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Optimizing Design for Resilience for Risk-Averse Firms Using Expected Utility and Value-at-Risk

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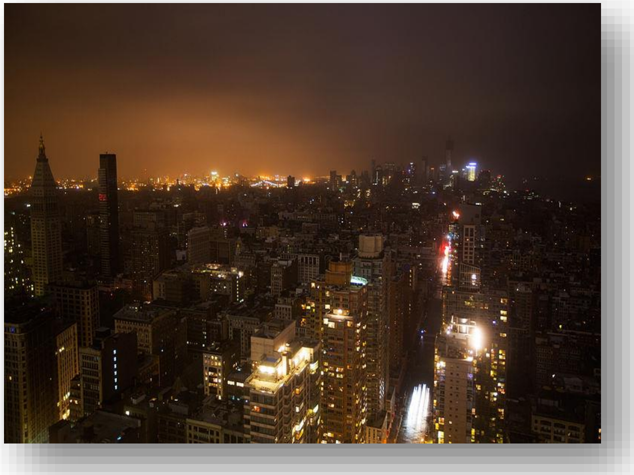
Adverse Events

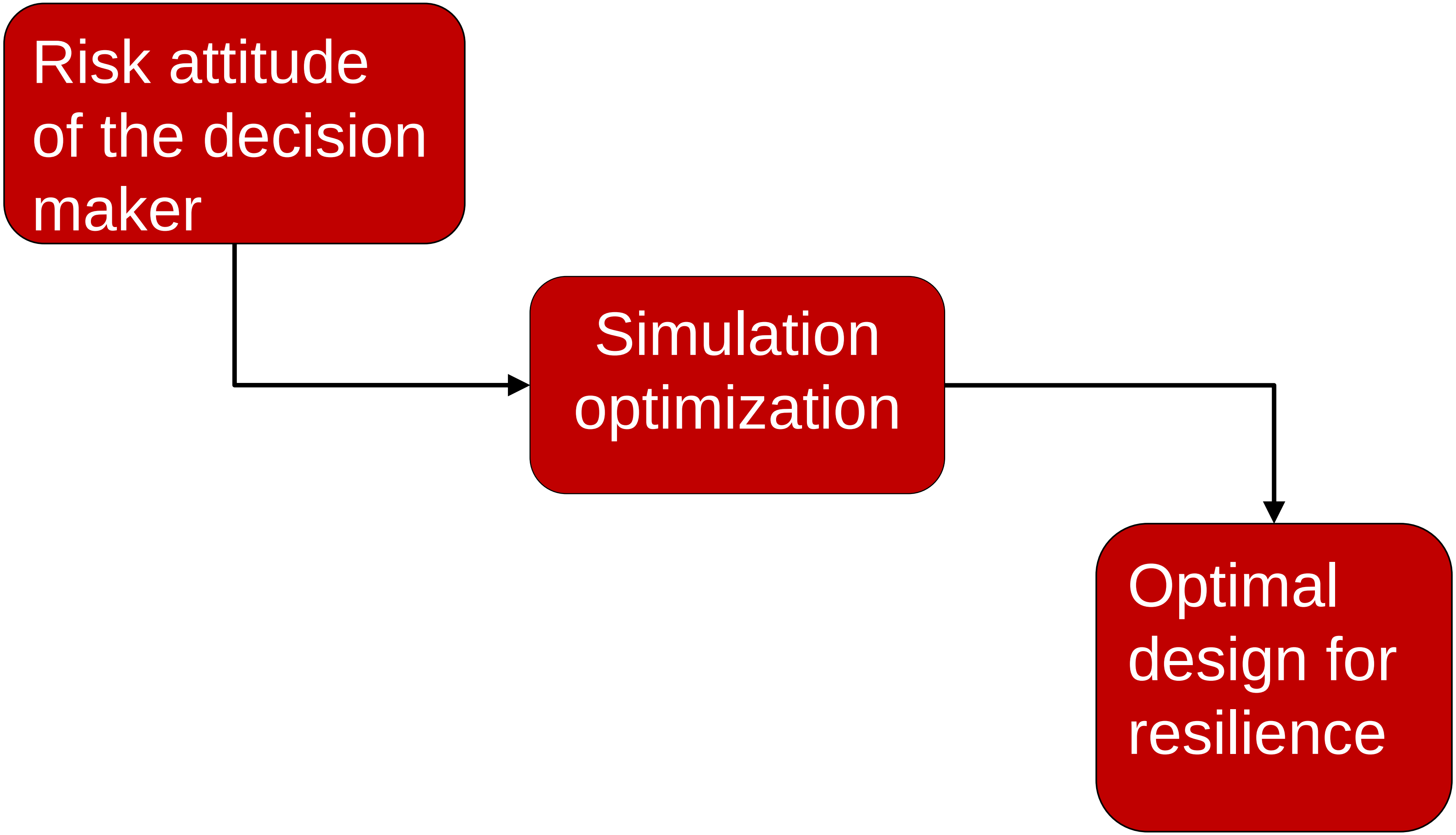


Hurricane Sandy New York City Power Outage

Washington Train Derailment

Wind Turbine Failure

Research Framework



Risk attitude of the decision maker

Simulation optimization

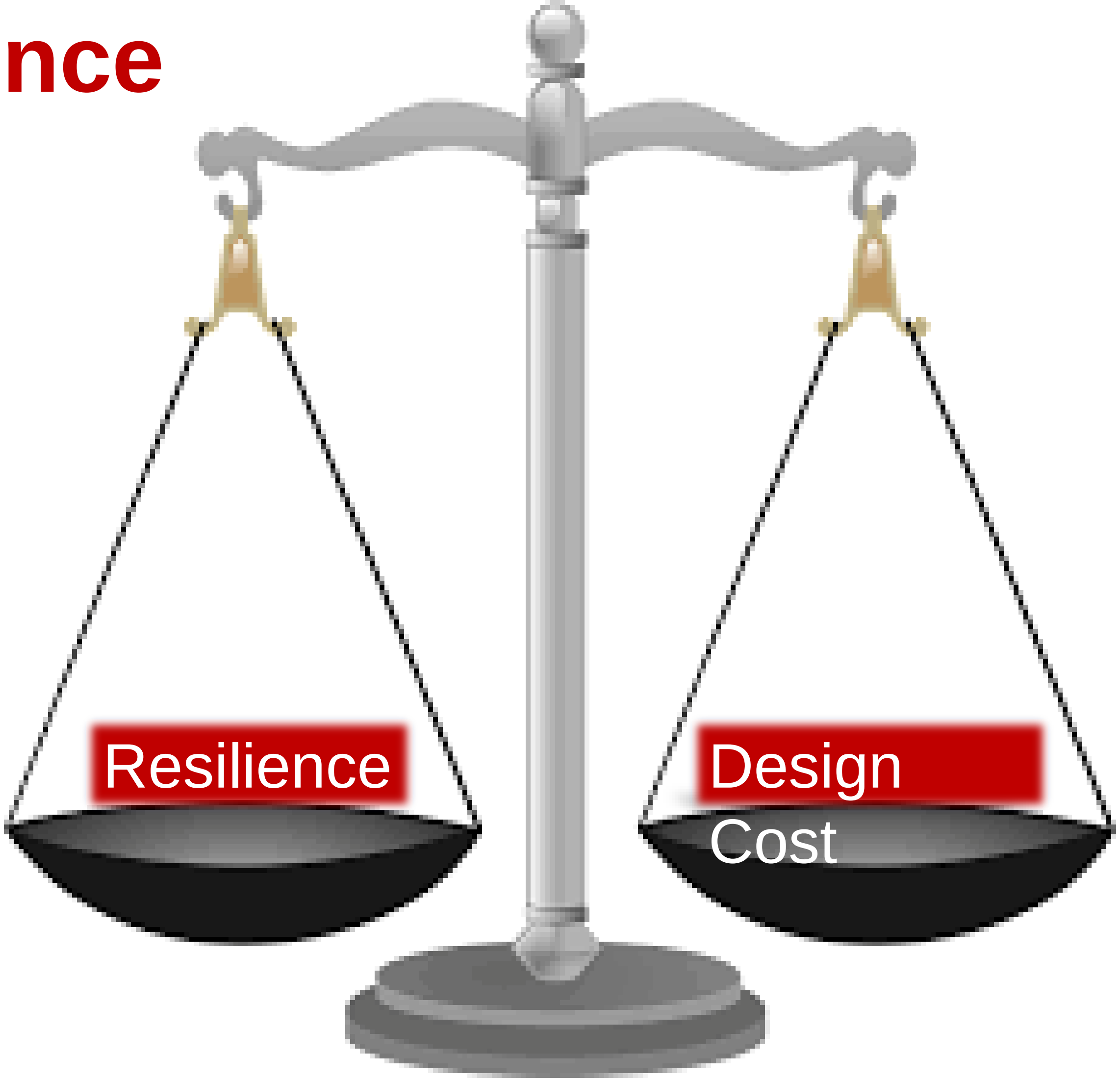
Optimal design for resilience

Research Problem

