LWRS LIGHT WATER REACTOR SUSTAINABILITY

INL Idaho National Laboratory

Rethinking Reliability in Terms of Margins

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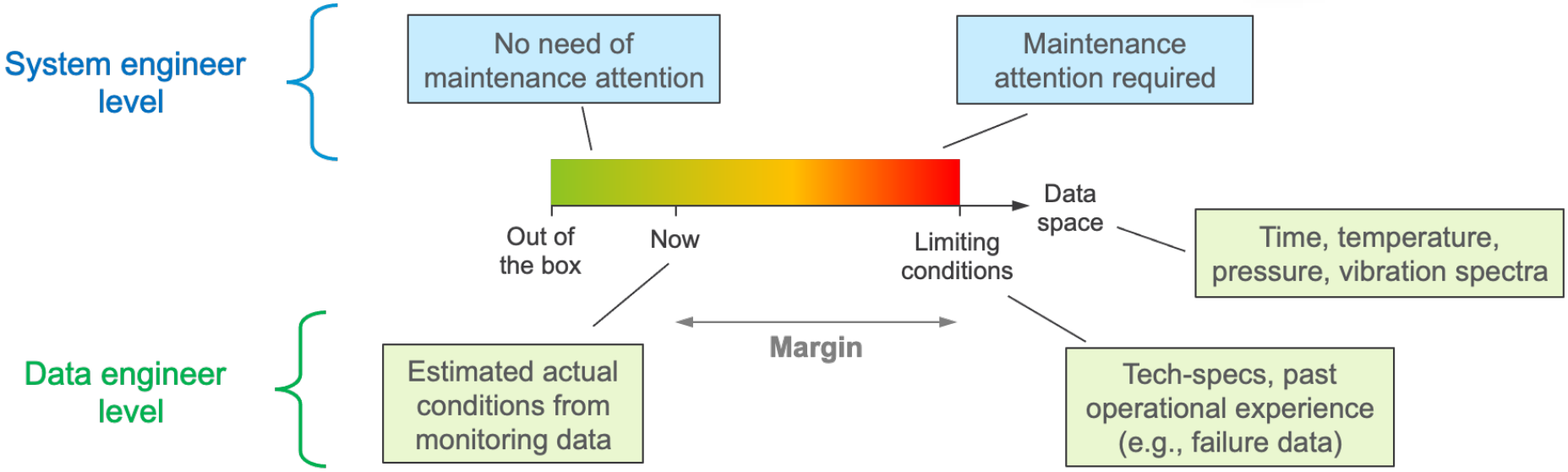
From Periodic to Predictive Maintenance

- Monitoring and data analysis technologies are essential to support predictive strategies
  - On-line continuous monitoring
  - Anomaly detection, diagnostic, and prognostic methods
- **Reliability approaches:** Deterministic models that depict system architecture from a functional perspective (e.g., fault trees, reliability block diagrams)
  - Boolean algebra operations used to calculate top event probability
- **Issues**
  - Data: Employed data are averaged over industry operational experience
    - Condition-based data are not effectively integrated into plant reliability models
  - Decision: Does "system failure probability" support a predictive maintenance context?
- **Failure rate:** Rate of occurrence of an aleatory variable
  - Assume diagnostic/prognostic monitoring are performed: Are we still dealing with an aleatory variable?
- **Meeting notes**
  - "Every time we talk about 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 status and an (estimated) undesired status for a specific component
  - Margin=1: Component perfectly healthy
  - Margin=0: Component at limiting conditions

