October 21st, 2020

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Cost and Risk-Based Seismic Design Optimization of Safety-Related Nuclear Systems

DOE/NRC Natural Phenomena Hazards (NPH) Meeting
October 2020

Idaho National Laboratory

Acknowledgments

- DOE Office of Nuclear Energy (NE), and Office of Technology Transitions (OTT)
- Team
  - INL (Justin Coleman and William Hoffman)
  - UB (Andrew Whittaker, Kaivalya Lal, and Sharath Parsi)
  - X-Energy (Paul Kirchman and Harlan Bowers)
  - TerraPower (Michael Cohen and Kevin Kramer)
  - Southern Nuclear Development Company (Jason Redd)

Outline

- Motivation
- Cost- and risk-based design optimization
- Design optimization of a generic NPP safety system
  - Without component seismic isolation
  - With component seismic isolation
- Summary and conclusions

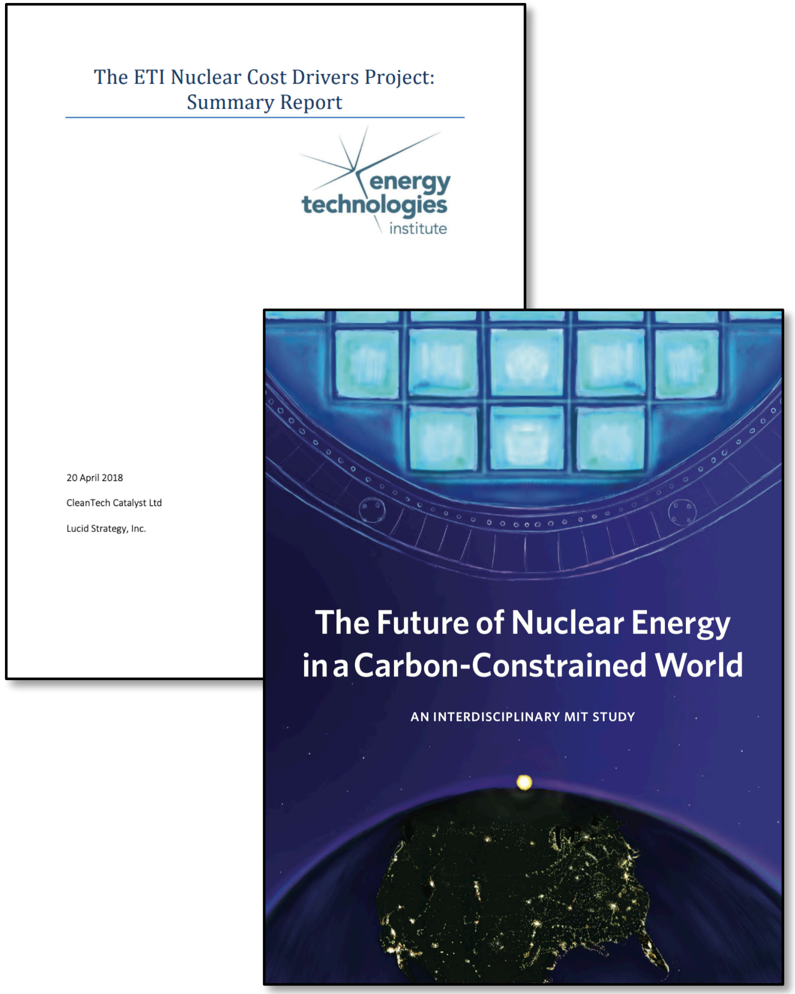
MASTODON

DAKOTA

Explore and predict with confidence.

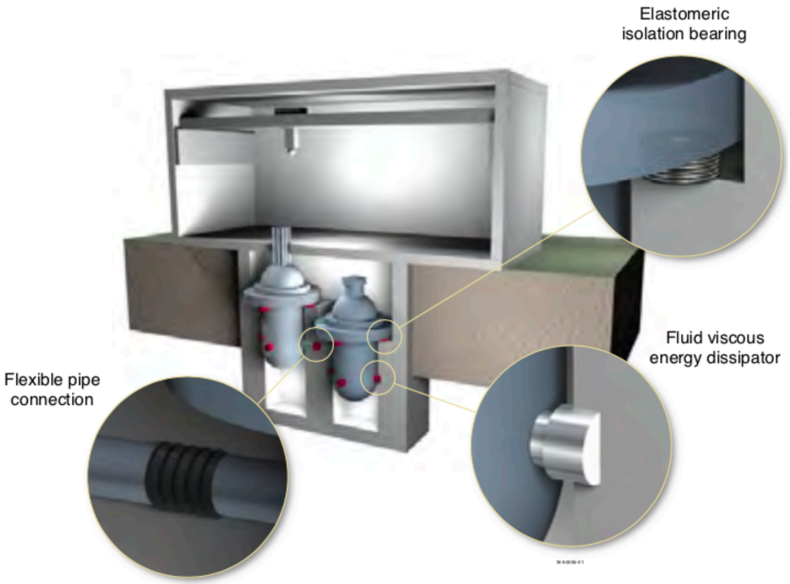
Economics of the nuclear industry

- Capital costs of new nuclear power plants are prohibitively high
  - commercial nuclear energy is uncompetitive
  - we need nuclear in the mix to meet climate change goals
- Major cost drivers are civil works (~50%), not the nuclear technology
- The role of seismic hazard
  - Up to 20-30% of capital costs
  - Most dominant factor for site-dependence
  - Barrier to design standardization

