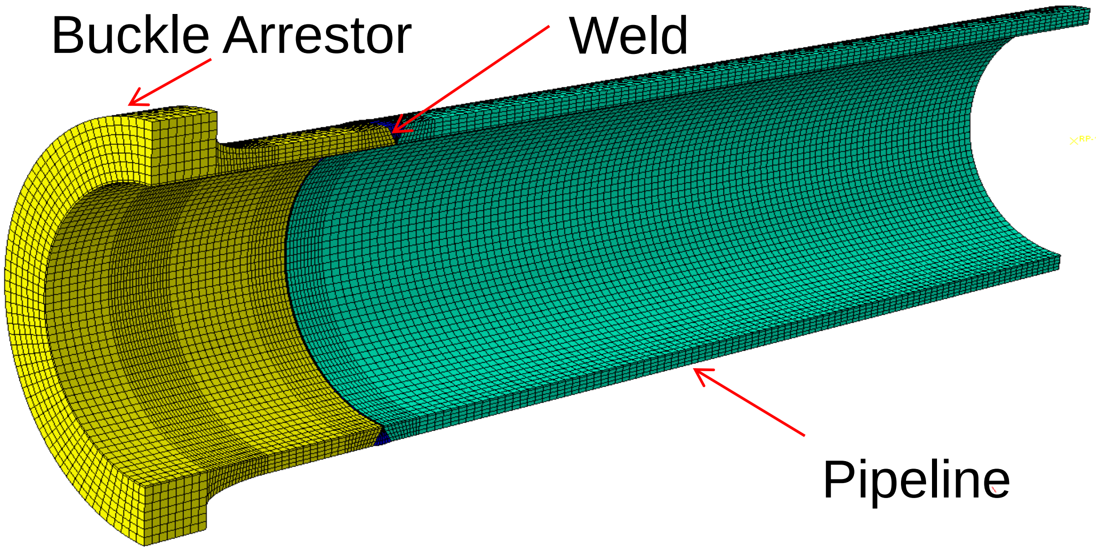
Geometry, BCs

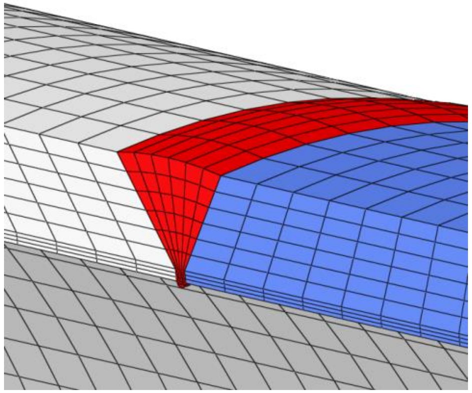


Load Controlled
Non-Linear Geometry
180° Quarter-Model

FE Model (Cont.)

Mesh

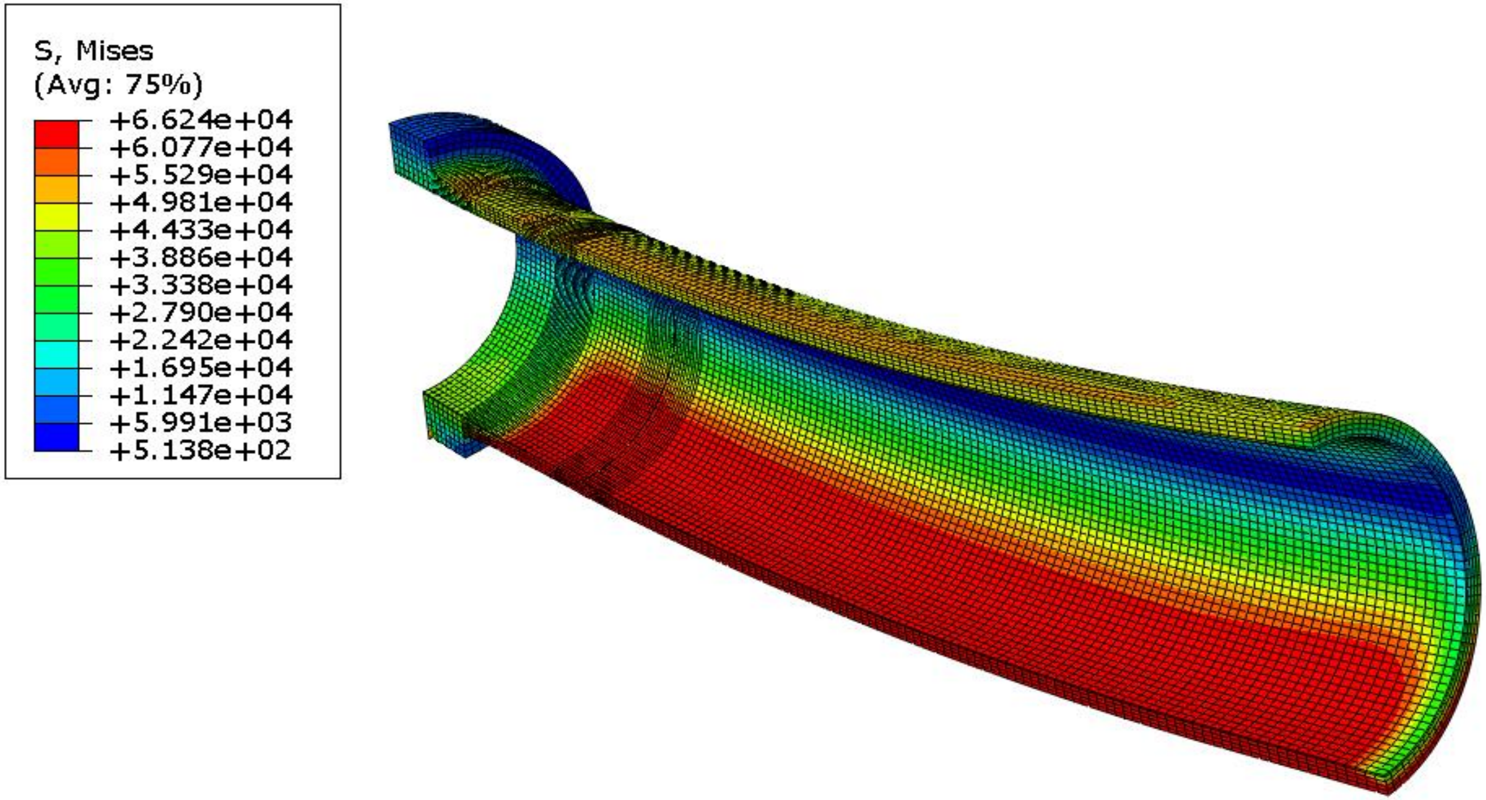




Parameter	Value
Element Type	C3D8R
No. of Elements	50940
Computational Cost	10 minutes/run

