INL/MIS-24-81826

D. Mandelli, C. Wang,
C. M. Godbole, V. Agarwal

System Engineer Approach to Capture and Analyze Equipment Reliability Data

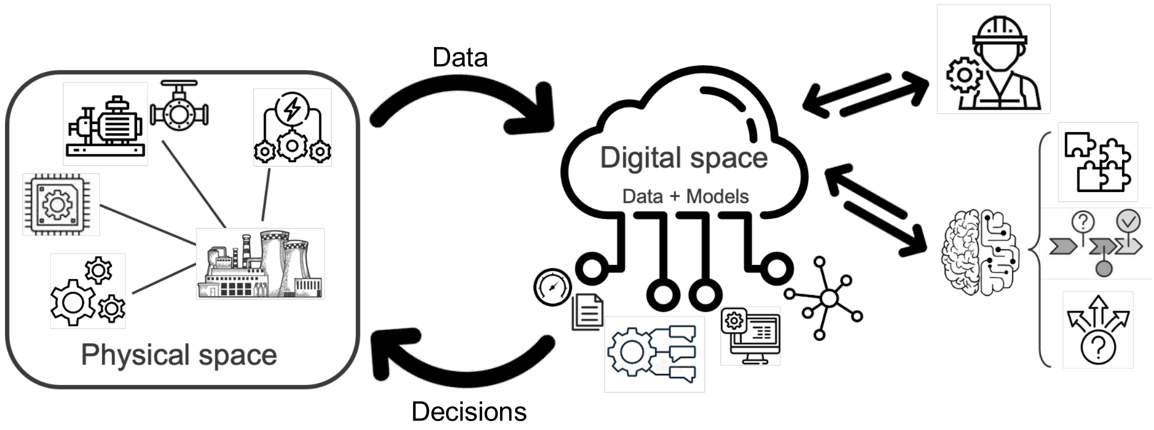
Context: Predictive Maintenance

- **Focus of this talk:** Creating a direct link between data and decisions through data analytics methods
- **Data:** Nuclear power plants collect large amounts of data elements
  - Record health performance throughout the lifecycle of assets
  - Can provide system engineers with insights into
    - Anomalous behaviors or degradation trends
    - Possible causes and their direct consequences
  - Data formats
    - Numeric: online monitoring data (e.g., pump vibration data)
    - Textual: issue reports and maintenance reports

Need to integrate information contained in numeric and textual data elements

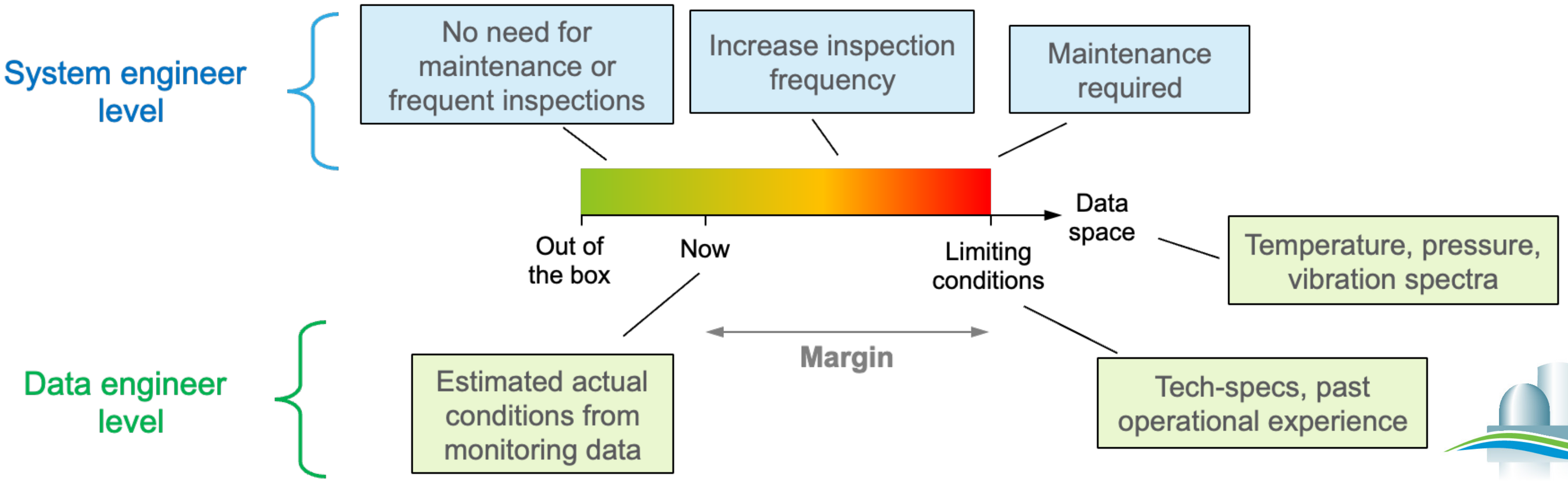
- **Decisions:**
  - Manage plant resources effectively
  - Automate decision process
- **Application:** Circulating water system (CWS) of an existing nuclear power plant
- **Special thanks:** Ontario Power Generation (Canada)