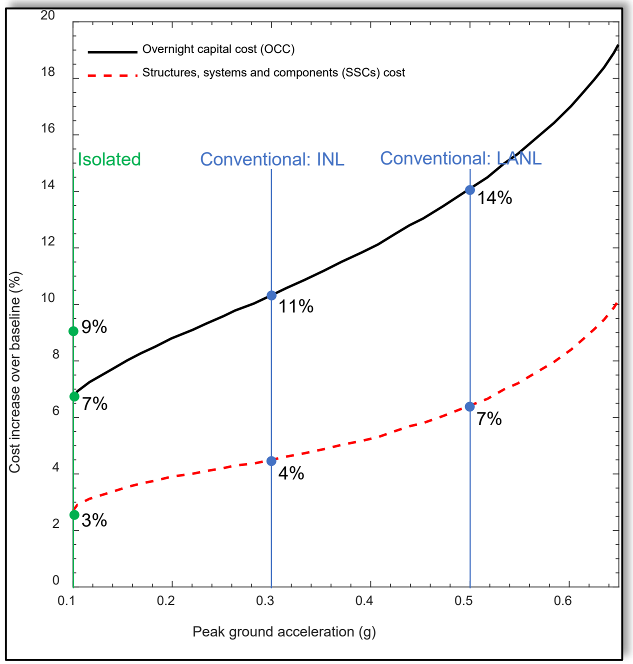


Solutions being pursued

- Reducing capital costs is currently a major focus for the nuclear industry
- Reduce conservatisms
  - NLSSI and advanced SPRA
- Seismic protective systems
  - Drastically reduce demands
  - Seismic isolation can enable standardization
- Design optimization using risk-based design
  - What is the optimal way to use all of the above?