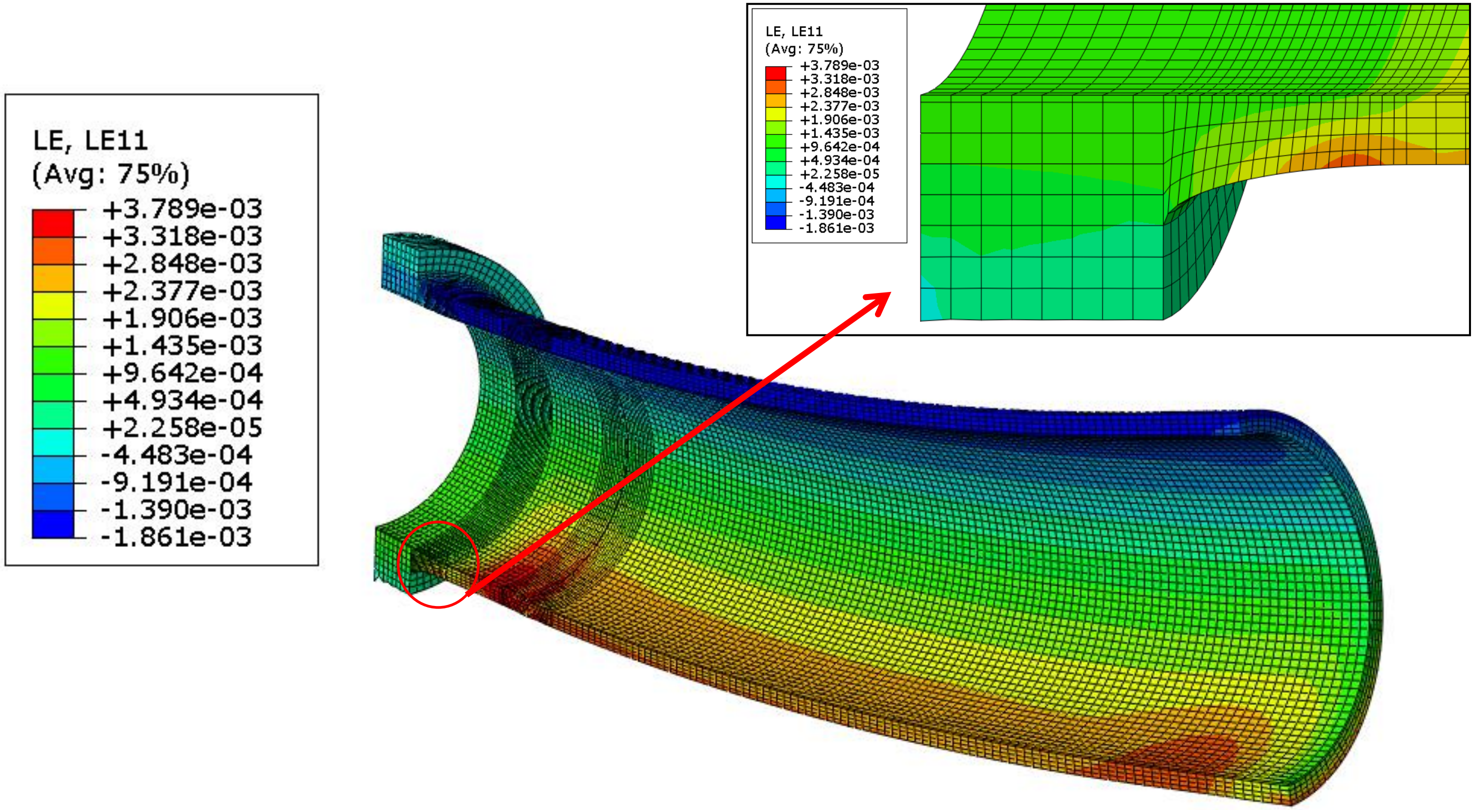
FE Model (Cont.)

Von Mises Stress



FE Model (Cont.)

Longitudinal Strain at BA Knee



FE Model (Cont.)

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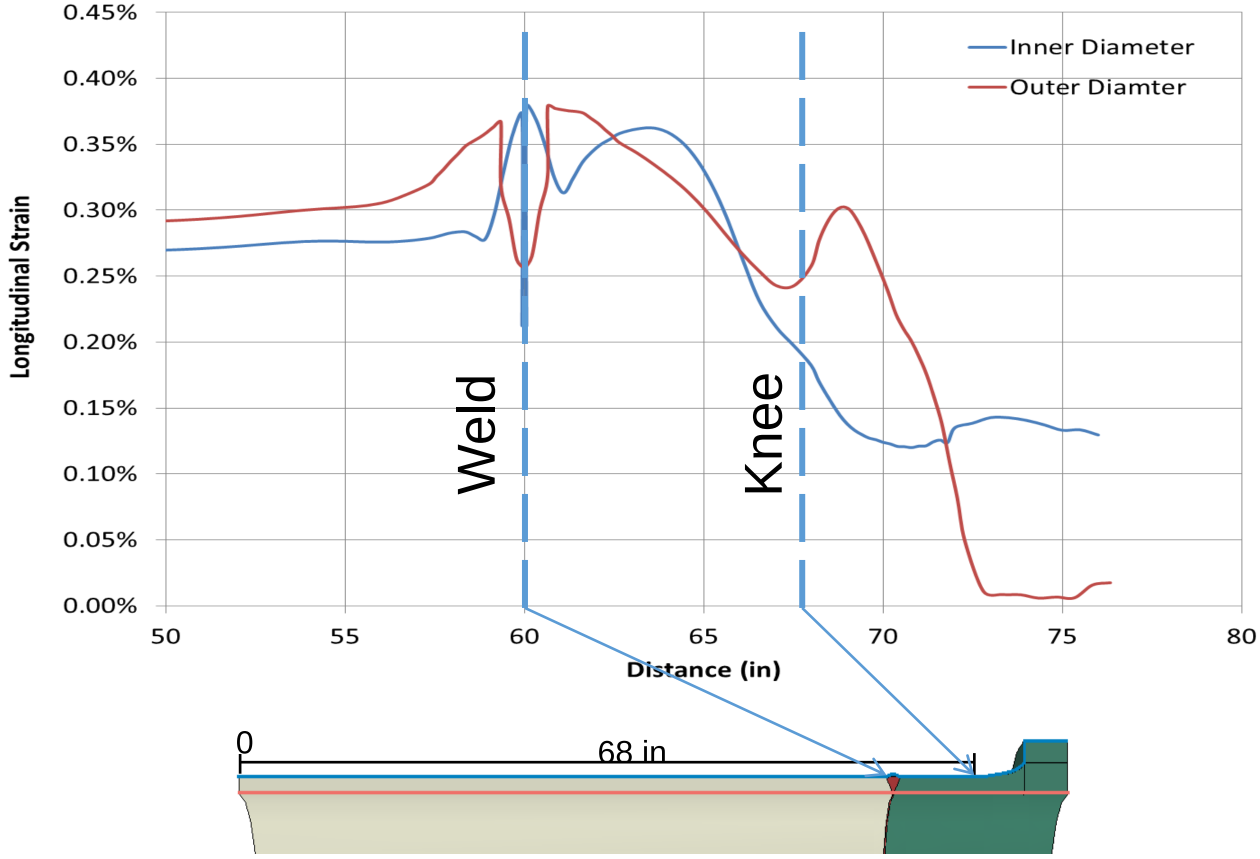
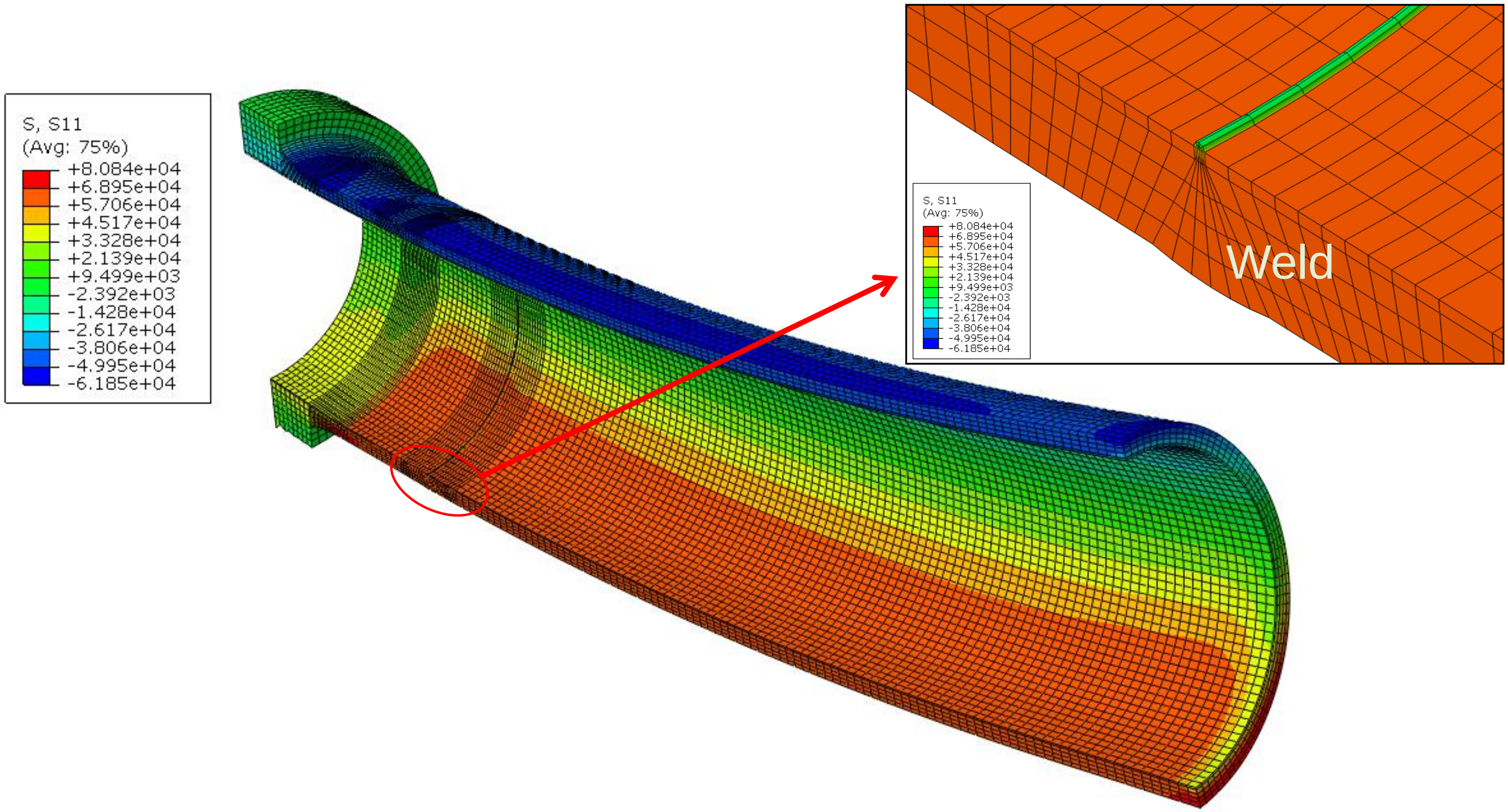
Longitudinal Strain Plot