Industry 4.0 Operational Context



Assessment of Asset and System Health

- **Reliability mindset**
  - Assess system health by integrating health information of all its assets
  - Identify the most critical assets that need attention
- **State of practice reliability methods** have limitations when dealing with condition-based data
  - **The problem** is that we think in terms of failure rates or probabilities
- **What if we re-think about reliability in terms of margins?**
  - **Margin definition:** The "distance" between present status and an undesired status for an asset
  - Margin value of an asset is based solely on actual and historic data
  - Analytical measure of the health of an asset

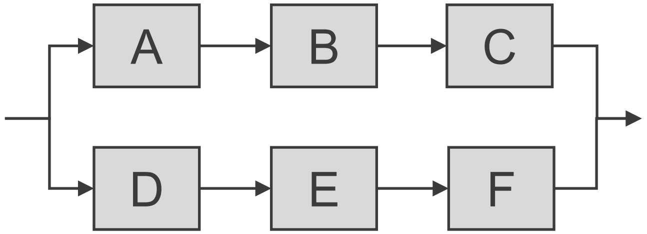


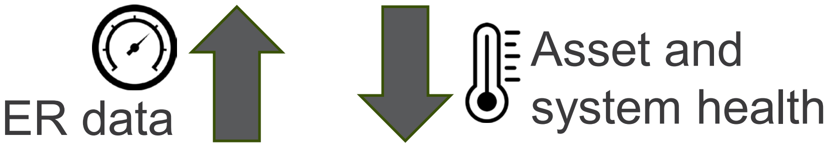
Assessment of Asset and System Health

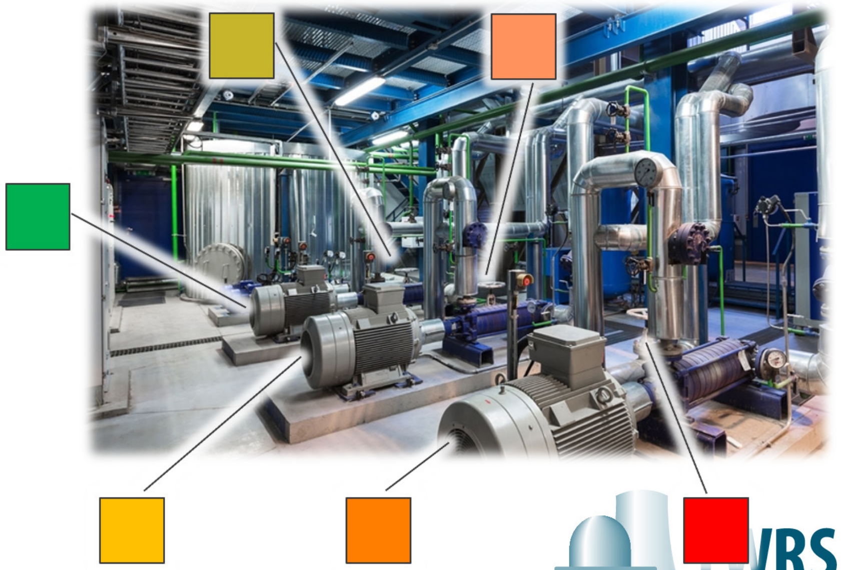
- **From asset to system level:** Propagate margin values through system reliability models
  - Analytical way to assess system health
  - Give importance measures to its assets

- **Input**
  - Condition-based and anomaly detection data
  - Diagnostic and prognostic assessments

- **Direct applications**
  - Identify minimal conditions to guarantee system operation
  - Identify the most critical assets





