

A Causal Approach to Integrate Component Health Data into System Reliability Models

D. Mandelli*, C. Wang

*diego.mandelli@inl.gov

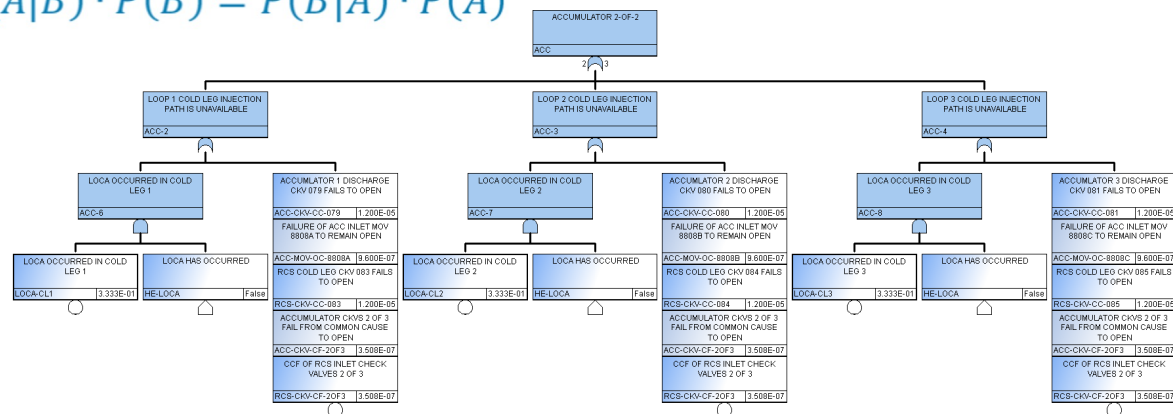


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Problem Setting

- **Context:** Nuclear industry is moving from periodic to predictive maintenance strategies
- Monitoring and data analysis technologies are essential to support predictive strategies
 - On-line continuous monitoring
 - Anomaly detection, diagnostic, and prognostic methods
- **Role of reliability**
 - Assess system health by integrating health information of all components
 - Identify the most critical components that need attention
- **Reliability approaches:** Deterministic models that depict system architecture from a functional perspective
 - Examples: Fault trees, Reliability Block Diagrams (RBD)
 - Boolean algebra operations used to calculate top event probability (set theory based)
 - OR: $P(A \cup B) = P(A) + P(B) - P(A \cap B)$
 - AND: $P(A \cap B) = P(A|B) \cdot P(B) = P(B|A) \cdot P(A)$

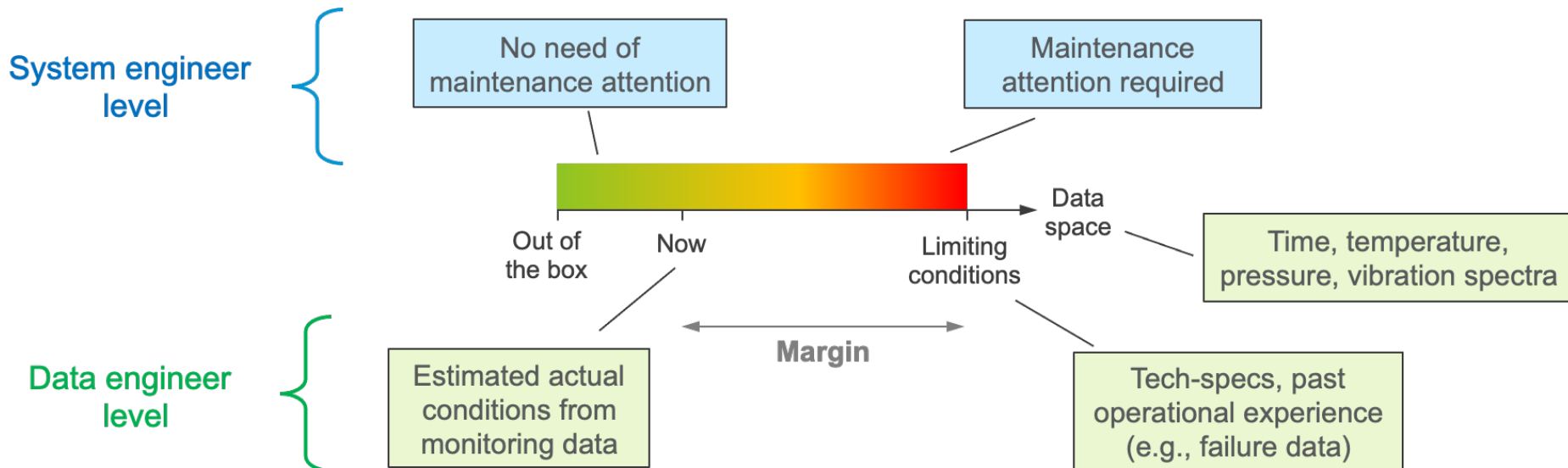


Current Reliability Approaches

- **Issues**
 - Data level: Employed data are averaged over industry operational experience
 - Condition-based data are not effectively integrated into plant reliability models
 - Decision level: Does “system failure probability” support ongoing decision-making?
- **Failure rate:** Rate of occurrence of an aleatory variable
 - Assume diagnostic/prognostic monitoring are performed: Are we still dealing with an aleatory variable?
 - “Every time we talk about system failure probability, we lose system engineers’ attention.”
 - “System engineers are more used to the concept of margins.”