- Determine how resilience should be integrated into a firm’s design decisions

- Optimize design for a risk-averse firm that incorporates resilience

Tradeoff Between Design Cost and Resilience



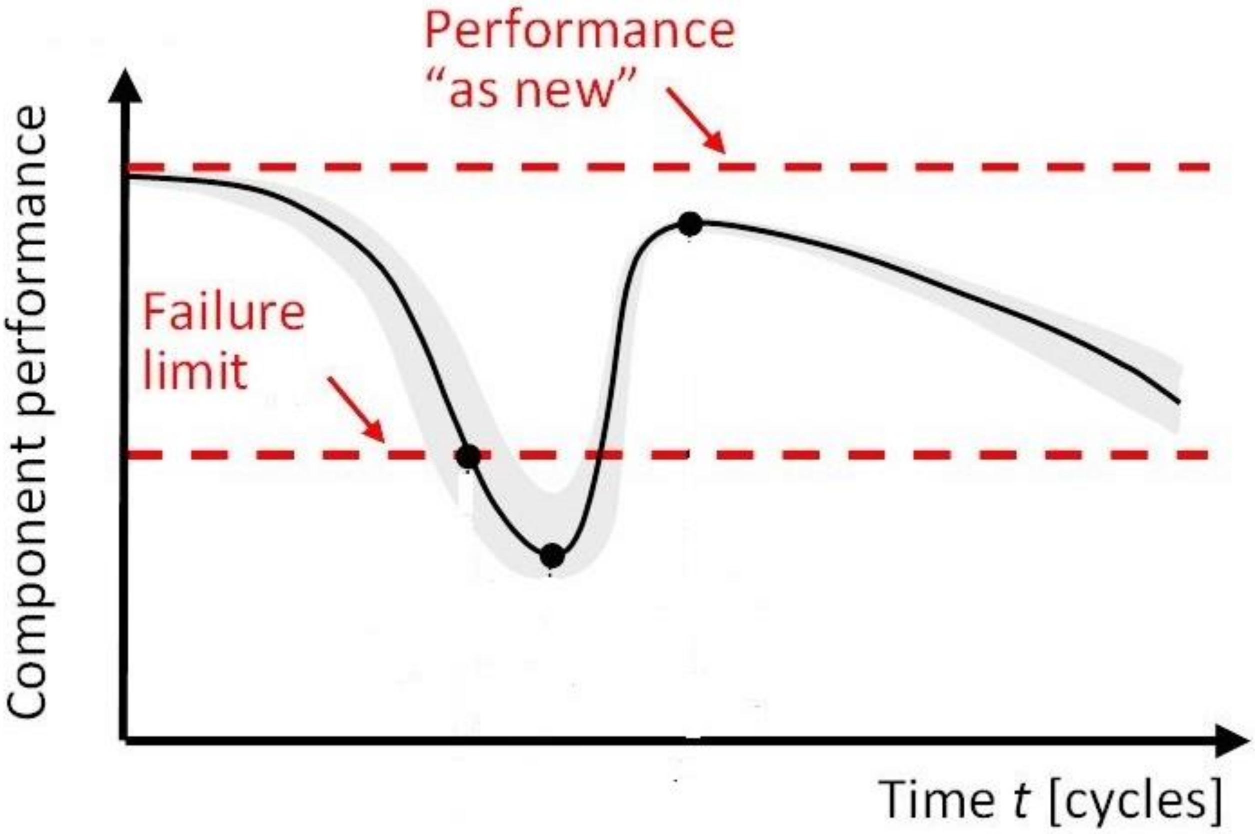
Resilience Definition

- Reliability: The ability of the system to stay above the failure limit
- Restoration: The ability to restore and recover a system’s performance after an adverse event occurs

B. D. Youn, C. Hu, and P. Wang, “Resilience-driven system design of complex engineered systems,” Journal of Mechanical Design, vol. 133, no. 10, p. 101011, 2011.