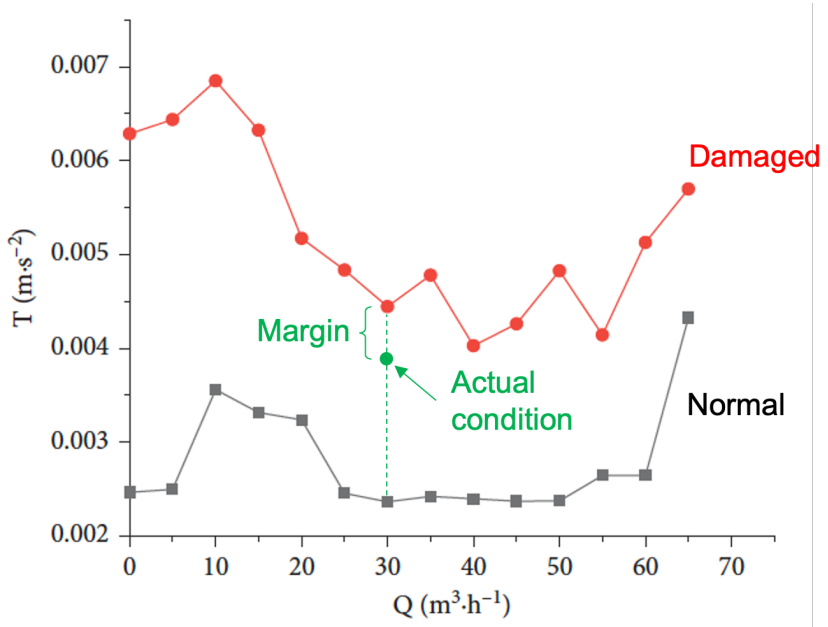
Component margin changes with ageing



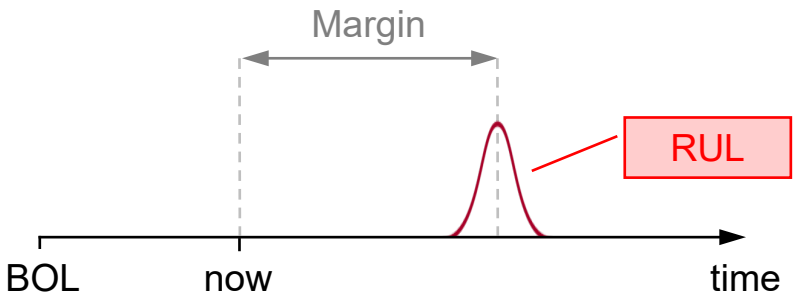
- **Tech specs data:** Limiting conditions can be specified by provided tech-specs (x_{LC})
  - E.g., oil viscosity for induction motors
  - Margin computation provided measured quantity x_{obs} : $M(x_{obs}) = \frac{x_{LC} - x_{obs}}{x_{LC} - \min(x_{obs})}$

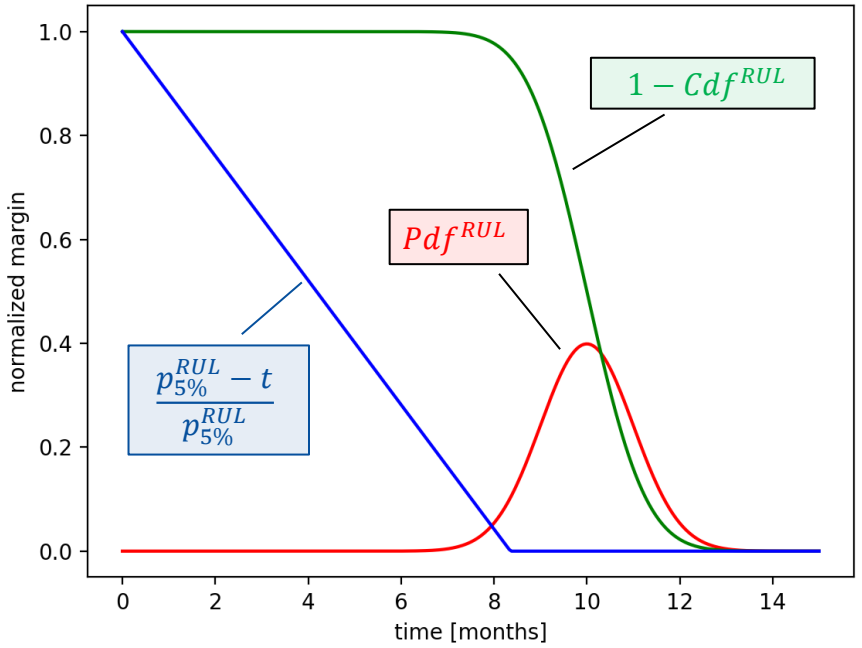
Margin Examples

- **Condition based data**
  - E.g.: vibration data for induction motors[1] (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}