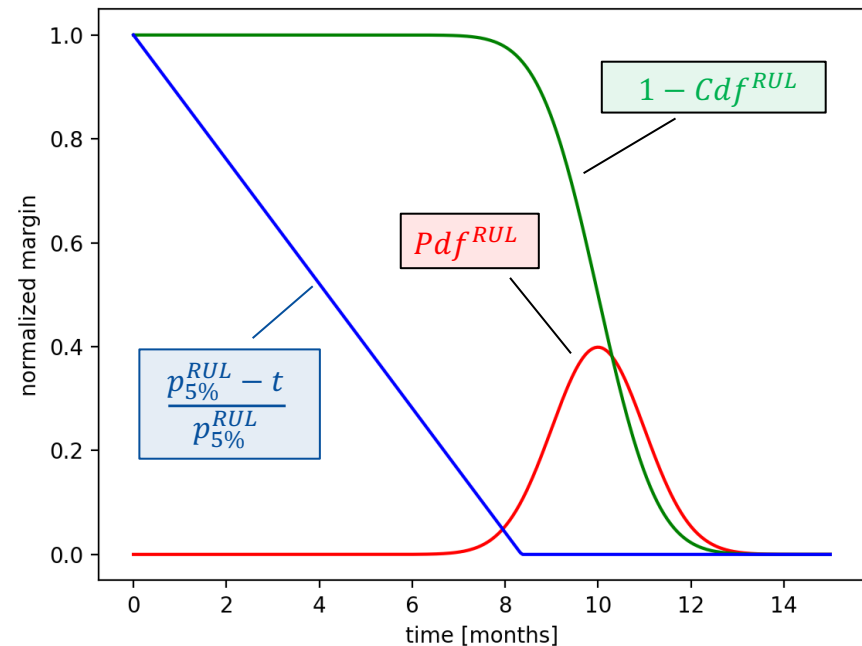
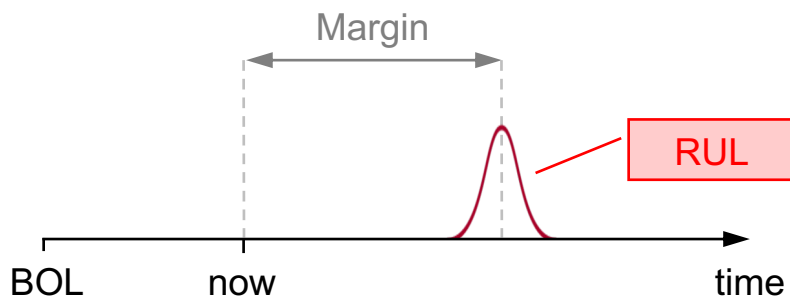
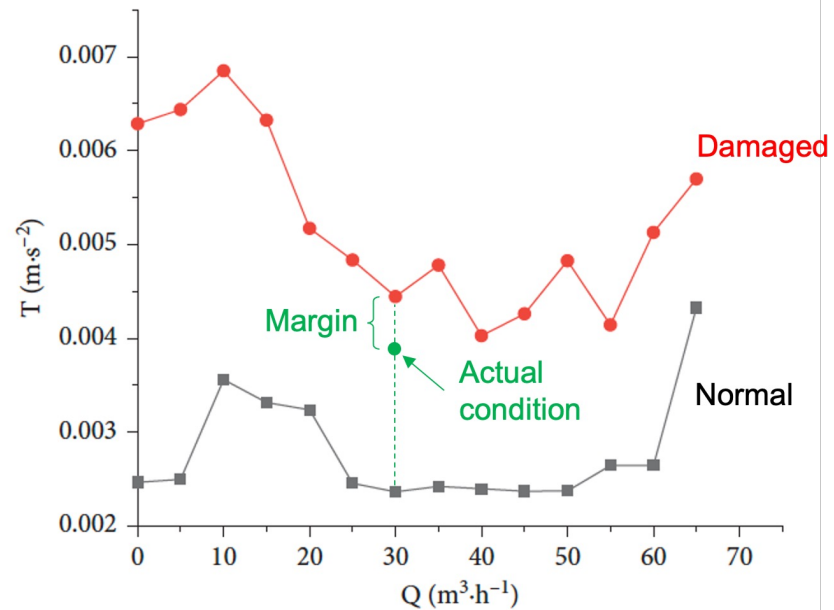
Changing Reliability Language

- **Key:** “What if we think about reliability in terms of margins?”
- **Margin definition:** The “distance” between present/actual status and an (estimated) undesired status for a specific component
 - Margin=1: Component perfectly healthy
 - Margin=0: Component at limiting conditions
- Component margin is an analytical measure of its health
 - Can you say the same for failure rate?