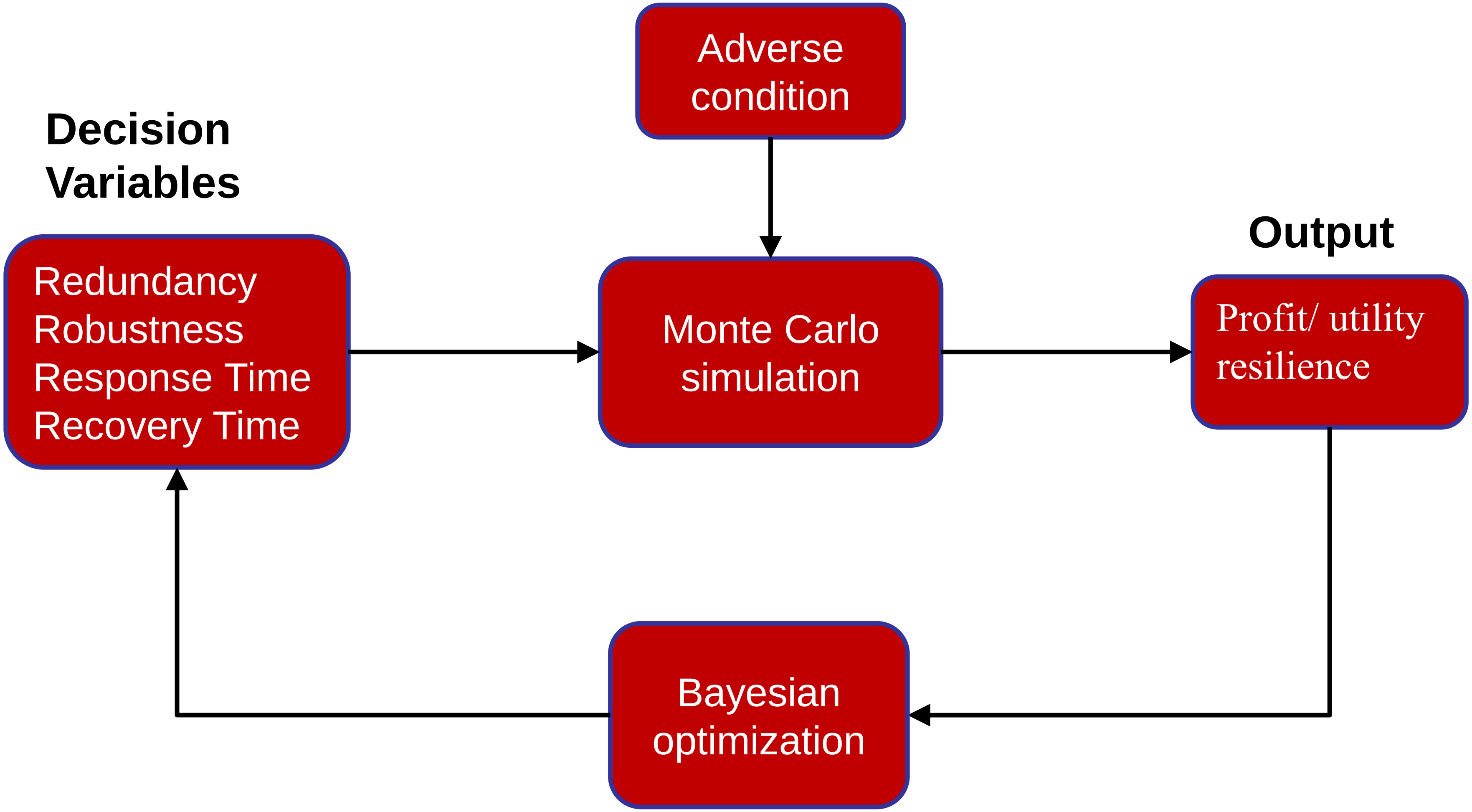
Time-Dependent Resilience Analysis

Resilience: Performance > Failure limit



C. A. MacKenzie and C. Hu, "Decision making under uncertainty for design of resilient engineered systems," Submitted to Reliability Engineering & System Safety, 2017.

Firm Decision Making for Resilience



Adverse condition

Decision Variables

Redundancy
Robustness
Response Time
Recovery Time

Monte Carlo simulation

Output

Profit/ utility resilience

Bayesian optimization

Optimization of Decision-Making Model

- Decision variables:

  - Redundancy (number of components)
  - Robustness (ability to withstand adverse event)
  - Response (time to respond after adverse event)
  - Recovery (time to recover system to functioning after failure)