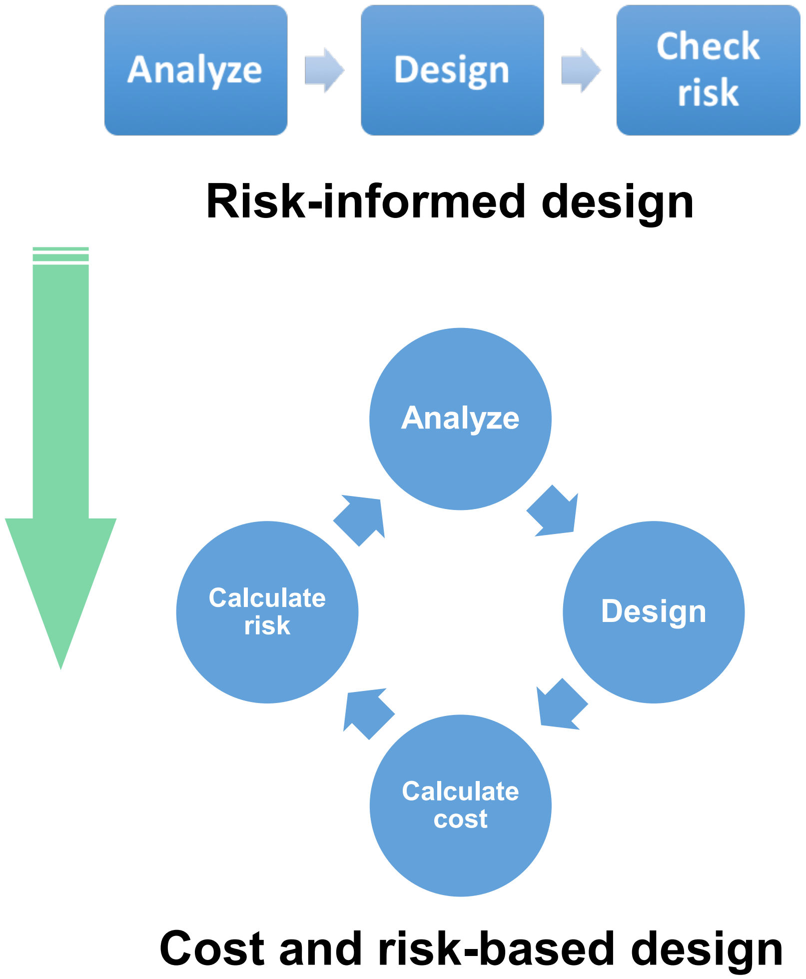
Kammerer et al., 2019



Yu et al, 2018

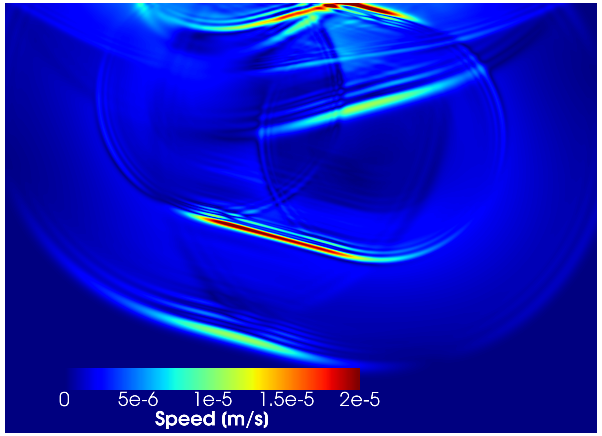
Cost and Risk-Based Design

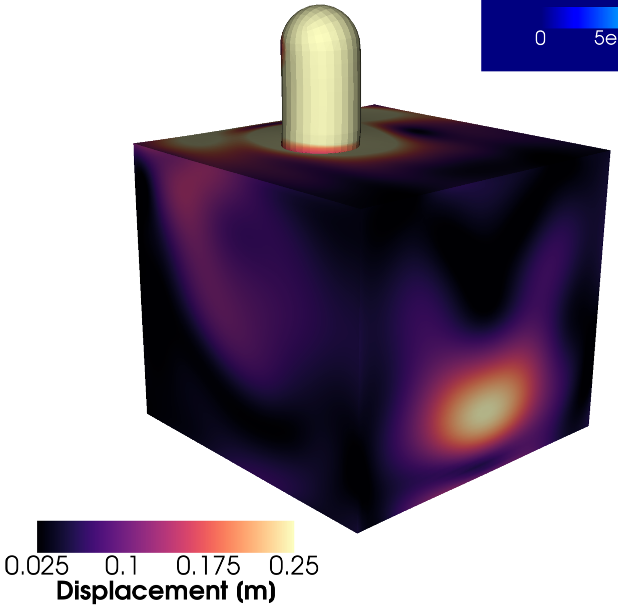
- Advance from risk-informed design to a risk-based design
- Optimize the design for both safety AND cost
- Enable strategic use of risk mitigation techniques such as seismic isolation and other energy dissipation mechanisms, as well as NLSSI modeling, to reduce capital cost while meeting safety goals
- Provide a ***decision-making*** tool and not a design tool