Margin Examples

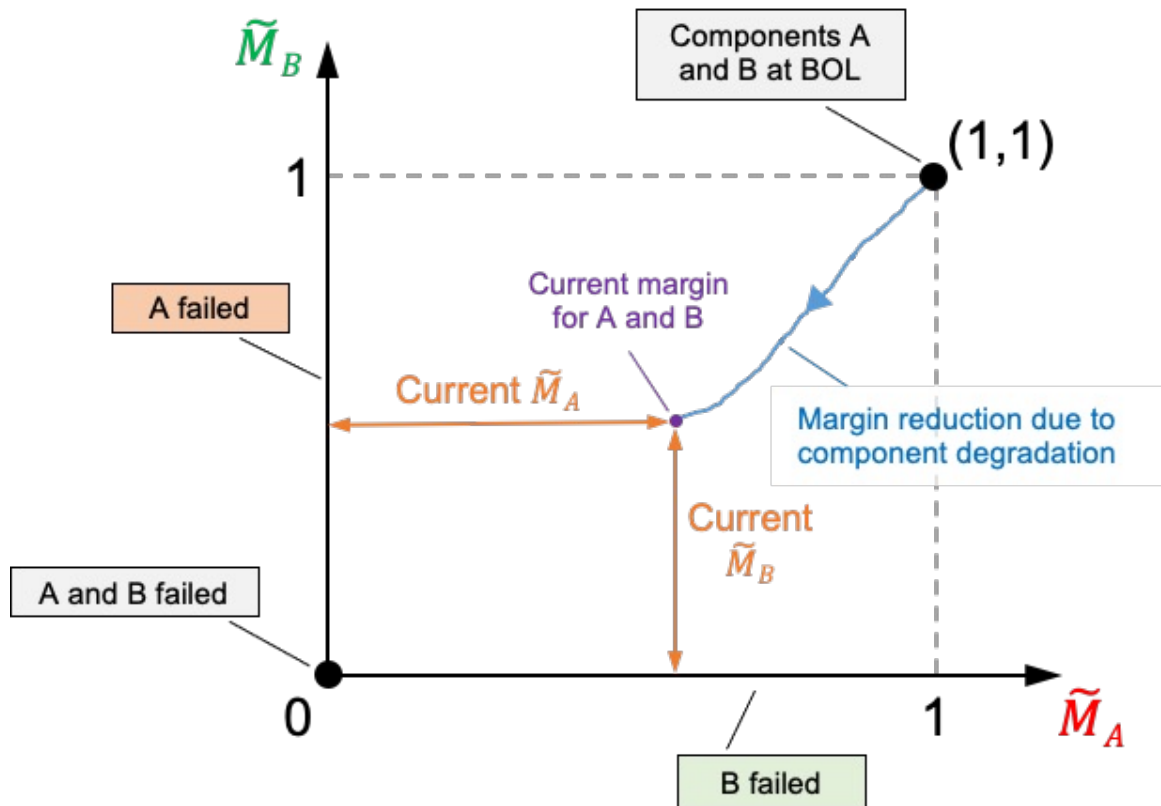
- Vibration data for induction motors¹ (root mean square [RMS])
 - RMS observed when seals are degraded beyond their limit for different pump rotation speeds
- Prognostic data
 - Input: component remaining useful life (RUL)
 - Typically expressed in terms of a probabilistic distribution function Pdf^{RUL}



¹ Luo, Y., Zhang W., Fan Y., Han, Y., Li, W., and Acheaw, E. 2021. "Analysis of Vibration Characteristics of Centrifugal Pump Mechanical Seal under Wear and Damage Degree." Vibration and Control of Fluid Machinery and Systems 2021.

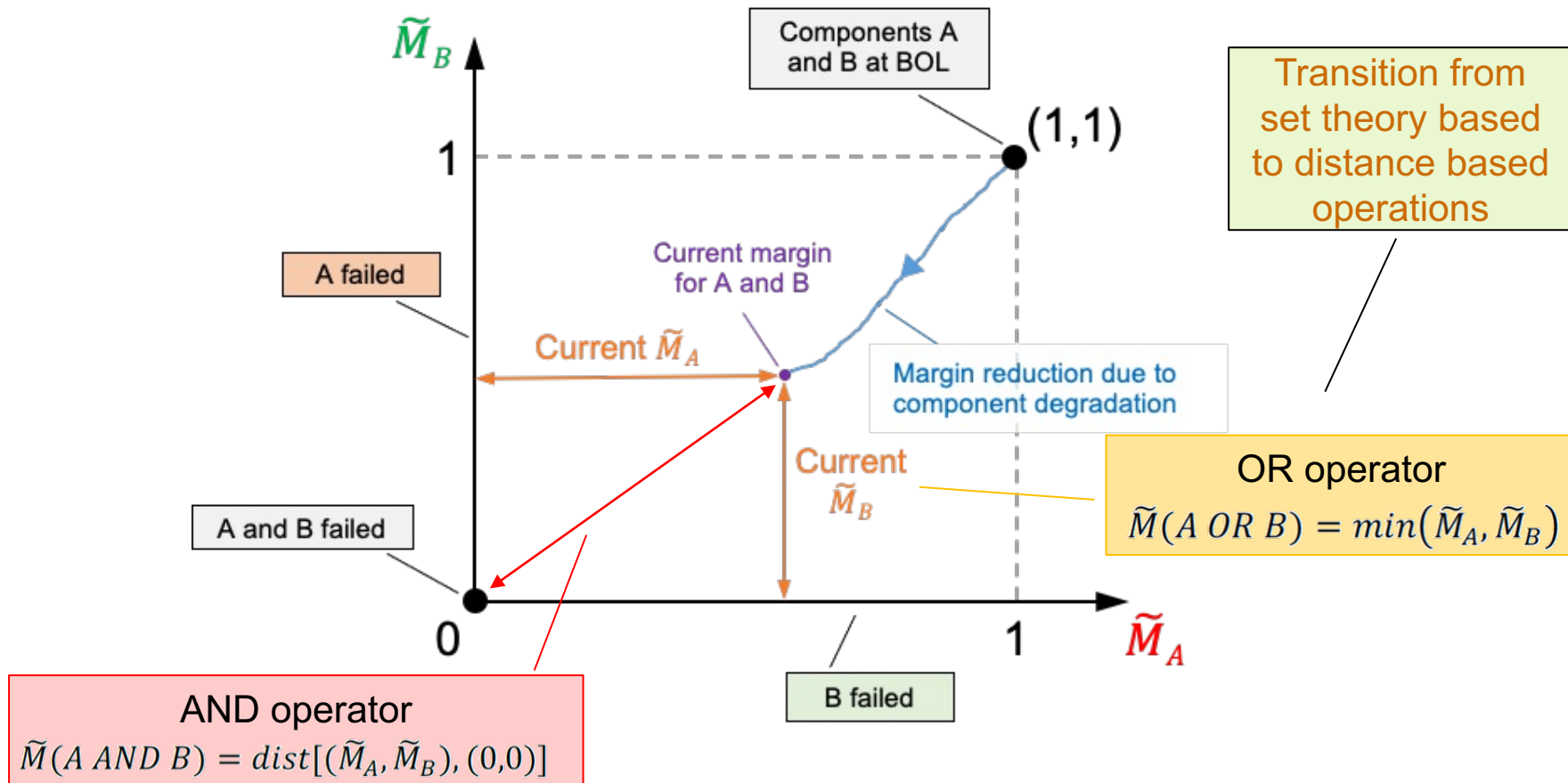
Margin-Based Reliability Modeling

- **Assessing system health:** Integrate component margin values into system reliability model
- System reliability models are typically based on fault trees
- Solving AND and OR operators in a margin context