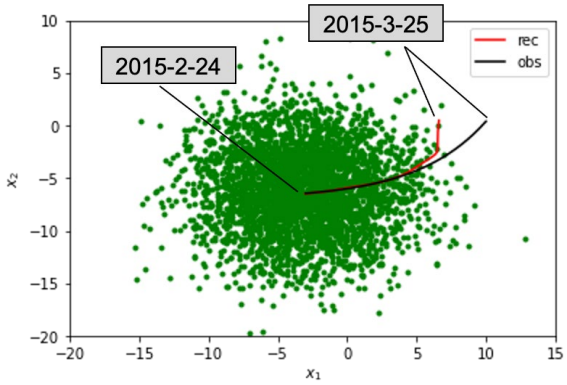


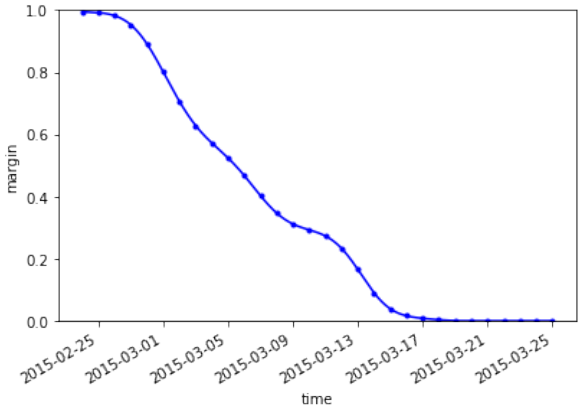
[1] Luo, Y., Zhang W., Fan Y., Han, Y., Li, W., and Acheaw, E. 2021. "Analysis of Vibration Characteristics of Centrifugal Pump Mechanical Seal under Wear and Damage Degree." Vibration and Control of Fluid Machinery and Systems 2021.

Integration of Machine Learning (ML) Methods

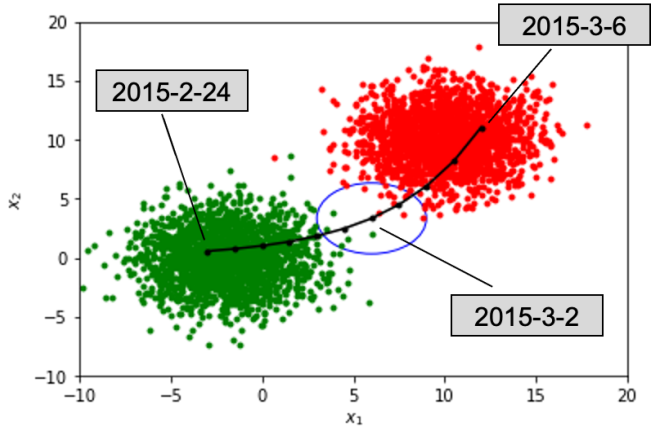
- **Anomaly detection:** Quantify residual between observed data ξ^{obs} and predicted data ξ^{rec}
  - Data collected exclusively when the asset was in a healthy state
  - Margin computation

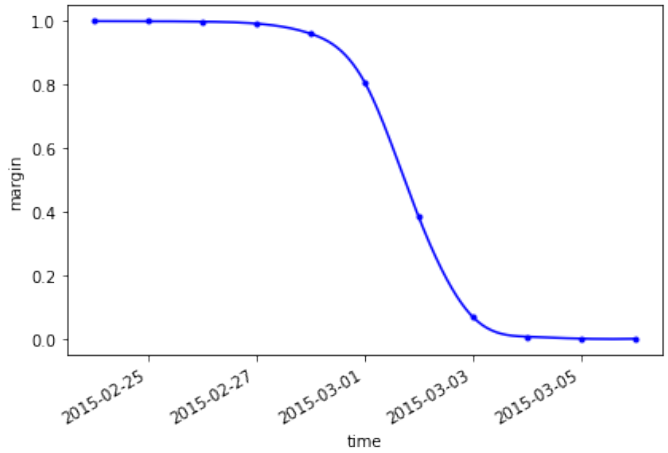
$$M\left(\xi^{obs}\right) = e^{-\left(\frac{\left\|\xi^{obs}-\xi^{rec}\right\|}{h}\right)^2}$$