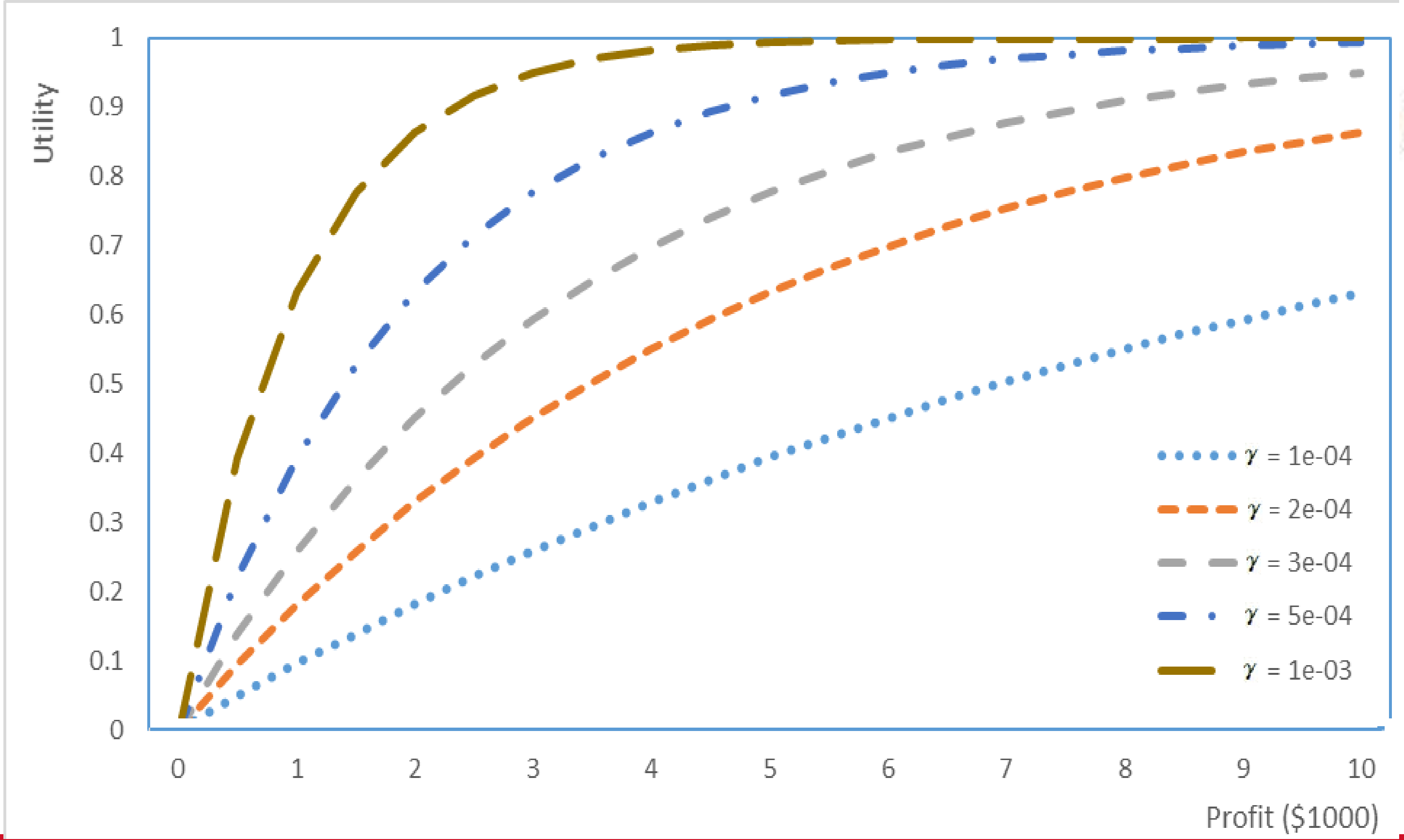
- Objective function (profit or utility) can only be evaluated via Monte Carlo simulation

Decision Making Models

- Develop and solve mathematical model for risk-averse design firms
  - Expected utility
  - Value-at-risk
- Integrate risk-averse decision-making model into design-for-resilience simulation

Expected Utility Model

- Risk aversion parameter (γ) for exponential utility function
- Analyze optimal design for risk-neutral to very risk averse firms
- Optimal design maximizes expected utility