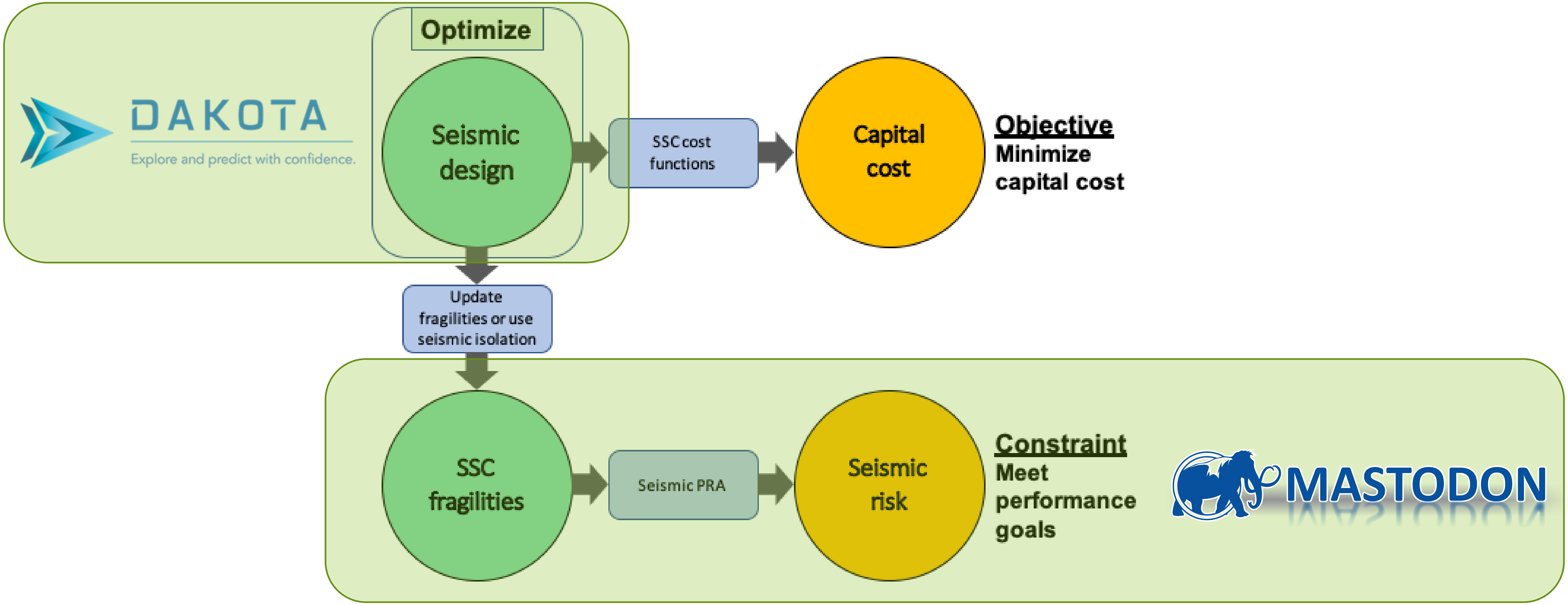
MASTODON

- Open-source code for seismic analysis and risk assessment
- MOOSE-based
  - Multi-physics platform
- Capabilities
  - Source-to-site simulation
  - Nonlinear site-response and soil-structure interaction
  - Automated SPRA including fault tree analysis
- Software quality assurance
  - ‘Documentation is code’
  - Towards NQA-1





Design optimization of safety systems



Design optimization of safety systems

- Use the SPRA and fault-tree analysis tools in MASTODON
- Optimization using the Genetic Algorithms available in Dakota (open source UQ code from Sandia National Laboratory)

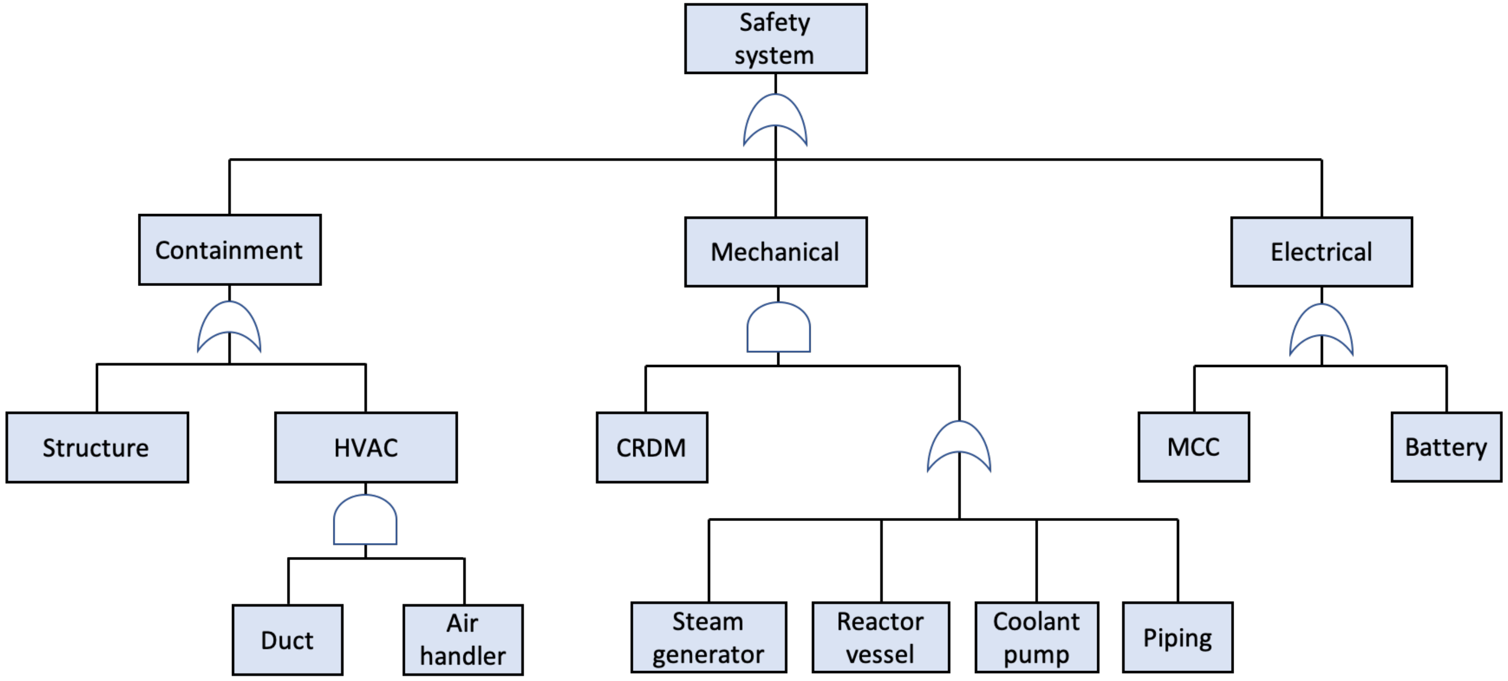
Inputs

- Safety goal (risk)
- Seismic fragilities (design)
- Approximate cost functions
  - Change in cost w/ design or the 'seismic penalty'
  - Seismic isolation cost