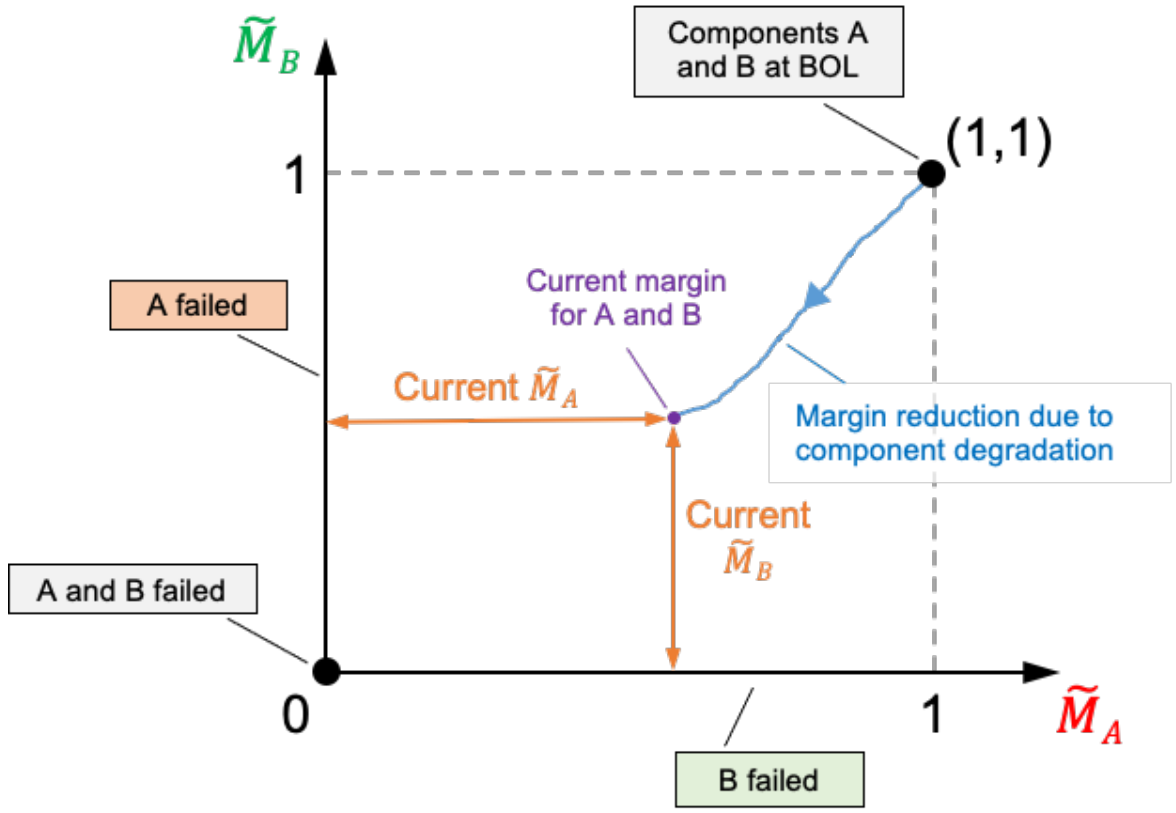
- **Diagnostic methods:** Data collected under healthy and faulty conditions
  - Margin computation (density-based): $M\left(\xi^{obs}\right) = \frac{pdf^{healthy}(\xi^{obs})}{pdf^{healthy}(\xi^{obs})+pdf^{faulty}(\xi^{obs})}$