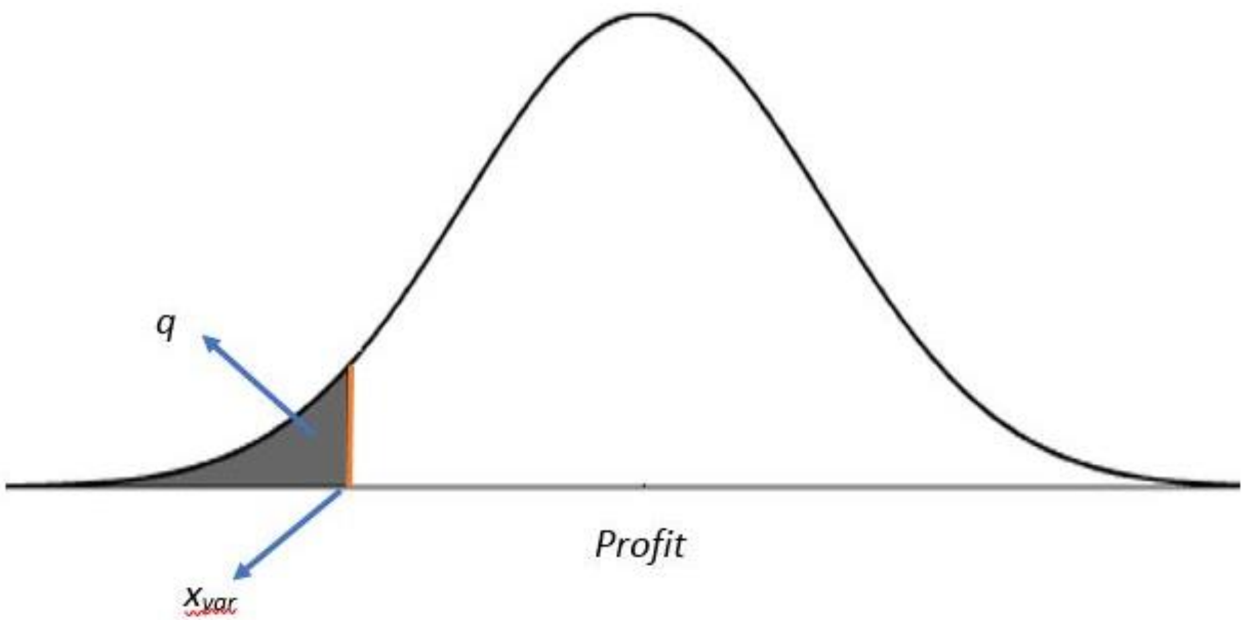


$$U(x) = 1 - \exp(-\gamma x)$$

Value-at-Risk (VAR) Model

- VAR is defined as the largest profit x_{var} such that there is a q probability that the profit is less than or equal to x_{var}
- The risk exposure of a firm can be limited by using VAR
  - Firm maximizes expected profit subject to VAR