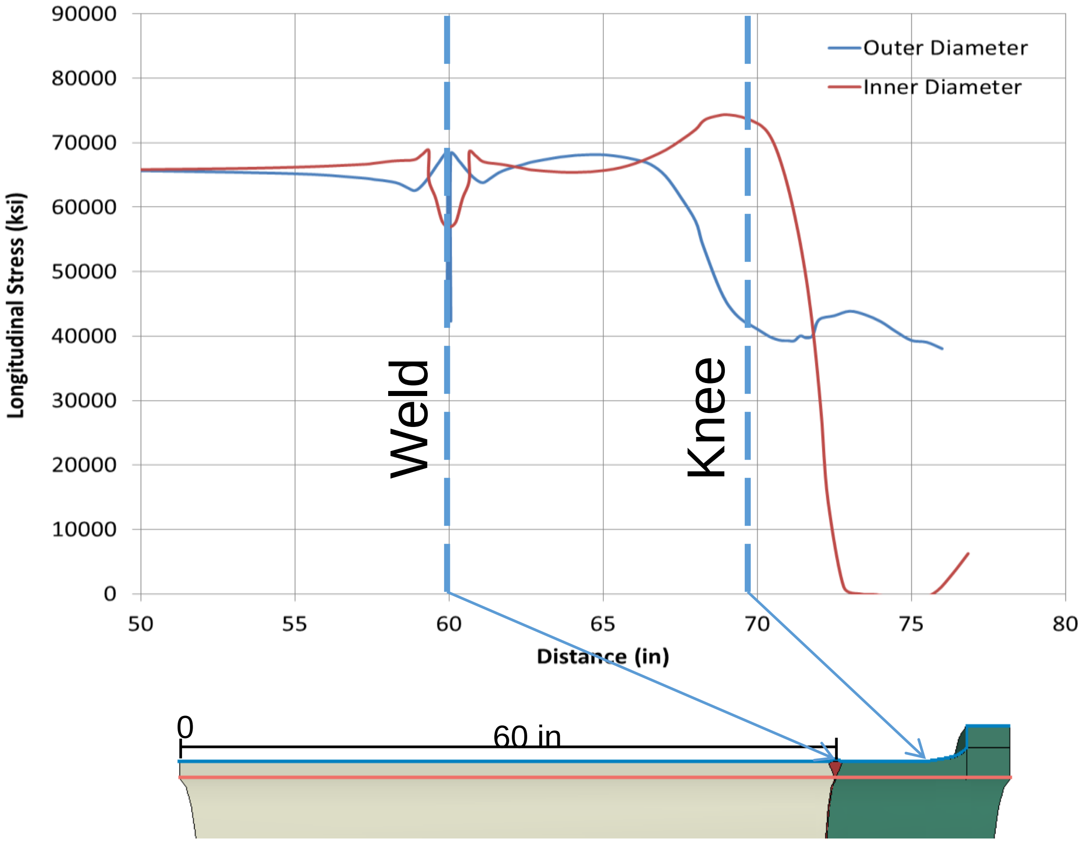
FE Model (Cont.)