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



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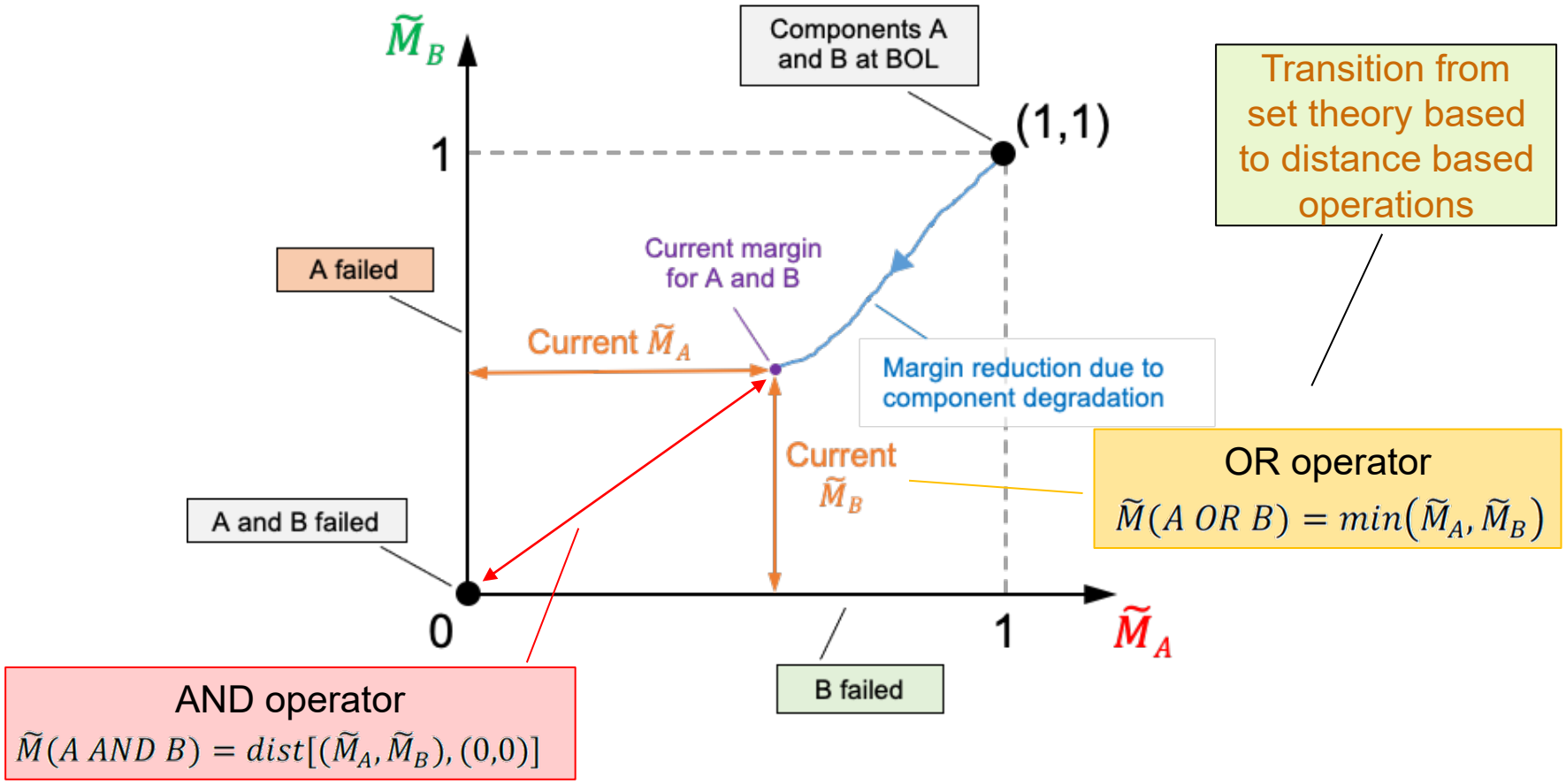
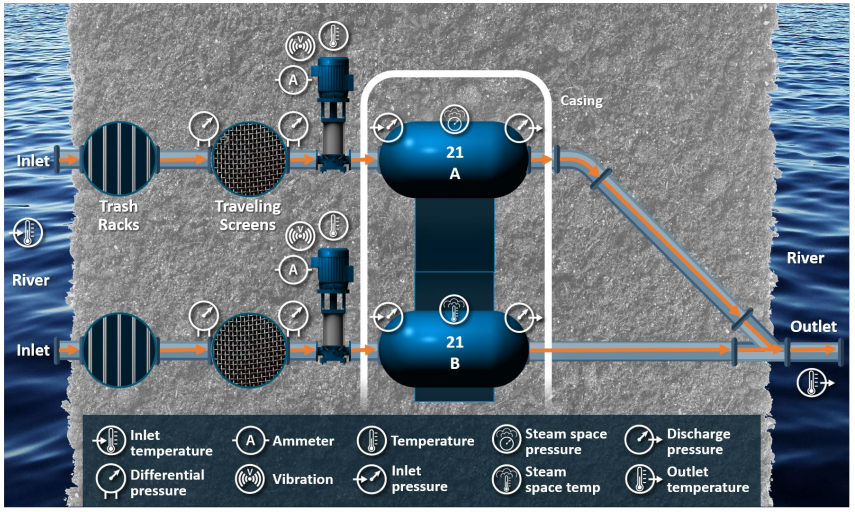
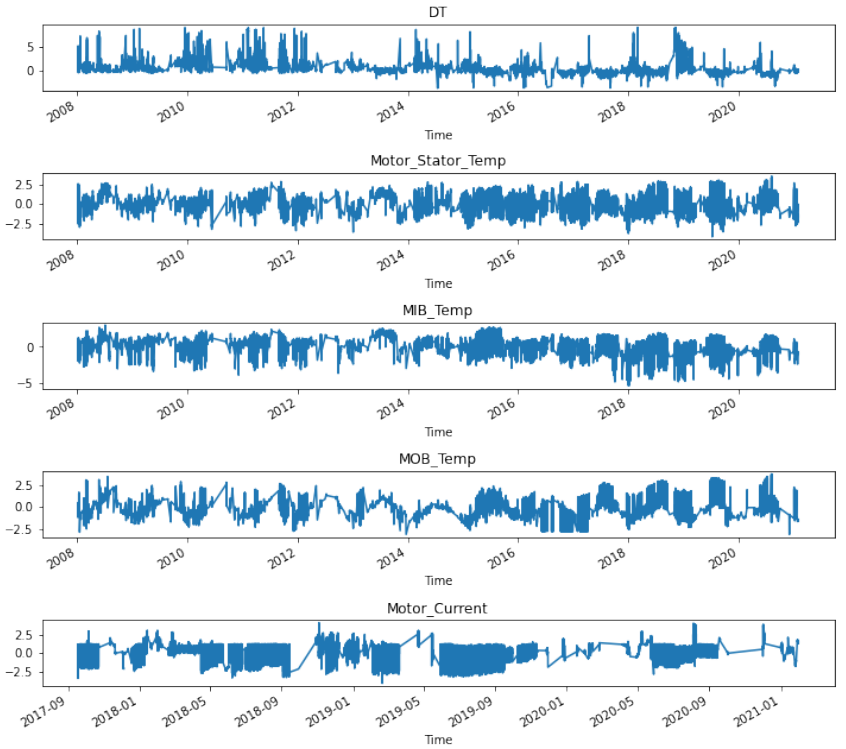