Outputs

- Optimized design
  - Optimal seismic capacities
  - Isolated SSCs
- Optimal capital cost
- Risk (automatically meets safety goal)

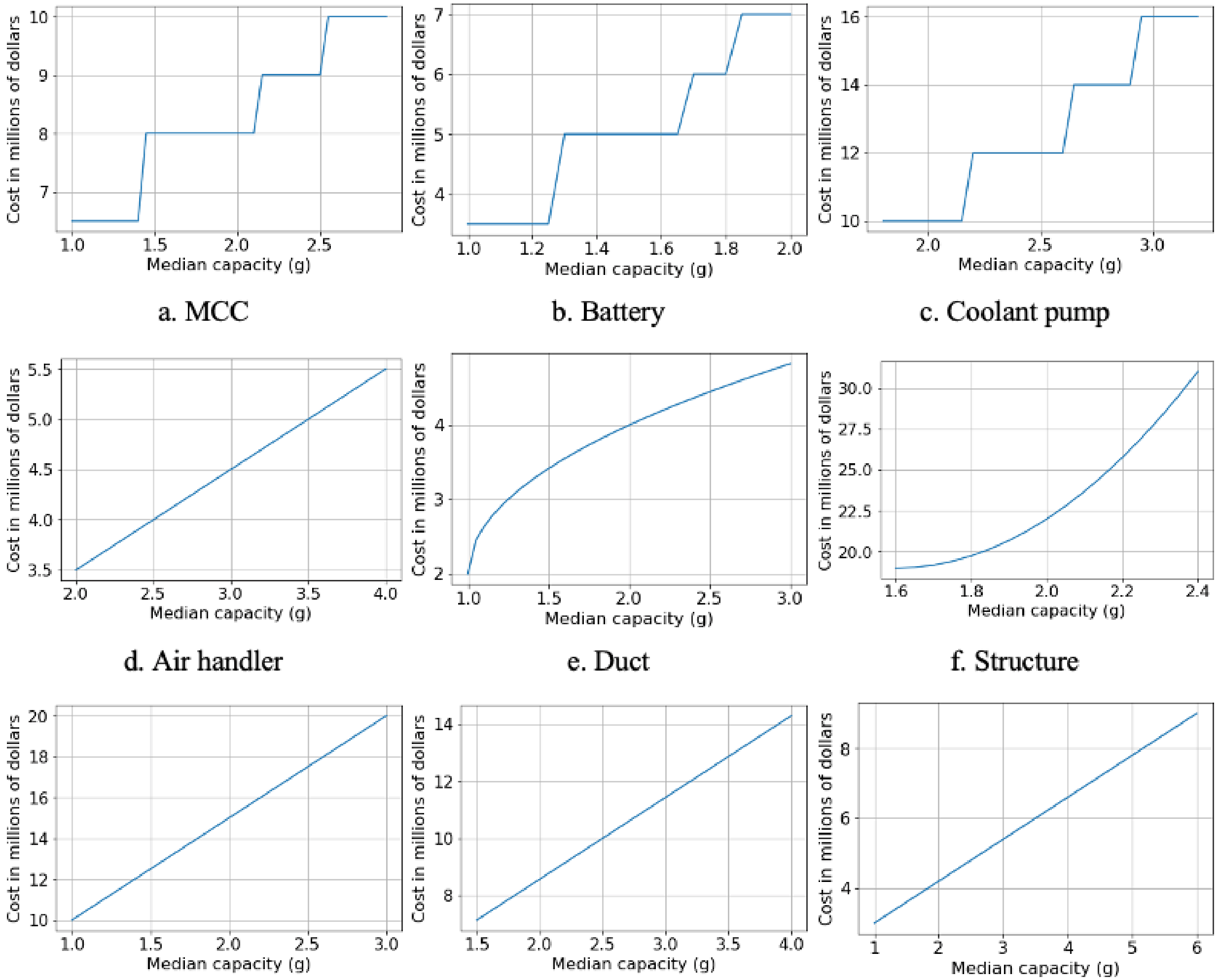
Demonstration for a generic nuclear facility



Initial seismic risk = 5.2×10^{-05}
Performance goal = 5×10^{-05}

- Representative fragilities from EPRI SPRA guide
- Fragilities are functions of GM parameter
  - Therefore, structural analysis is NOT performed
- **10** basic events and **8** minimal cutsets
- System risk = System fragility convolved with hazard curve
- Using INL site hazard curve