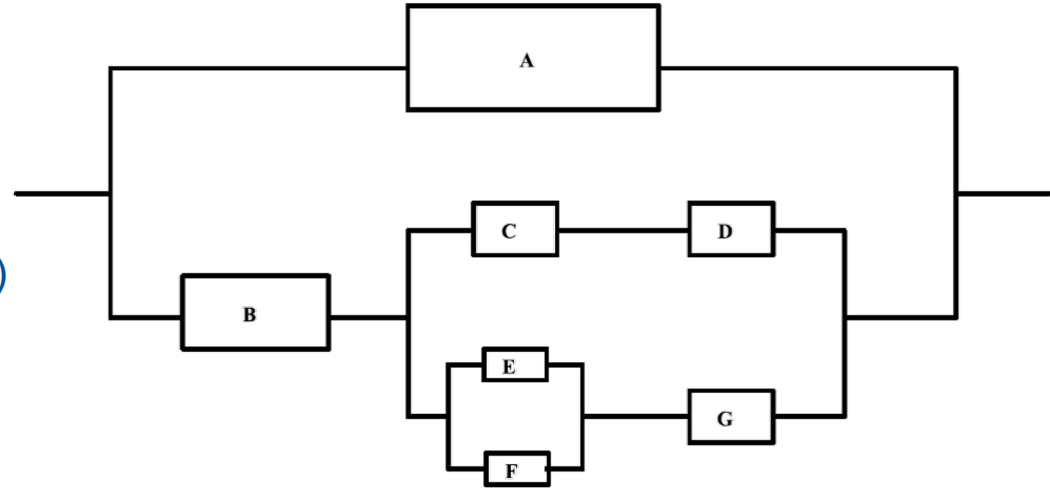
Margin-Based Reliability Modeling

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Example

- RBD description of a system
- **Goals**
 - Integrate prognostic data (RUL) into system reliability model
 - Assess plant health
 - Periodically identify critical components
- System fault tree used to generate
 - Minimal cut sets
 - Minimal path sets

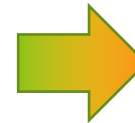


Minimal conditions to reach system failure

#	Cut set
1	A B
2	A D G
3	A C G
4	A D E F
5	A C E F

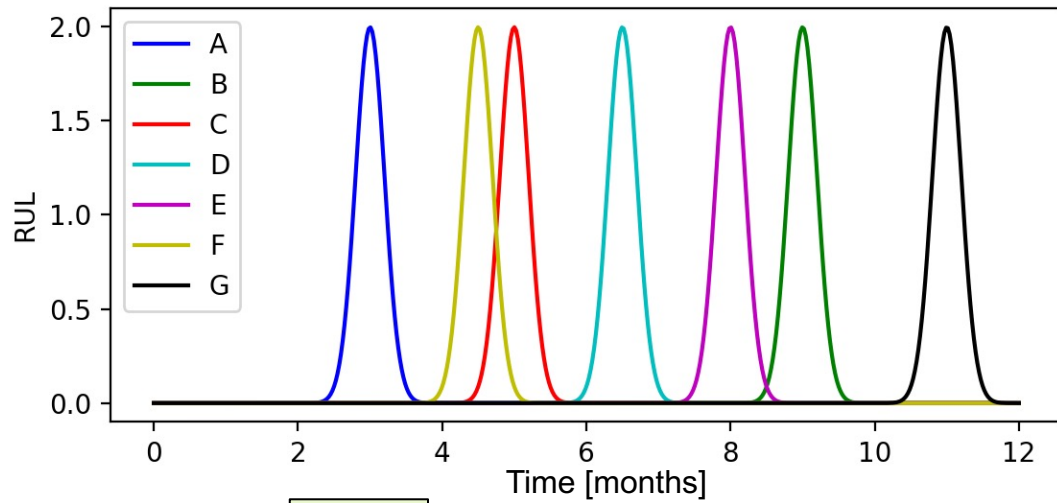
Minimal conditions to guarantee system operation