Longitudinal Stress at Weld



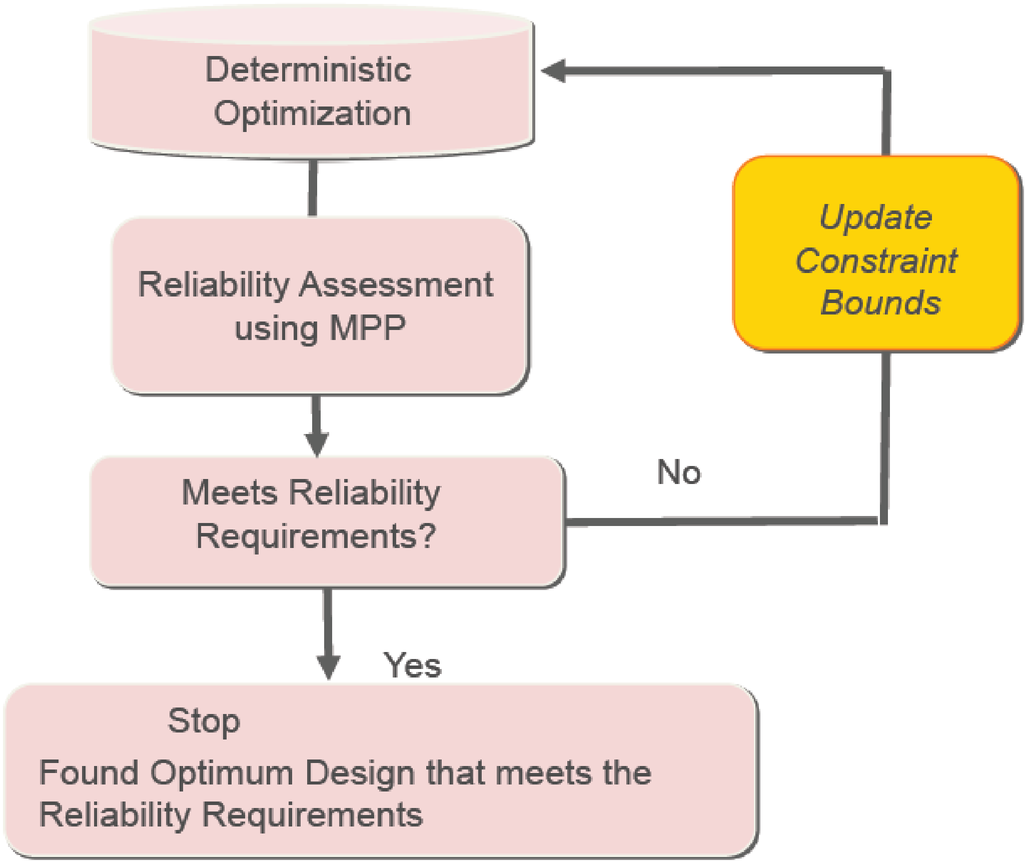
FE Model (Cont.)