Cost data and cost functions



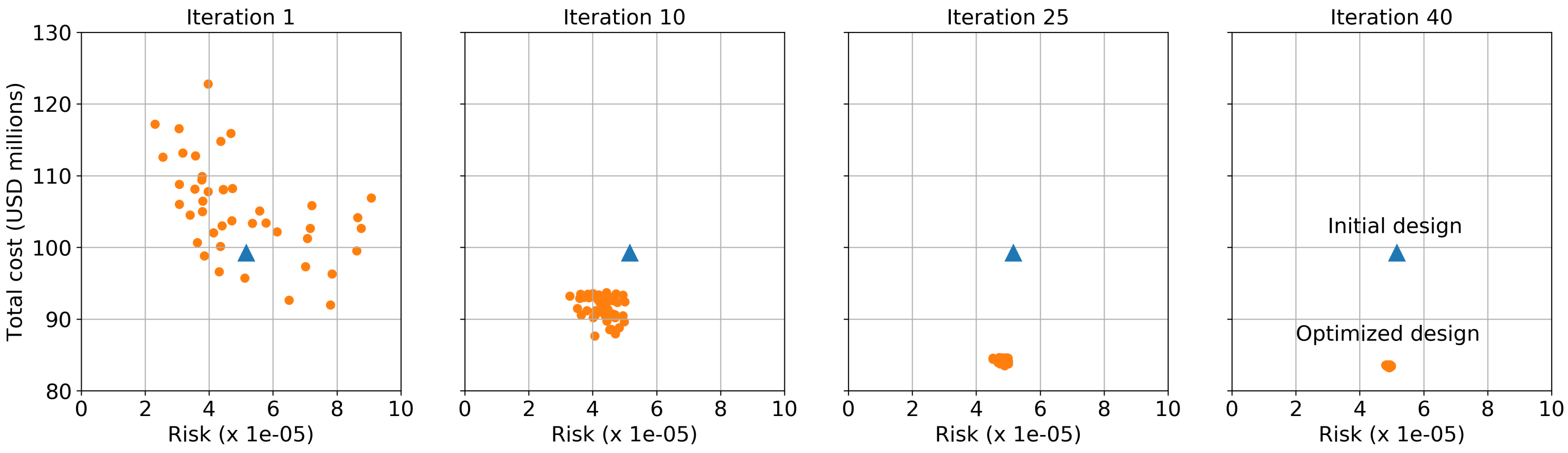
a. MCC b. Battery c. Coolant pump
d. Air handler e. Duct f. Structure
g. Reactor vessel h. Steam generator i. CRDM

- SSC cost vs. fragility
- No data available (except recent UB/EPRI work)
- Need approximate data capturing
  - **trends** (slope) in seismic cost with seismic capacity
  - **range** of costs expected for the range of seismic hazard

Total initial cost = $99.2 million

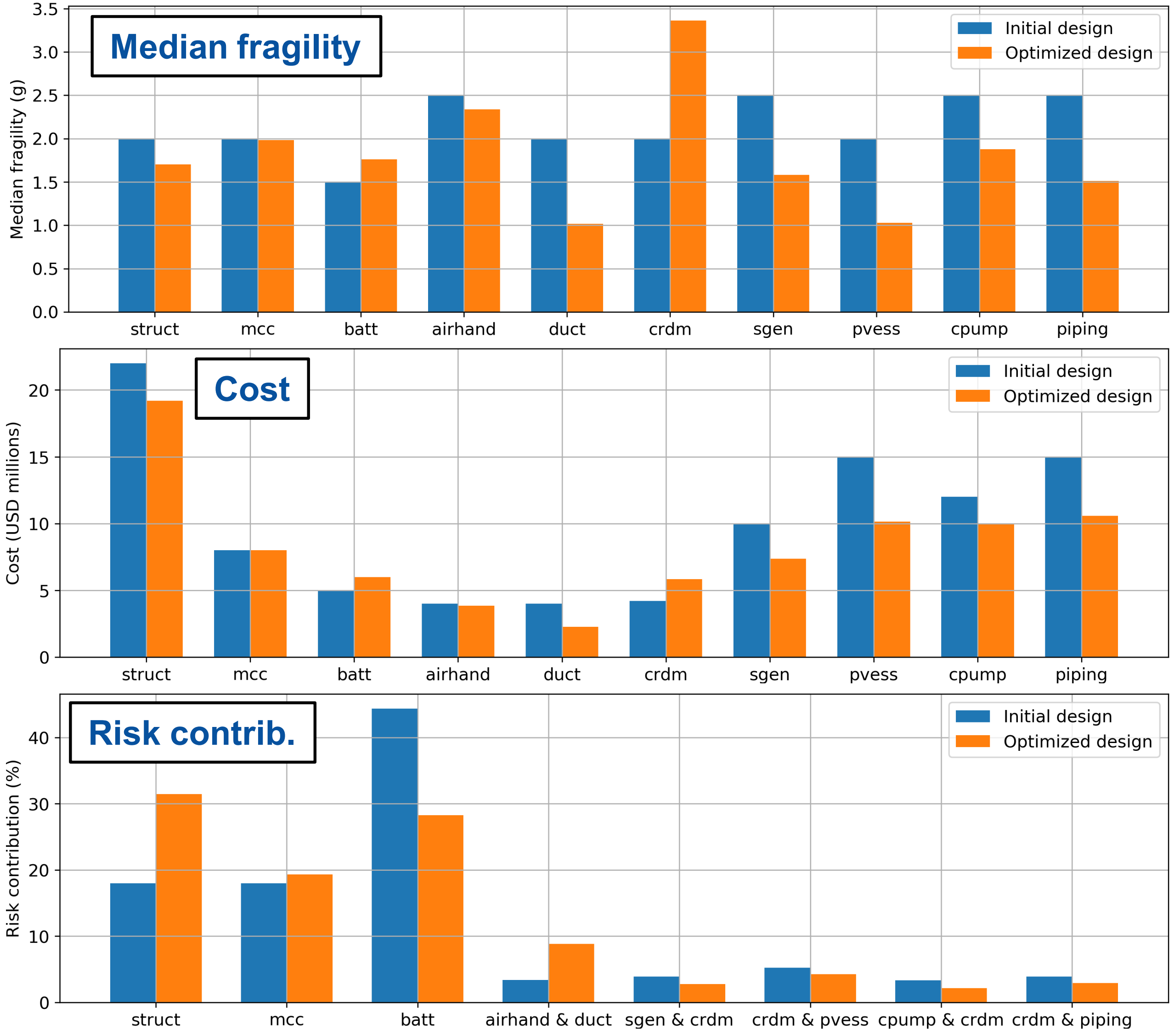
Results of the design optimization (without SI)