VAR constraint: Probability (profit < x_{var}) < q

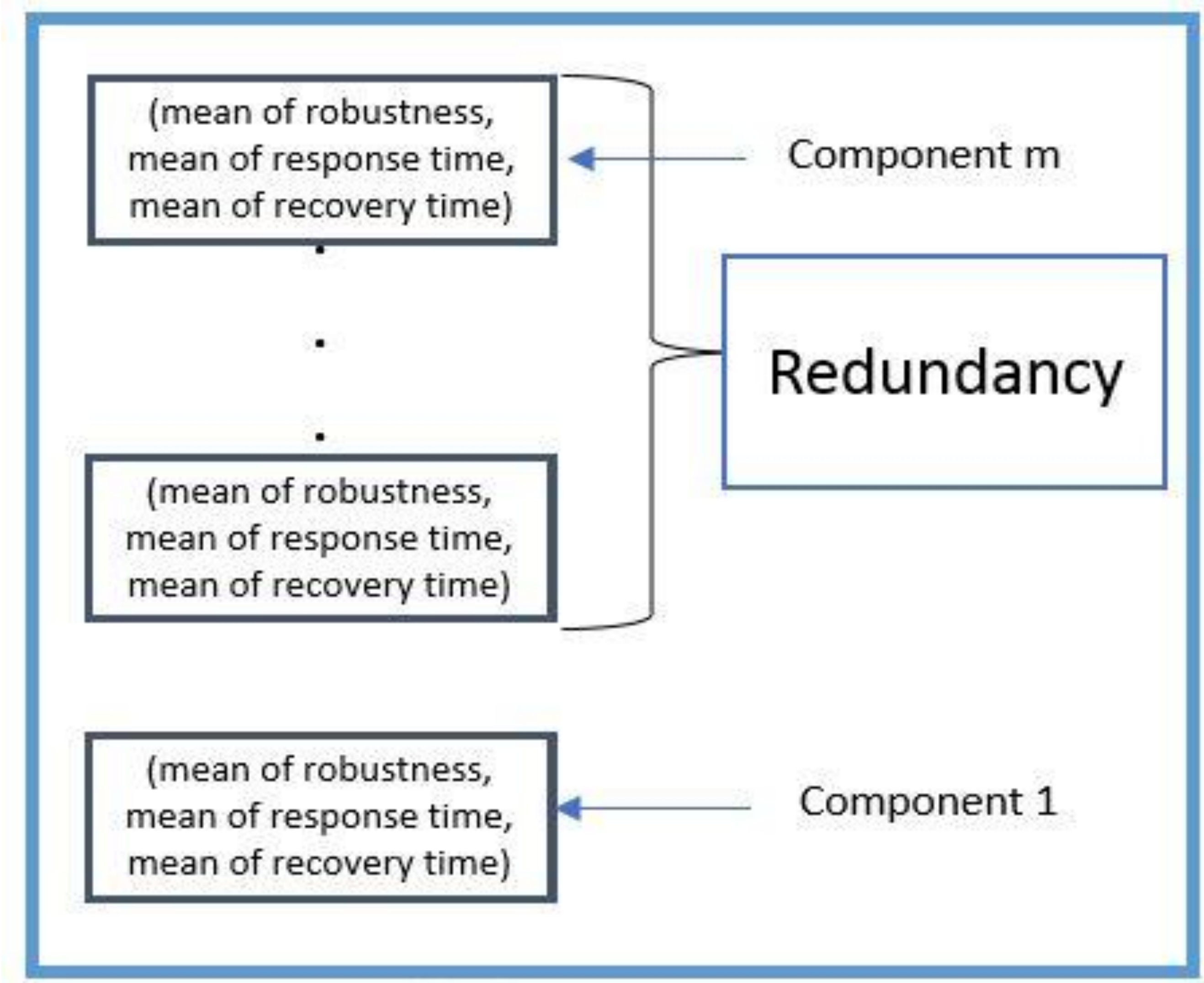


Two Illustrative Examples

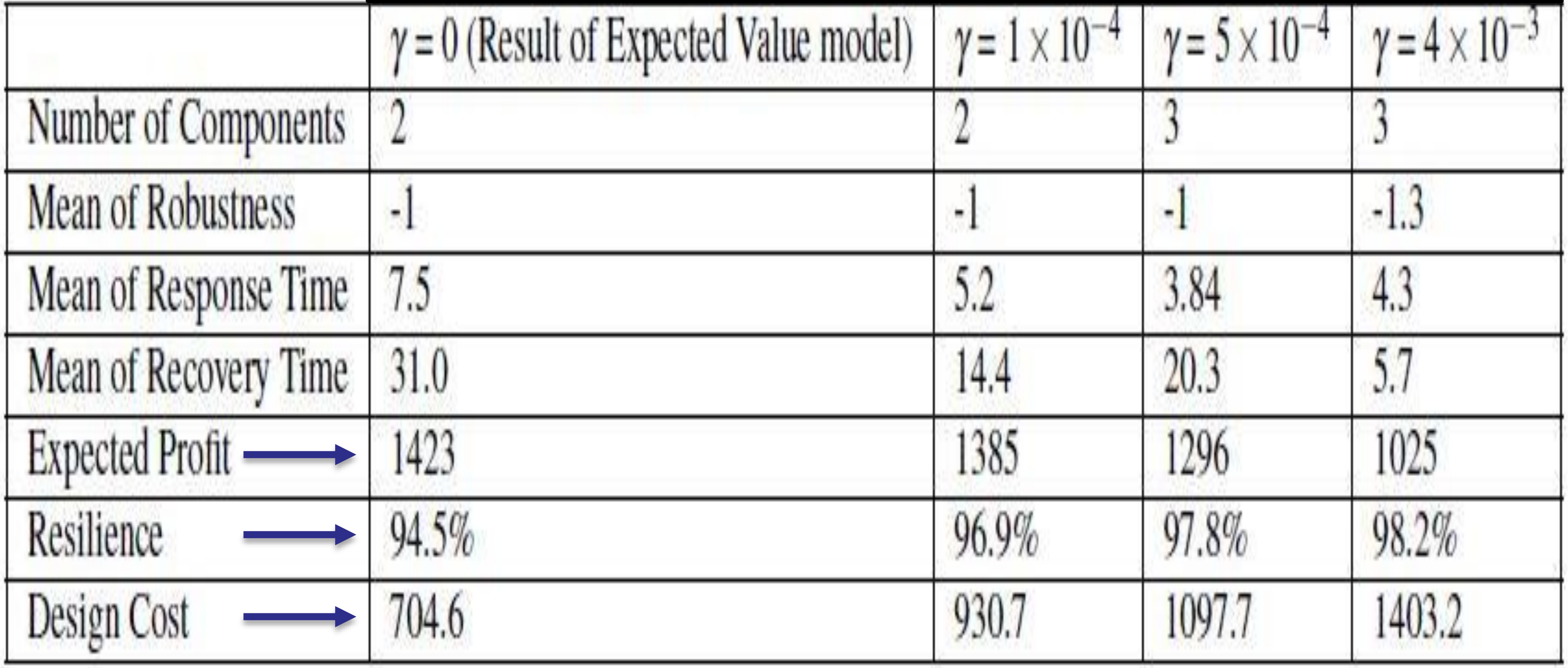
- One-subsystem example

- Three-subsystems example

One-Subsystem Example



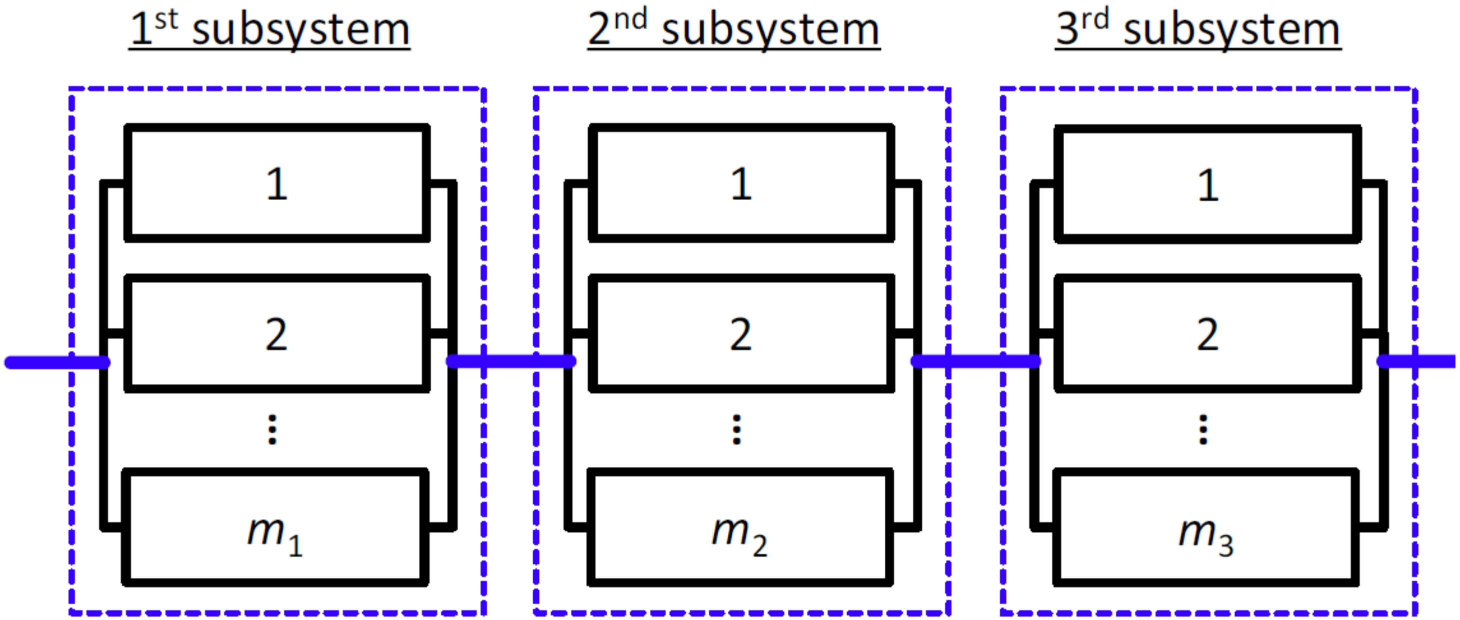
Optimal Design of One Subsystem Example



	Risk neutral decision maker	Risk averse decision maker		
	$\gamma = 0$ (Result of Expected Value model)	$\gamma = 1 \times 10^{-4}$	$\gamma = 5 \times 10^{-4}$	$\gamma = 4 \times 10^{-3}$
Number of Components	2	2	3	3
Mean of Robustness	-1	-1	-1	-1.3
Mean of Response Time	7.5	5.2	3.84	4.3
Mean of Recovery Time	31.0	14.4	20.3	5.7
Expected Profit	1423	1385	1296	1025
Resilience	94.5%	96.9%	97.8%	98.2%
Design Cost	704.6	930.7	1097.7	1403.2

Three-Subsystems Example

- Subsystems in series
- Identical components in parallel