Longitudinal Stress Plot



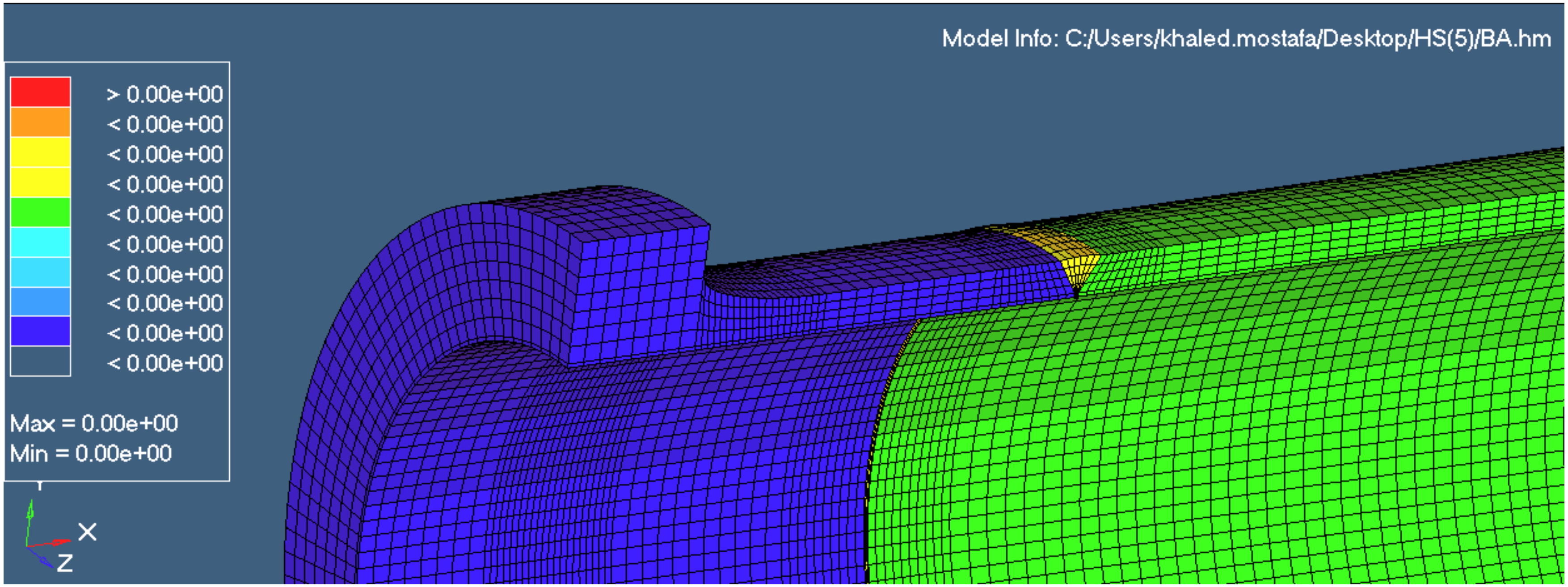
RBDO Model

SORA



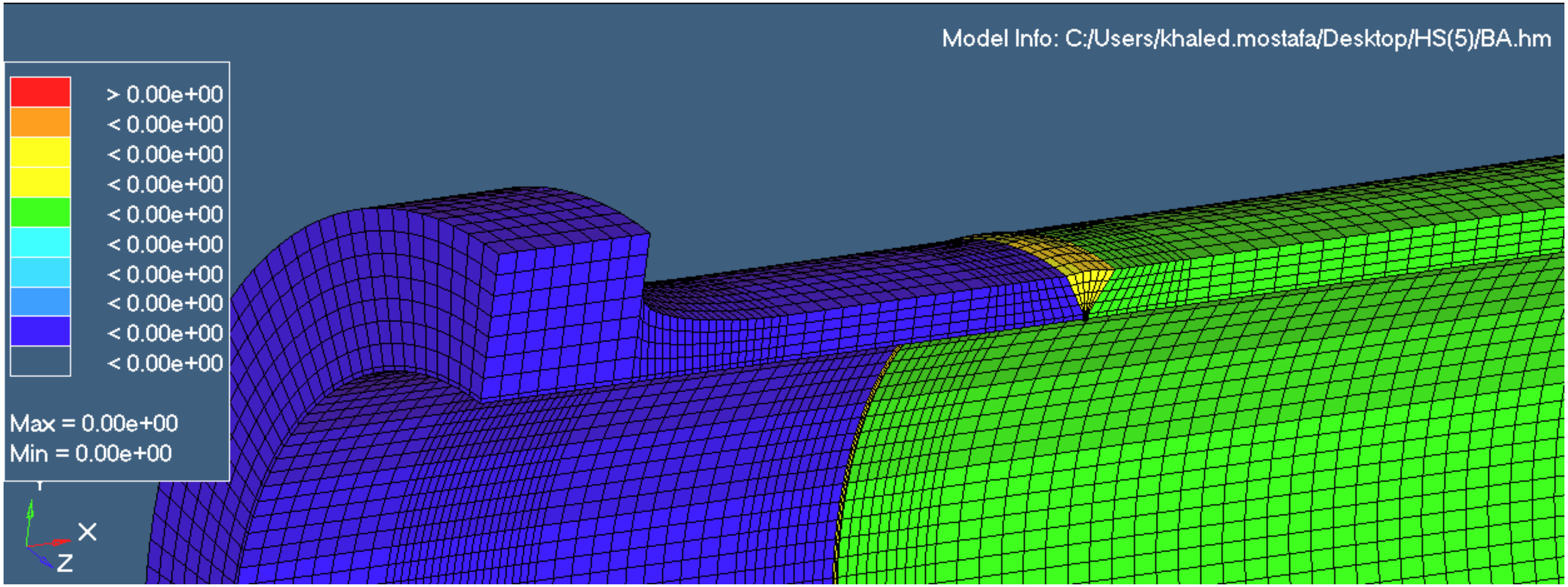
RBDO Model

Design Variable – E



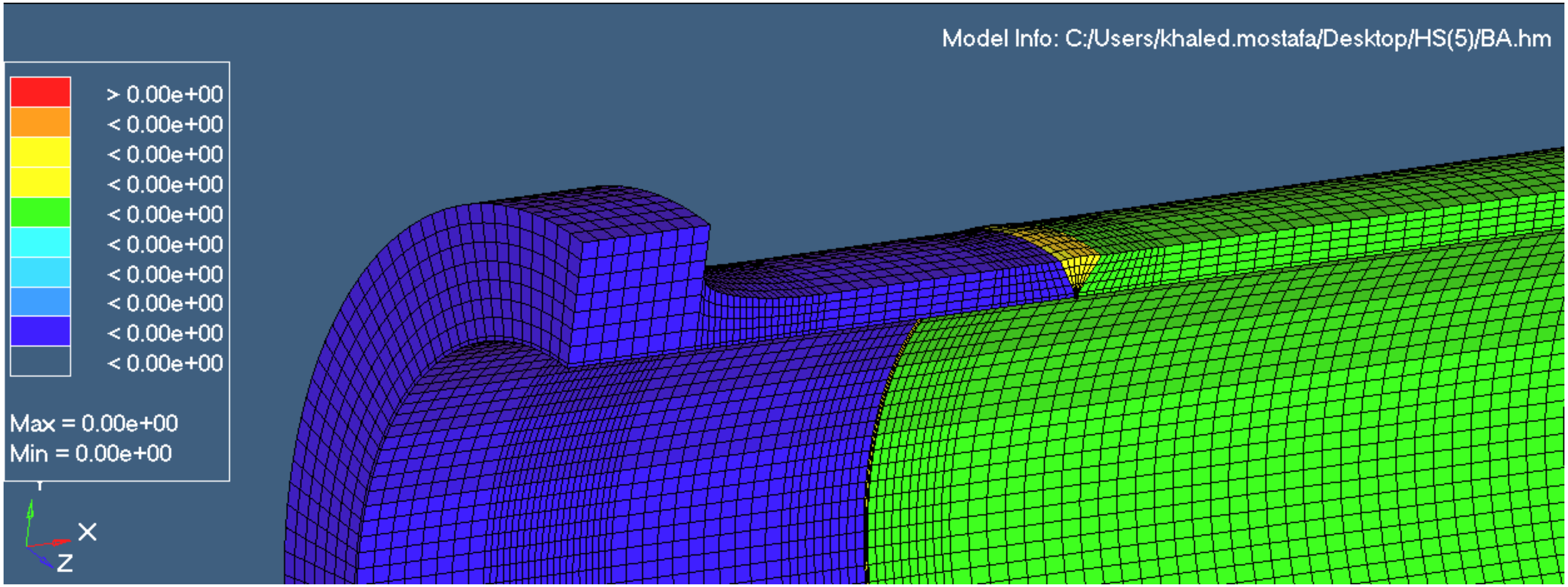
RBDO Model

Design Variable – L



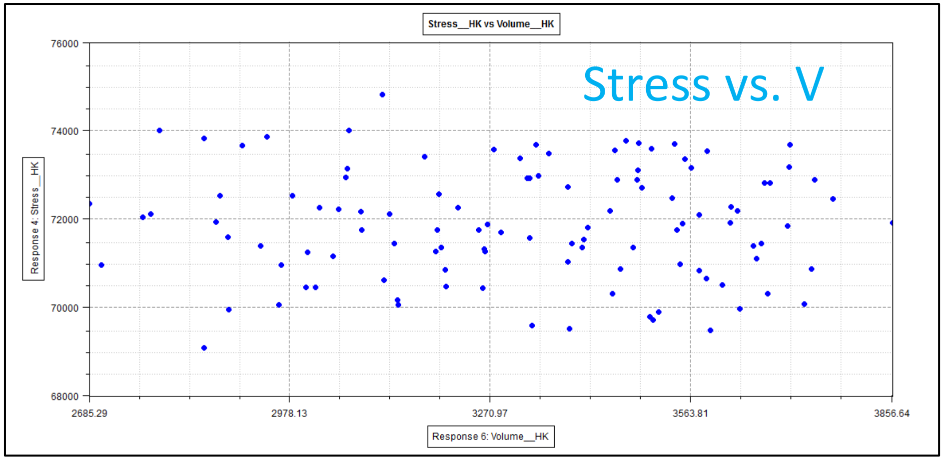
RBDO Model

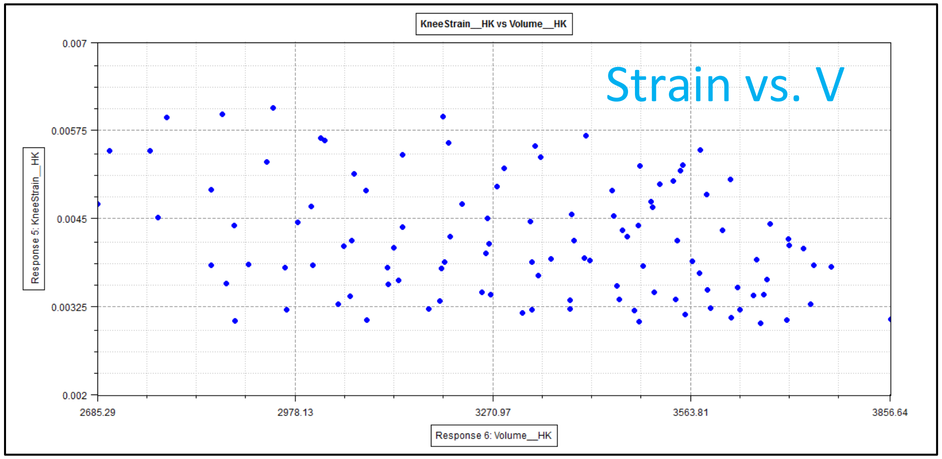
Design Variable – R



Results & Conclusions

Randomness in Response