- Using a genetic algorithm in Dakota
  - Performs black box optimization and is well-suited for parallel computing
  - Well studied and widely implemented and used in engineering
  - Gives an ‘engineering optimum’ that is better than the initial design



	Capital cost	Seismic risk
Initial	\$99.2 M	5.2×10^{-5}
Optimized	\$83.2 M	4.9×10^{-5}

Results of the design optimization (without SI)

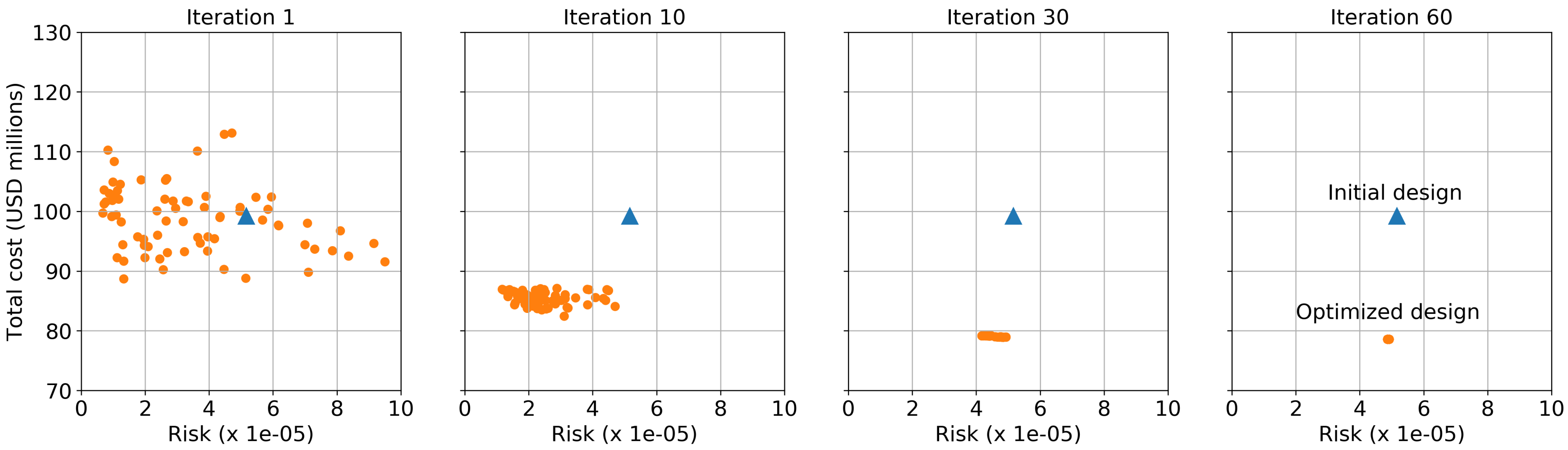


Key takeaways

- Rewarding redundancy
  - CRDM fragility increased and other NSSS components reduced
- Risk profile vs. cost profile
  - Increased risk contribution from the most expensive SSC