Test Case: CWS System

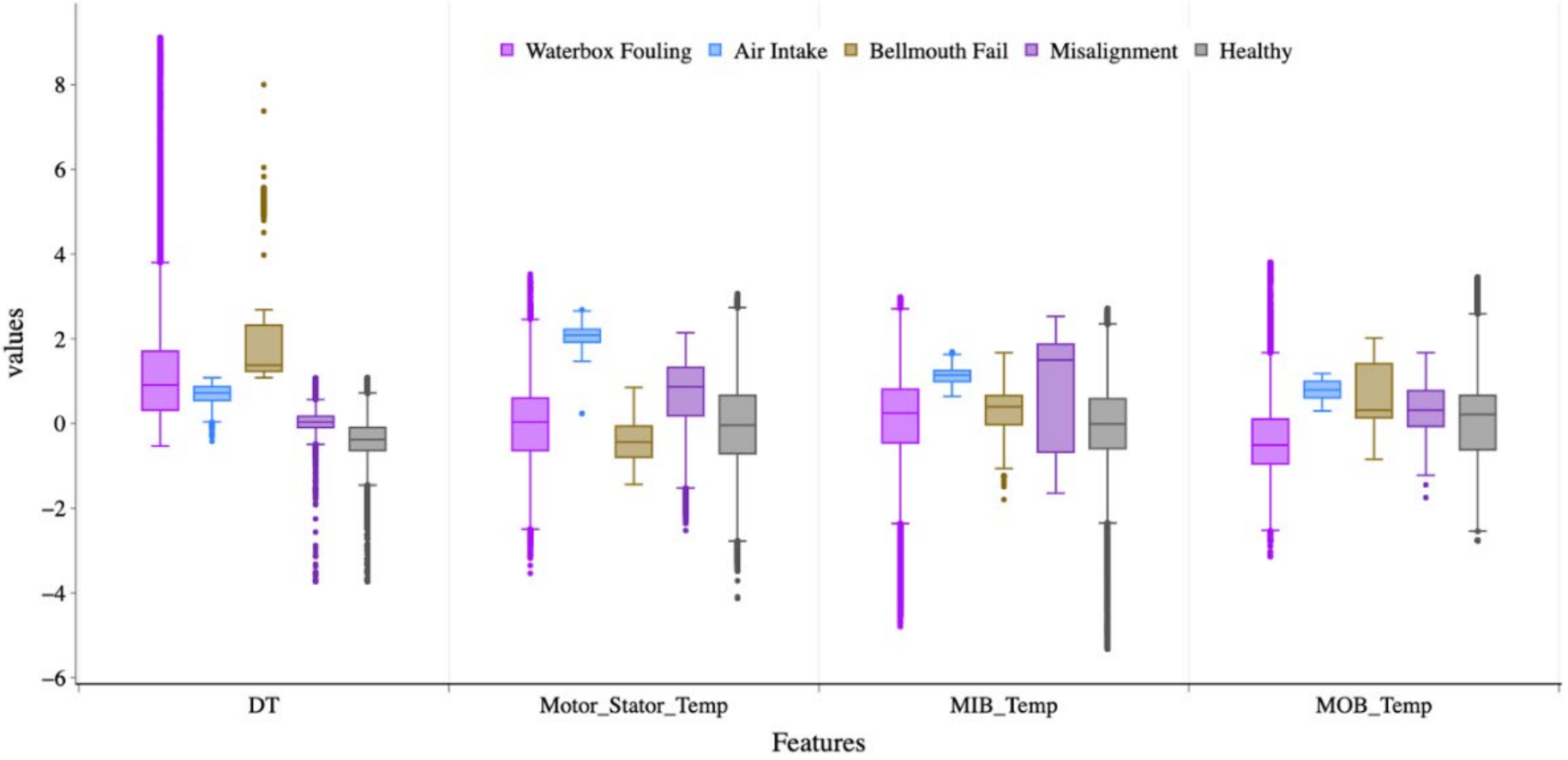
- Non-safety-related system
- Heat sink for the main steam turbine
- Architecture
  - Circulating water pumps (CWPs)
  - Trash rack and traveling screen
  - Main condenser
  - Condenser waterbox air removal system
  - Screen wash system
- Monitoring data include
  - CWP inlet river temperature (°F)
  - CWP outlet water temperature (°F)
  - CWP motor status (ON or OFF)
  - CWP stator winding temperature (°F)
  - CWP motor inboard-bearing (MIB) temperature (°F)
  - CWP motor outboard-bearing (MOB) temperature (°F)
  - CWP motor current (amps)