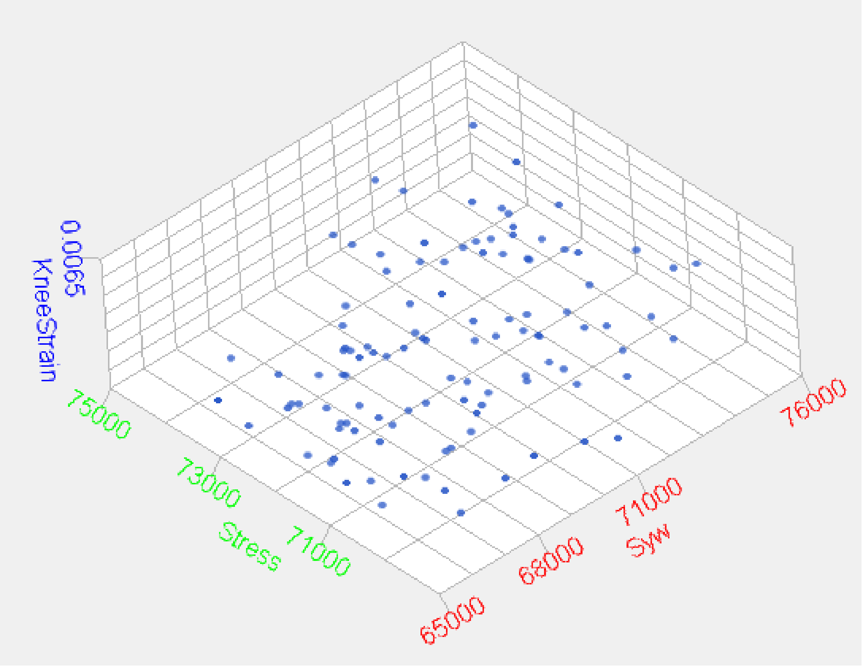




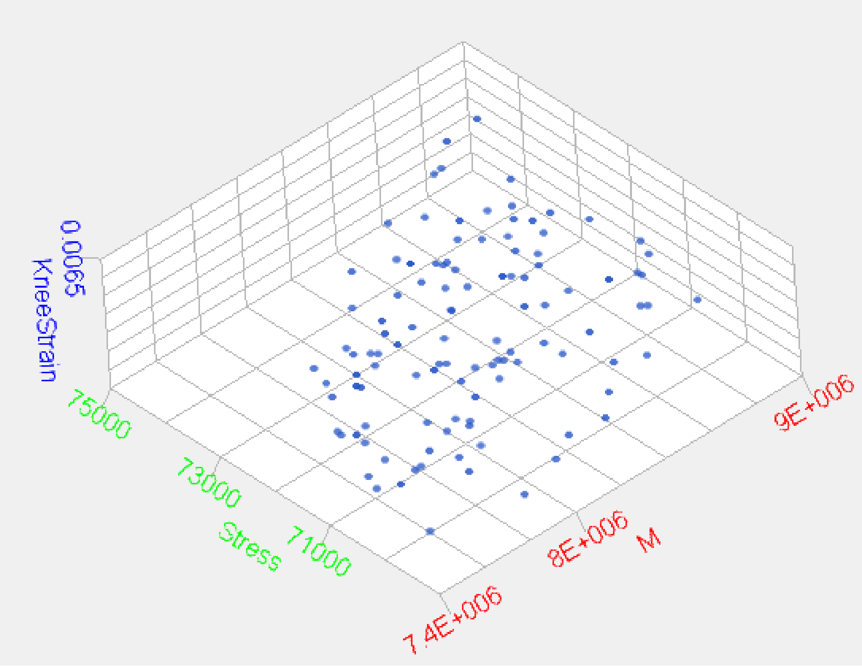
Results & Conclusions

DOE (Hammersley – 110 Runs)

Stress-Strain-Material



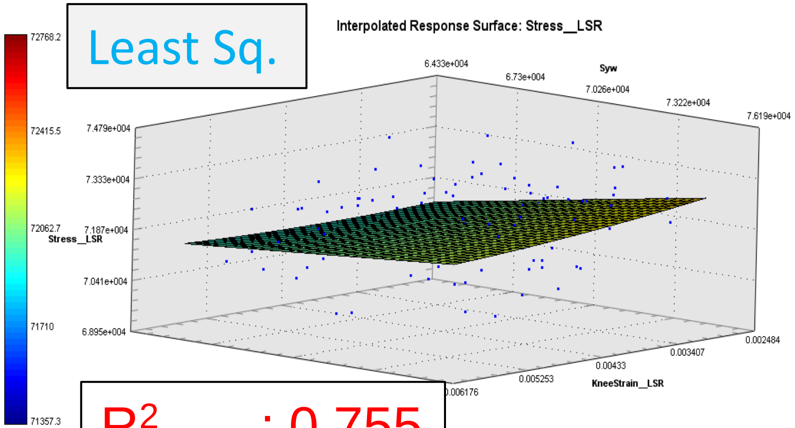
Stress-Strain-Load



Results & Conclusions

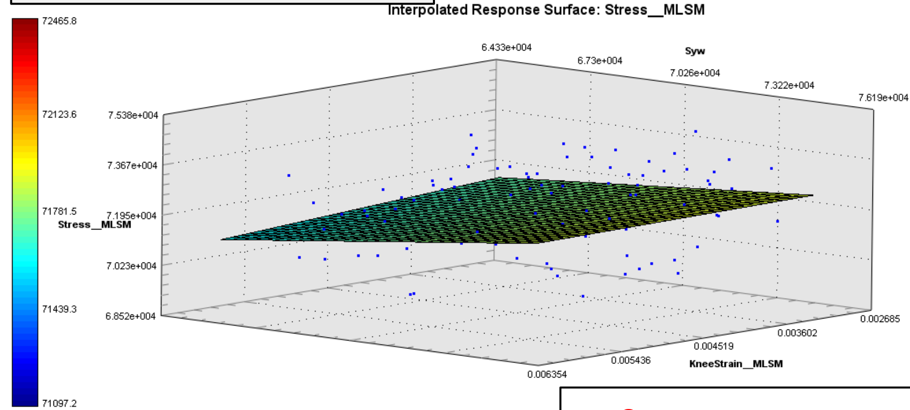
Approximation (HK)

Least Sq.



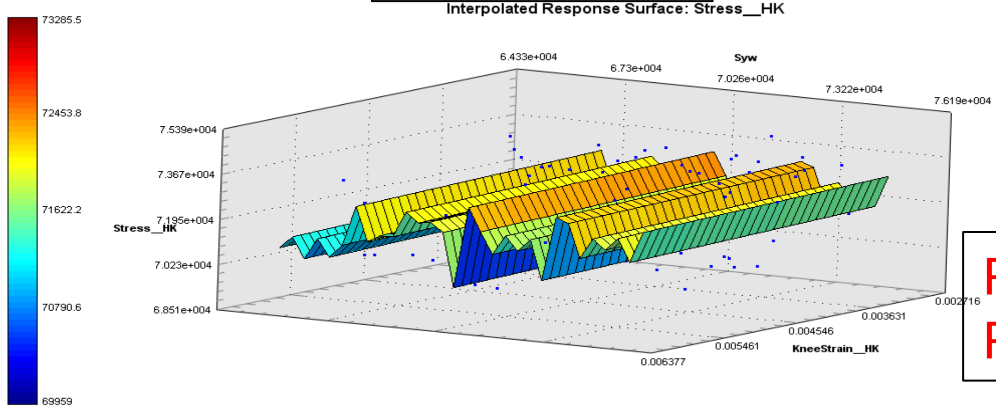
R^2_{Stress}: 0.755
R^2_{Strain}: 0.964

Moving Least Sq.