#	Path set
1	A
2	B C D
3	B E G
4	B F G

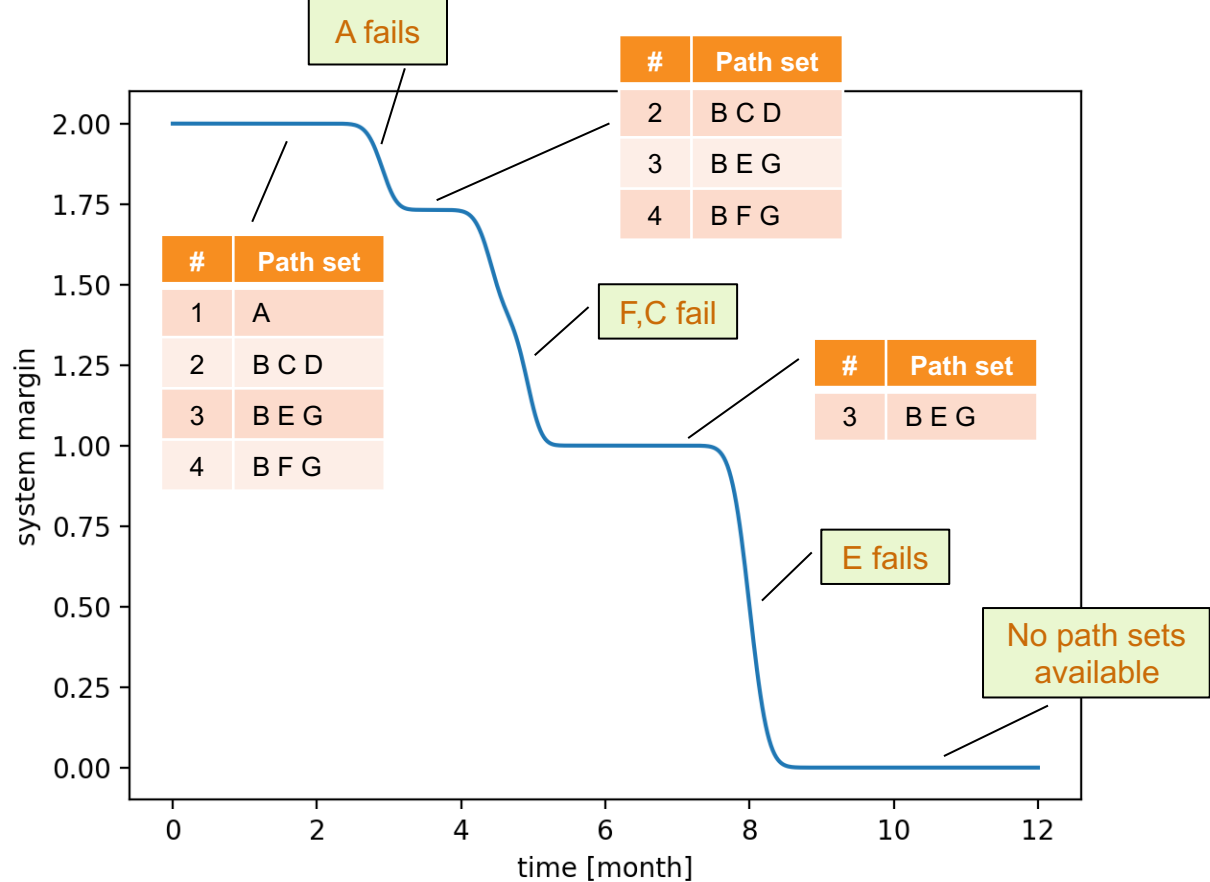


Example

Input data: RUL for all components (A through G)



Output data: system margin



Example

#	Path set
1	A
2	BCD
3	BEG
4	BFG

#	Path set
3	BEG

@ about t=8:

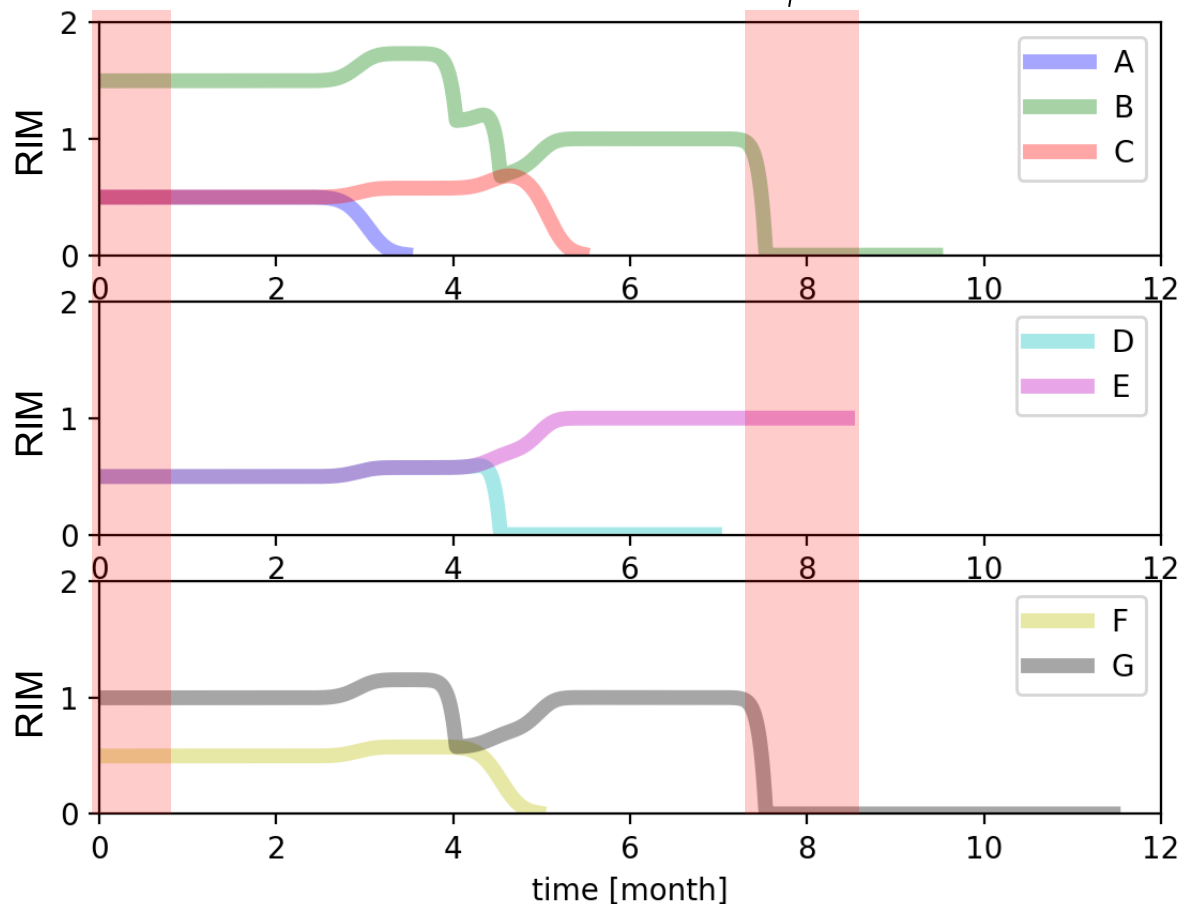
- B and G are “doing well”
- Time is approaching RUL of E
- Importance of E is thus greater than B or G