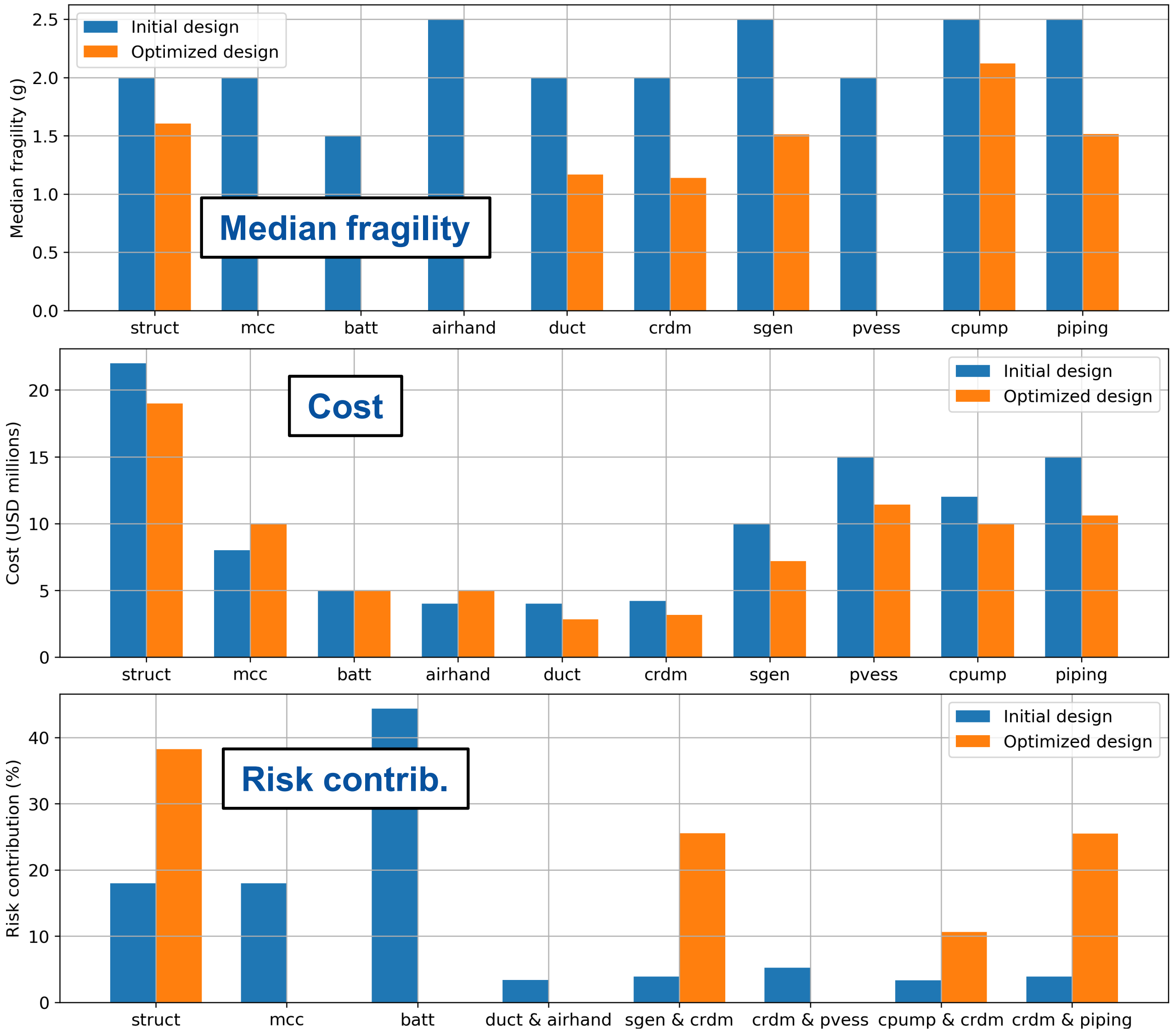
Results of the design optimization (with SI)

- Which components should be isolated for minimum capital cost?
  - SSC isolation added as a binary variable in the genetic algorithm
  - Not all SSCs can be isolated
  - Assuming almost zero probability of failure when SSC is isolated
  - Isolation cost of an SSC is 10% of its capital cost



	Capital cost	Seismic risk
Initial	\$99.2 M	5.2×10^{-5}
Optimized	\$78.6 M	4.9×10^{-5}

Results of the design optimization (with SI)



Key takeaways

- Isolate: MCC, battery, air handler, and pressure vessel
- Risk is redistributed in the non-isolated systems (not always a good thing)

Summary

- Real design can be complex, but intelligent ‘fine-tuning’ can result in significant cost savings
- Optimization doesn’t need accurate cost data – approximate cost data that capture the ranges and trends will suffice (e.g., UB/EPRI work)
- SSC isolation can provide capital cost reduction and flexibility
- Genetic algorithms provide a robust option for large-scale optimization of complex systems
- Design optimization is possible for complex systems and can be used as a ***decision-making*** tool, not a design tool

To radically reduce capital costs, we need innovation in balance of plant design procedures

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