R^2_{Stress}: 0.987
R^2_{Strain}: 0.998

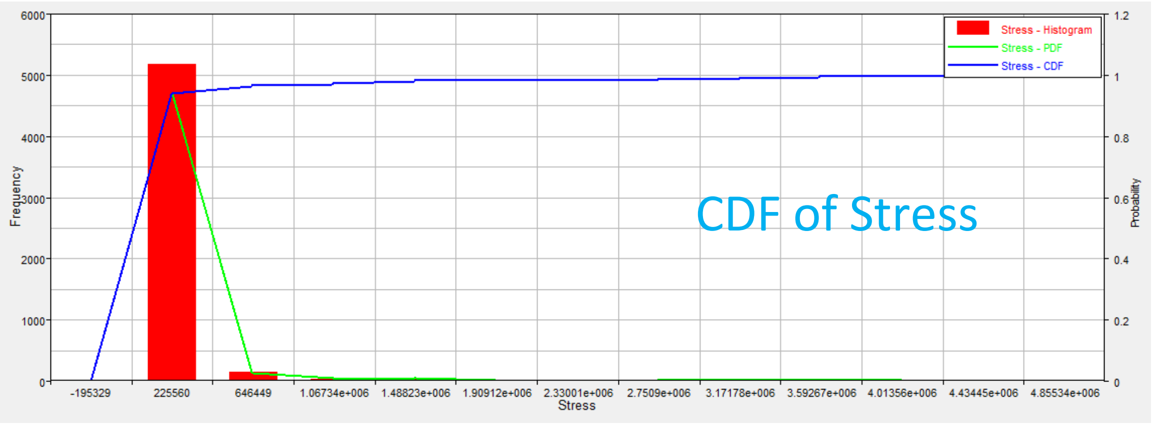
HyperKriging

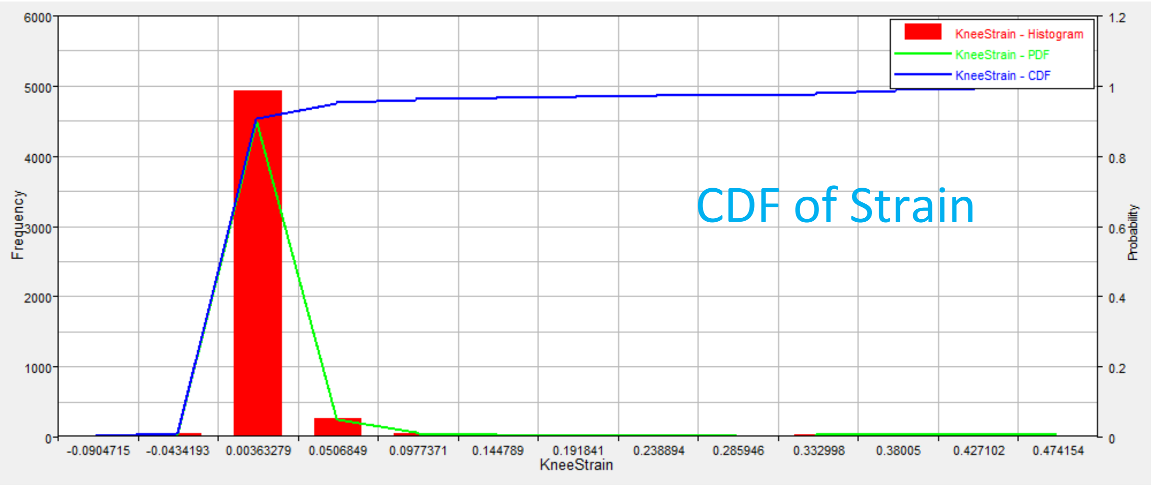


R^2_{Stress}: 0.998
R^2_{Strain}: 0.999

Results & Conclusions

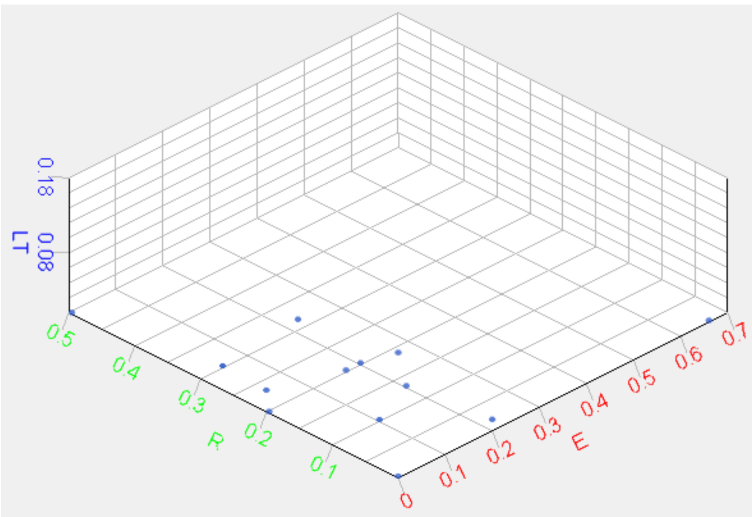
Reliable Design (SORA) – Probabilistic Constraint





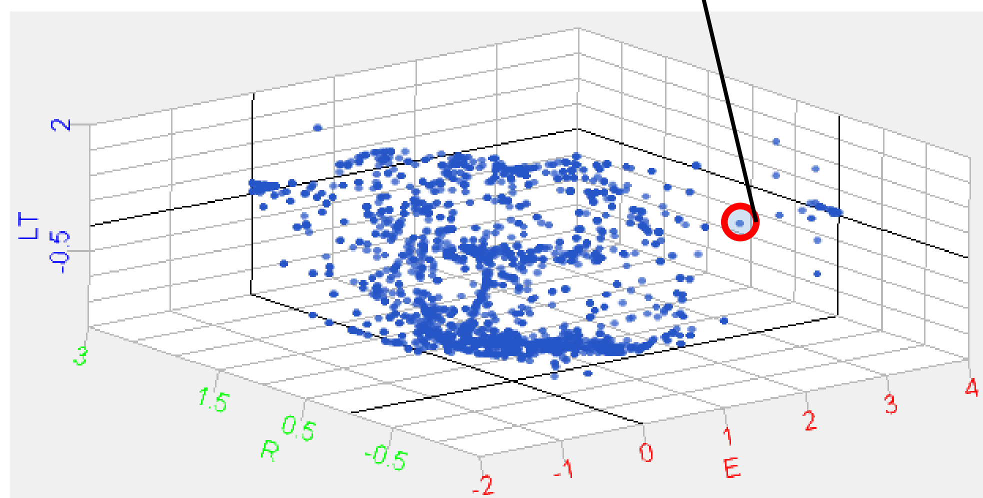
Results & Conclusions

Computational Demand



Deterministic (ARSM)

Failure Prob. Calculated at each Design Points

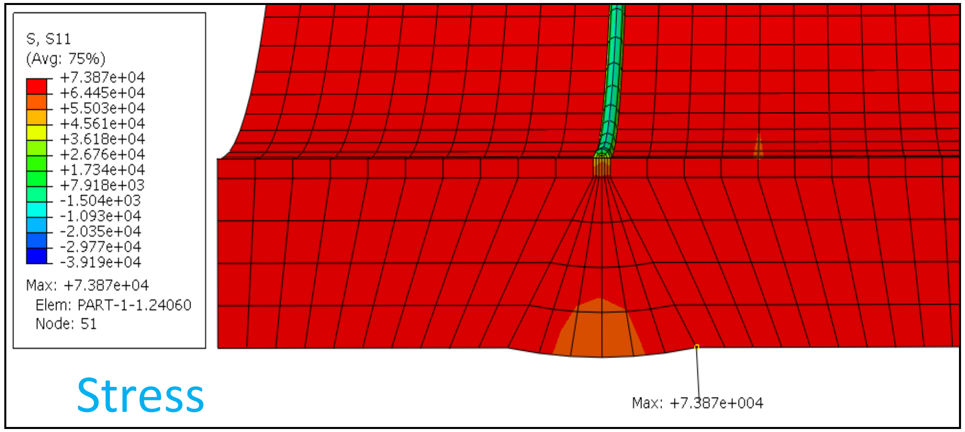


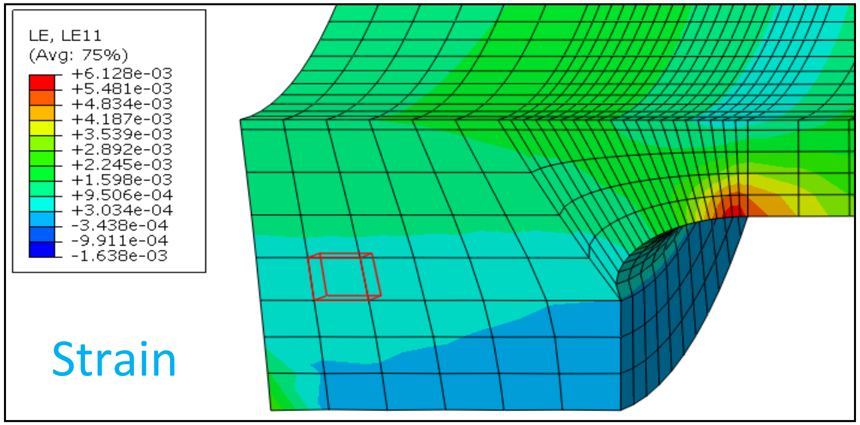
RBDO (SORA)