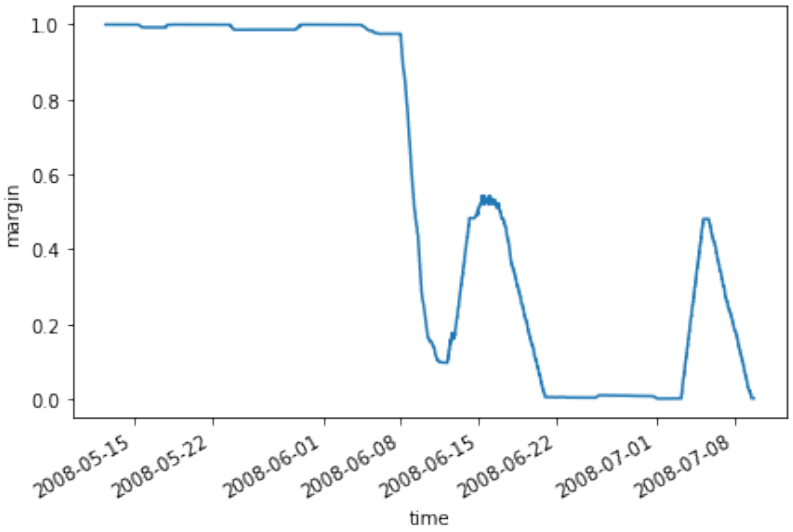
Test Case: CWS System

- Statistical analysis of condition data under normal conditions and for the considered failure modes



Test Case: CWS System

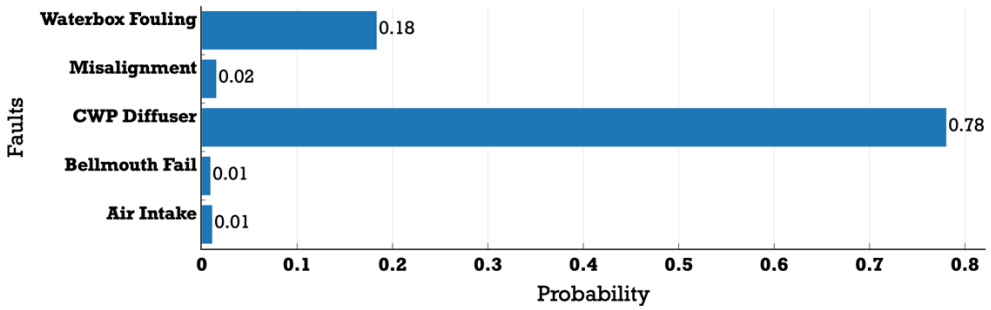
- **Margin from data**
  - Margin computation (density-based)
  - $M(\xi^{obs}) = \frac{pdf^{healthy}(\xi^{obs})}{pdf^{healthy}(\xi^{obs}) + pdf^{faulty}(\xi^{obs})}$
  - Example: air intake failure mode

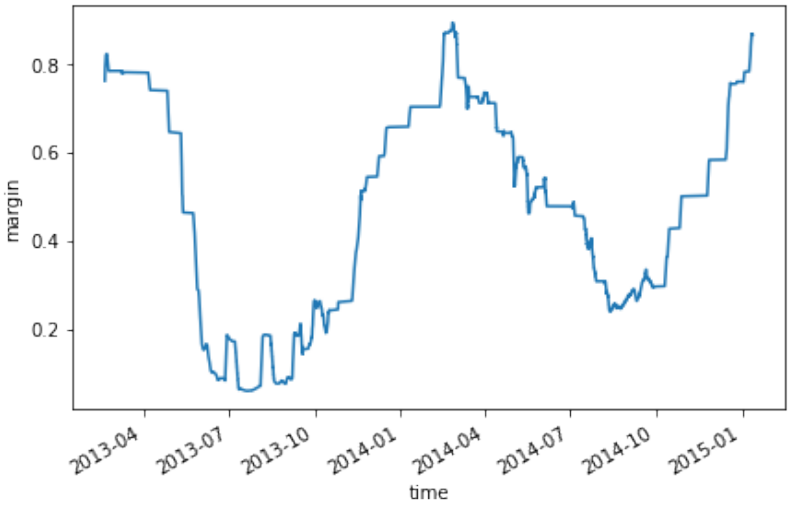


- **Margin from ML models**
  - XGBoost binary classifier (nominal vs. abnormal conditions)