@ t=0: Importance for B is the highest since it supports three path sets

- Reliability importance measure (RIM) for component i

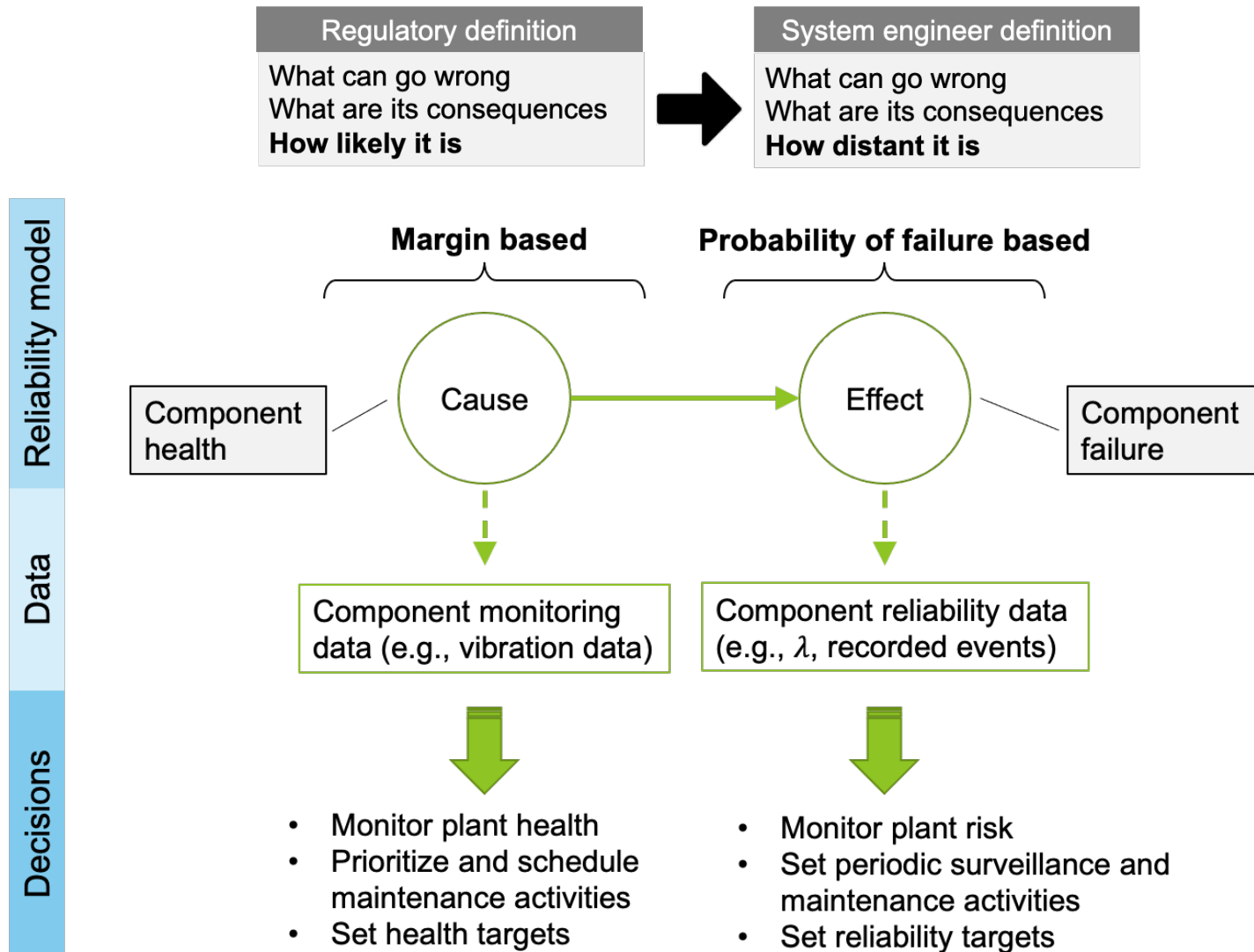
$$RIM_i = \frac{d \text{Margin}_{sys}}{d \text{Margin}_i}$$

- Semantic value
 - What are the most critical components?
 - What is the added value of O&M funds spent for component i ?
 - When should I assess component i health status?