Results & Conclusions

Nominal Case

E (in)	R (in)	L (in)	T (in)	Volume (in^3)
8.6	1.4	10.0	3.4	2944.5

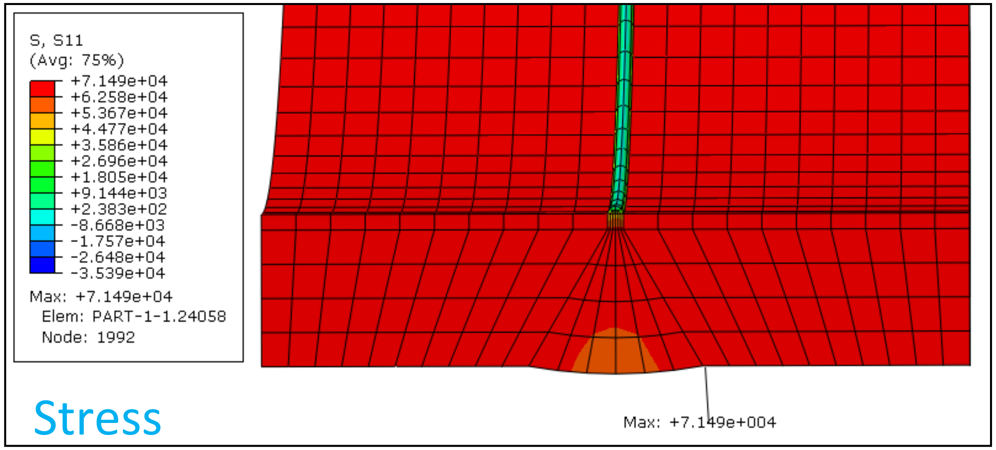


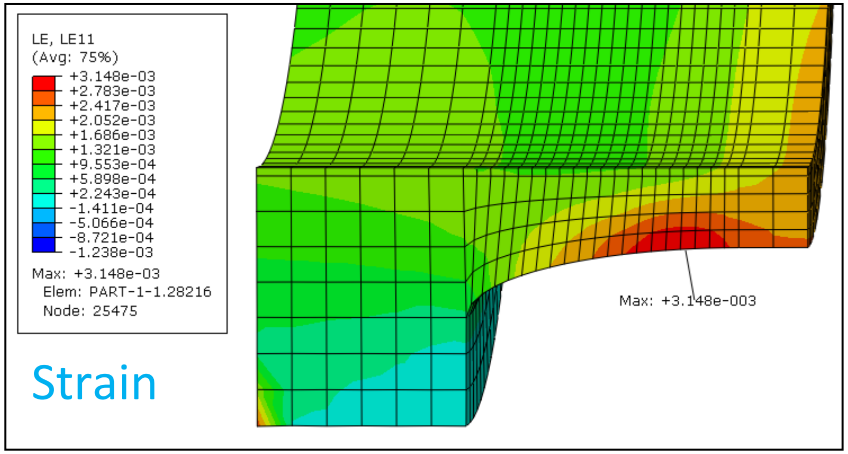


Results & Conclusions

Deterministic Optimum

E (in)	R (in)	L (in)	T (in)	Volume (in^3)
8.1	3.9	8.0	3.6	2796.8

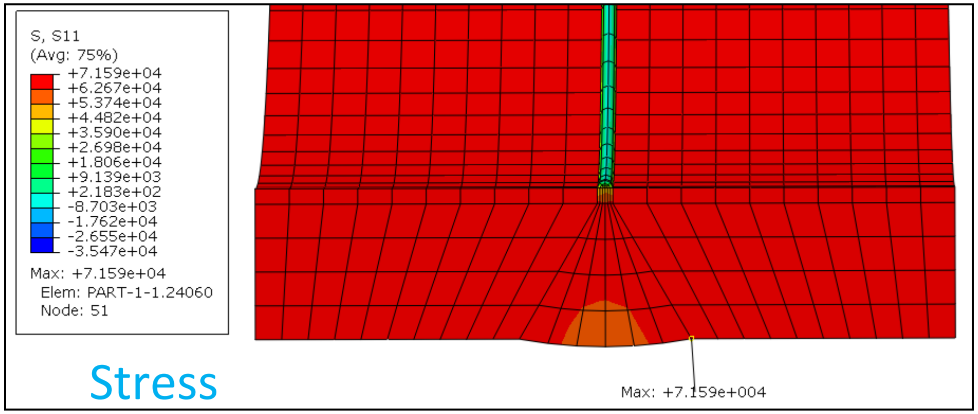


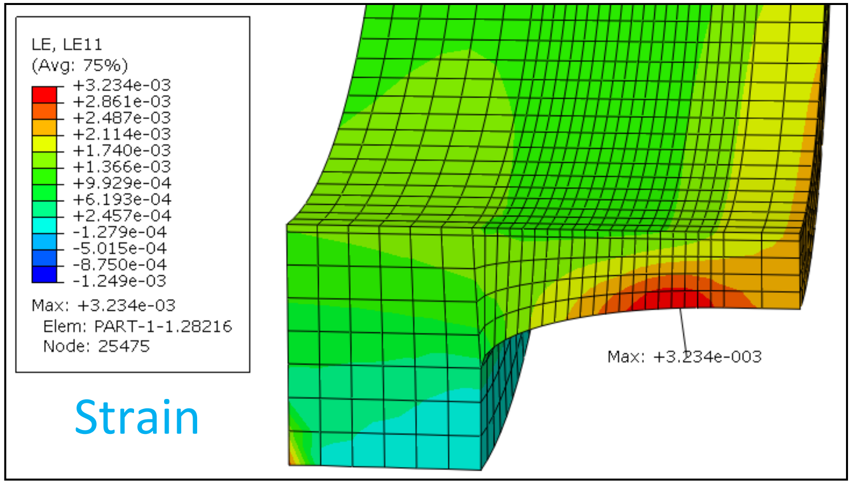


Results & Conclusions

Reliability Based Optimum

E (in)	R (in)	L (in)	T (in)	Volume (in^3)
9.0	3.7	8.0	3.6	2844.1





Results & Conclusions

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Optimized Designs

- Deterministic

E (in)	R (in)	L (in)	T (in)	Volume (in^3)
8.1	3.9	8.0	3.6	2796.8

- Reliability Based

RBDO requires more material but with higher reliability

E (in)	R (in)	L (in)	T (in)	Volume (in^3)
9.0	3.7	8.0	3.6	2844.1

Results & Conclusions

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Conclusions

- General Design Framework has been developed for design optimization
- Both deterministic & RBDO analysis of BA performed
- Problem captures bounded but deterministic design variables, uncertainty in input parameter values, complex input-output relationship
- Implicit problem involving FEA converted to an analytical problem (feasible to do stochastic)
- RBDO: more material required but decreased probability of failure compared to deterministic design

Questions?

Contact: arindam.chakraborty@woodgroupkenny.com

Thank You