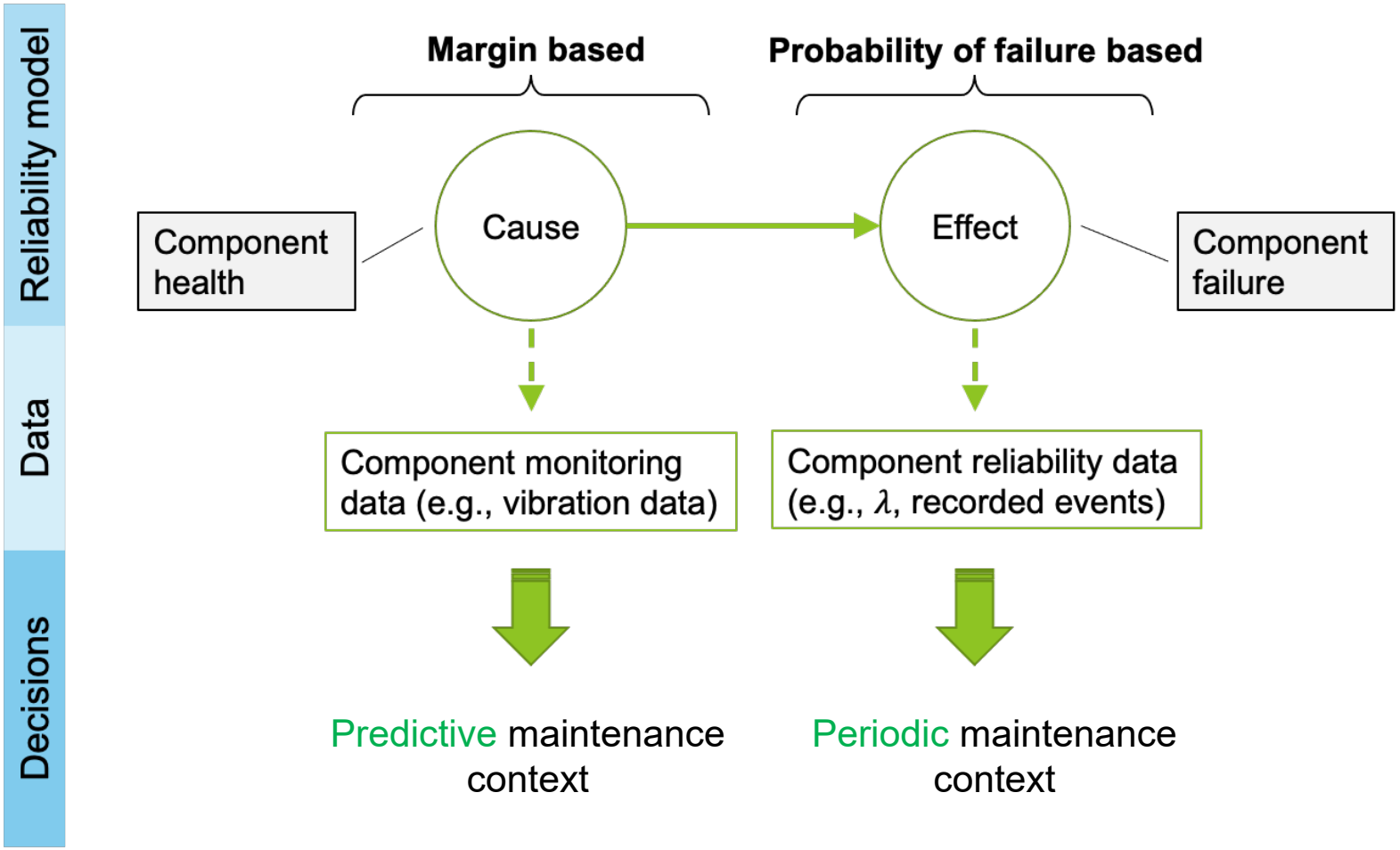
Time	Condition	Probability
2020-04-01	Unhealthy	0.873438

  - Diagnostic model: Multiclass classifier. For CWP data, it predicts the type of fault a CWP is currently undergoing





Classical vs. Margin-Based Reliability



Final Remarks

- Recall that reliability should assess system health by integrating health information of all its components
- Our work: A margin-based reliability approach designed to integrate condition-based, diagnostic, prognostic, and anomaly detection models
  - Heterogenous equipment reliability data elements and ML models can be employed to assess asset status via a margin value
  - Margin serves as an analytical measure of asset health
- Developed and tested a novel way to assess system health
  - Propagate margin values from the component to the system level
  - Directly addresses the limitations of classical reliability modeling approaches