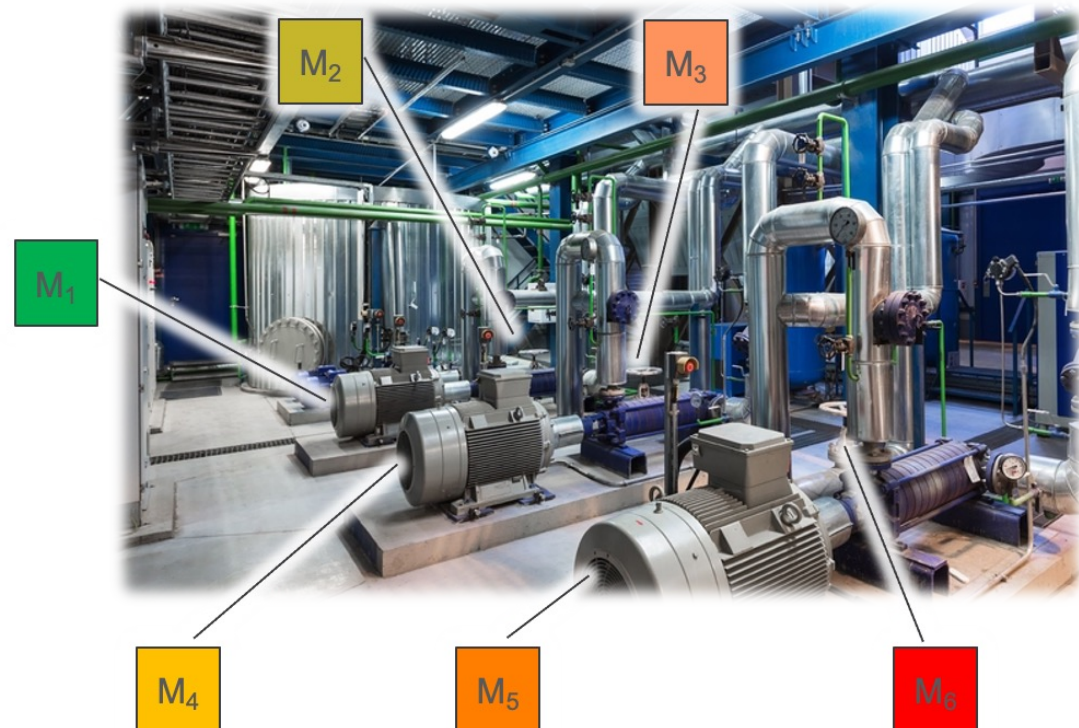
Final Remarks (1)

- Margin-based reliability modeling implies a redefinition of risk



Final Remarks (2)

- Recall that reliability should assess system health by integrating health information of all its components
- Our work
 - Developed and tested a novel way to propagate margin values from the component to the system level
 - Compatible with employed system reliability models (fault trees), we solve them in a different way!
 - Analytical way to assess system health
- Based solely on current and historic monitoring data
- Support plant health and asset management decisions through explainable models





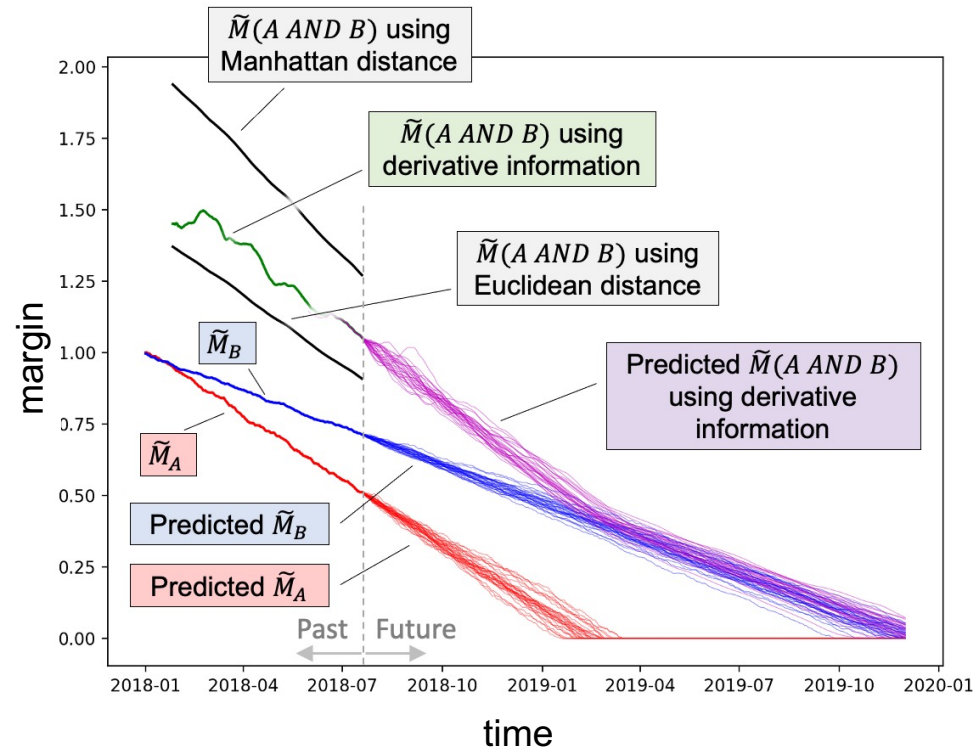
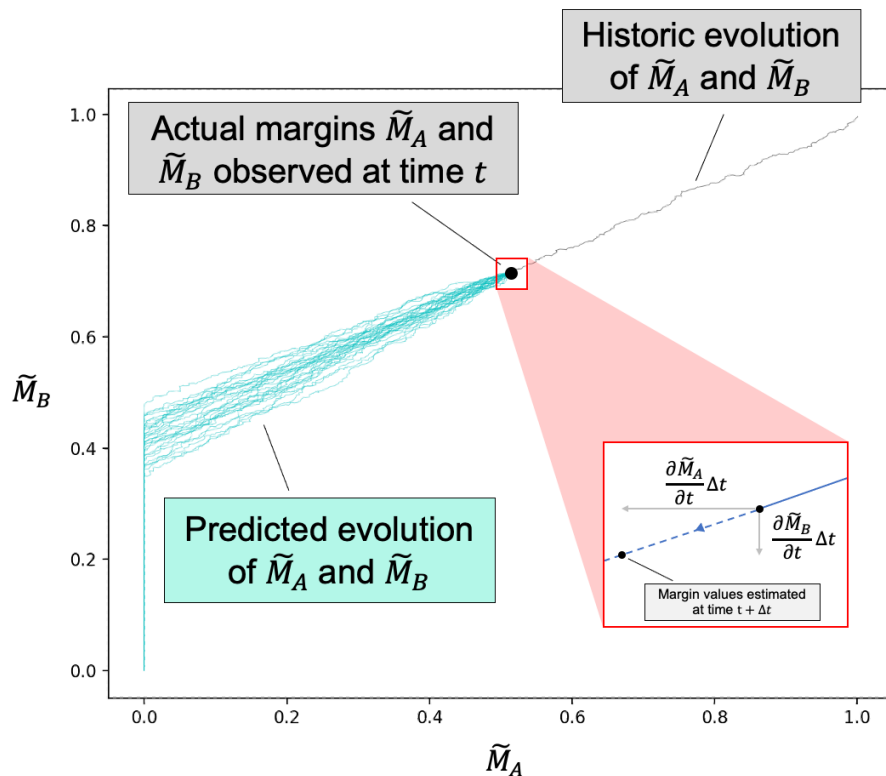
Backup Slides