- Identical components in the *i*th subsystem possess the same resilience properties



Optimal Design of three-Subsystem Example for the Expected Utility Model

	Redundancy (number of components)			Mean robustness			Mean response time		
	Subsystem			Subsystem			Subsystem		
	1	2	3	1	2	3	1	2	3
Risk neutral	3	1	2	-1	-13	-1	1	2	1
Moderately risk averse	3	1	2	-1	-14	-1	1	1	1

	Mean recovery time			Expected profit	Resilience	Design cost
	Subsystem					
	1	2	3			
Risk neutral	29	50	42	3970	97.7%	918
Moderately risk averse	50	12	1	3932	98.2%	1021
Very risk averse	1	49	1	3906	98.8%	1136

Optimal Design of three-Subsystem Example for Expected Profit with VAR Constraint

	Redundancy (number of components)			**Mean robustness**			**Mean response time**		
Probability (profit < alpha) < 0.05	**Subsystem**			**Subsystem**			**Subsystem**		
	1	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
Expected profit	3	1	2	-1	-13	-1	1	2	1
alpha = 3300	3	1	2	-1	-13	-1	1	10	1

	Mean recovery time			**Expected profit**	**Resilience**	**Design cost**
	Subsystem					
	1	**2**	**3**			
Expected profit	29	50	42	3970	97.7%	918
alpha = 3300	6	3	4	3953	98.4%	1023
alpha = 3600	16	47	1	3919	98.7%	1080

Interpret Results

- As risk aversion increases
  - Firm should design more resilient systems
  - Firm should sacrifice some profit by paying more in design costs
- Having more resilience requires
  - More redundancy (components)
  - More robustness
  - Quicker response time
  - Quicker recovery time

Conclusions

- Trade off between designing a more resilient but costly system

- Framework to incorporate the risk aversion of the decision maker (expected utility and VAR)

- Solve for the optimal design for engineered systems (illustrative examples)