Margin-Based Reliability Modeling

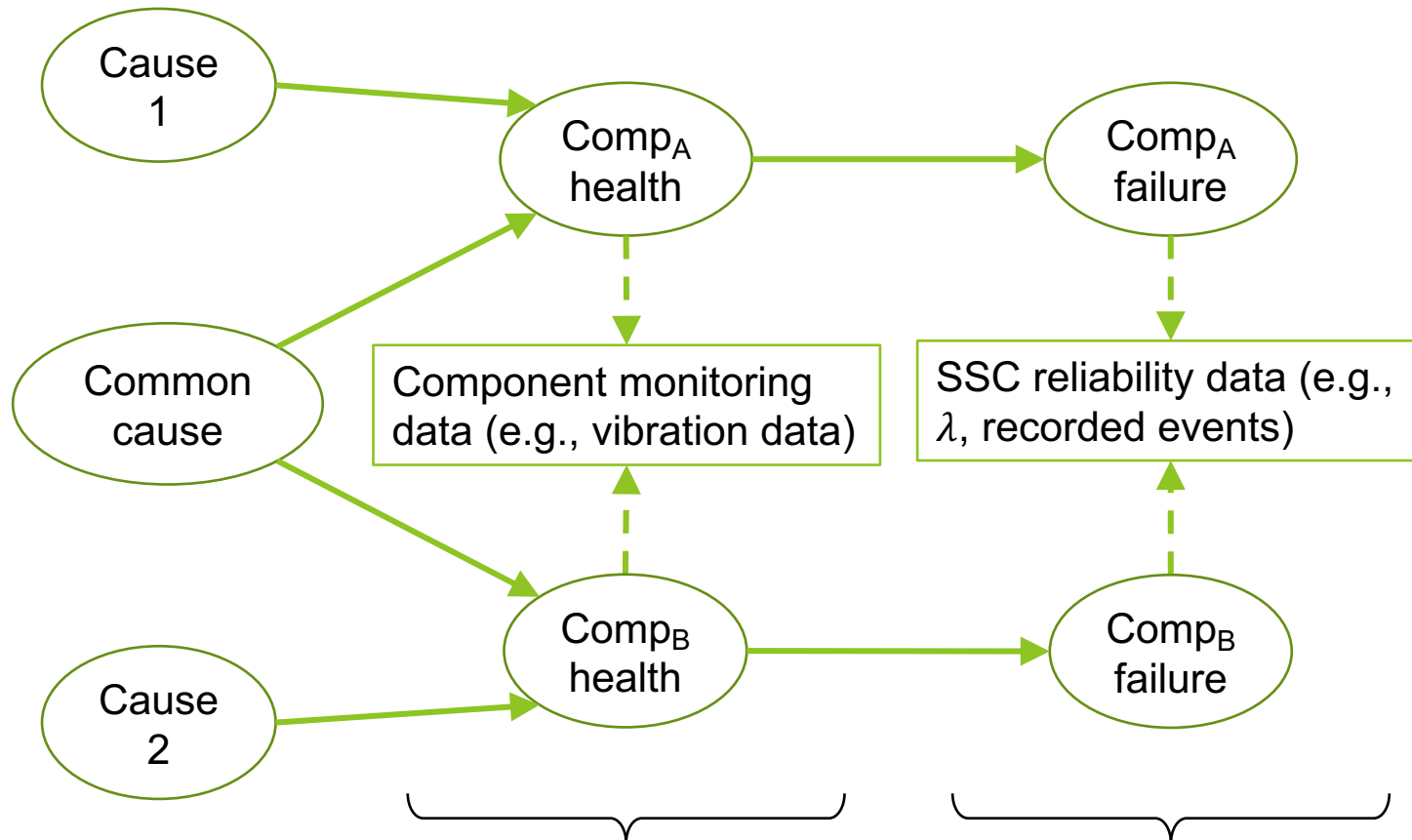
- Margin values capture monitored component degradation
- **Margin values change with time**
 - New SSC condition data are observed
 - Maintenance operations are performed
- Temporal evolution of component degradation can be extrapolated from historic data

Degradation: Margin ↓

Margin ↑



CCFs: Probability and Margin Calculations



Margin-based

Effect of CC variables is accounted on monitoring data, but margin calculation requires double counting

Probability-based

Effect of CC variables on SSC reliability data is not easily filtered to avoid double-counting