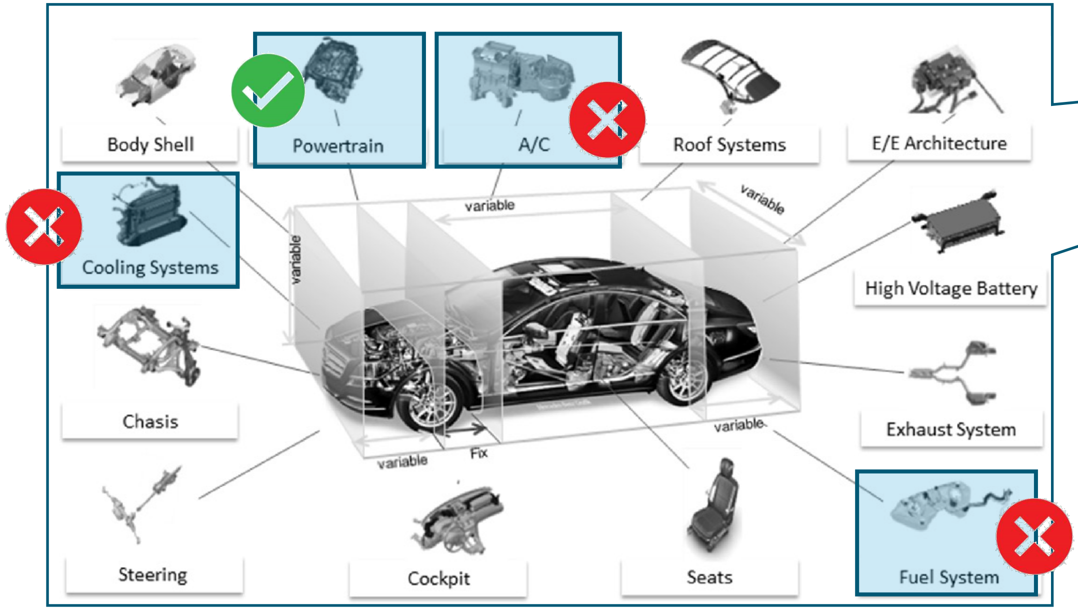


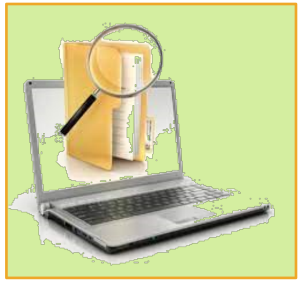
Data Analytics and Reliability: An Intuitive Example

Asset

Data

Abnormal event





Check

Fix

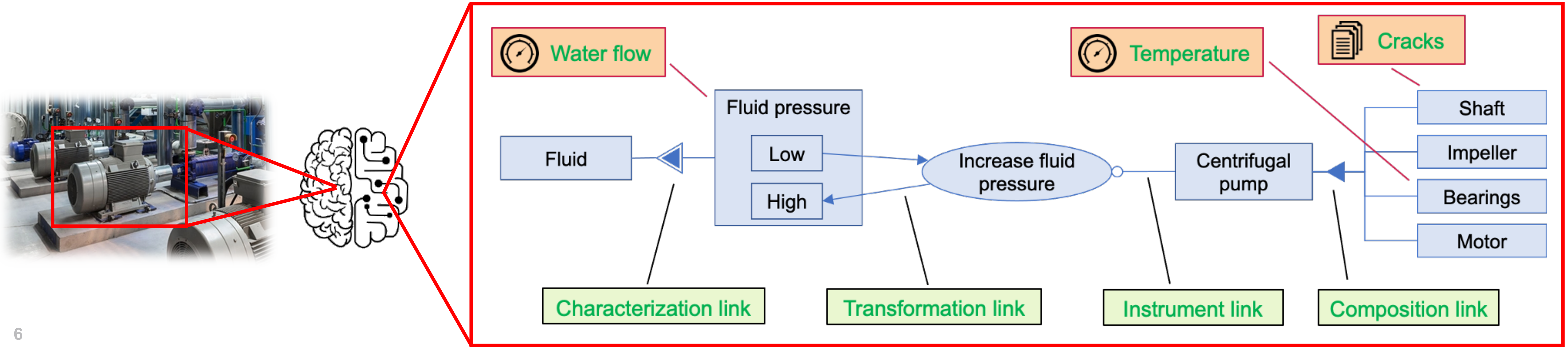
Restore

Record

Putting Data into Context

- **Claim:** Pure data-centric methods do not support robust and resilient decisions
- **Challenge:** Provide context to available data (toward machine reasoning)
- **Goal:** Need to emulate system engineer knowledge about assets and systems
- **Solution:** Model-Based System Engineering (MBSE) diagram-based representation
  - Identify causal links between “Form” and ”Function” elements
  - MBSE languages: Object Process Methodology (OPM), Lifecycle Modeling Language (LML)
- Link between MBSE models and data can be established
- **Machine reasoning:** Identify logical links between data elements through MBSE models

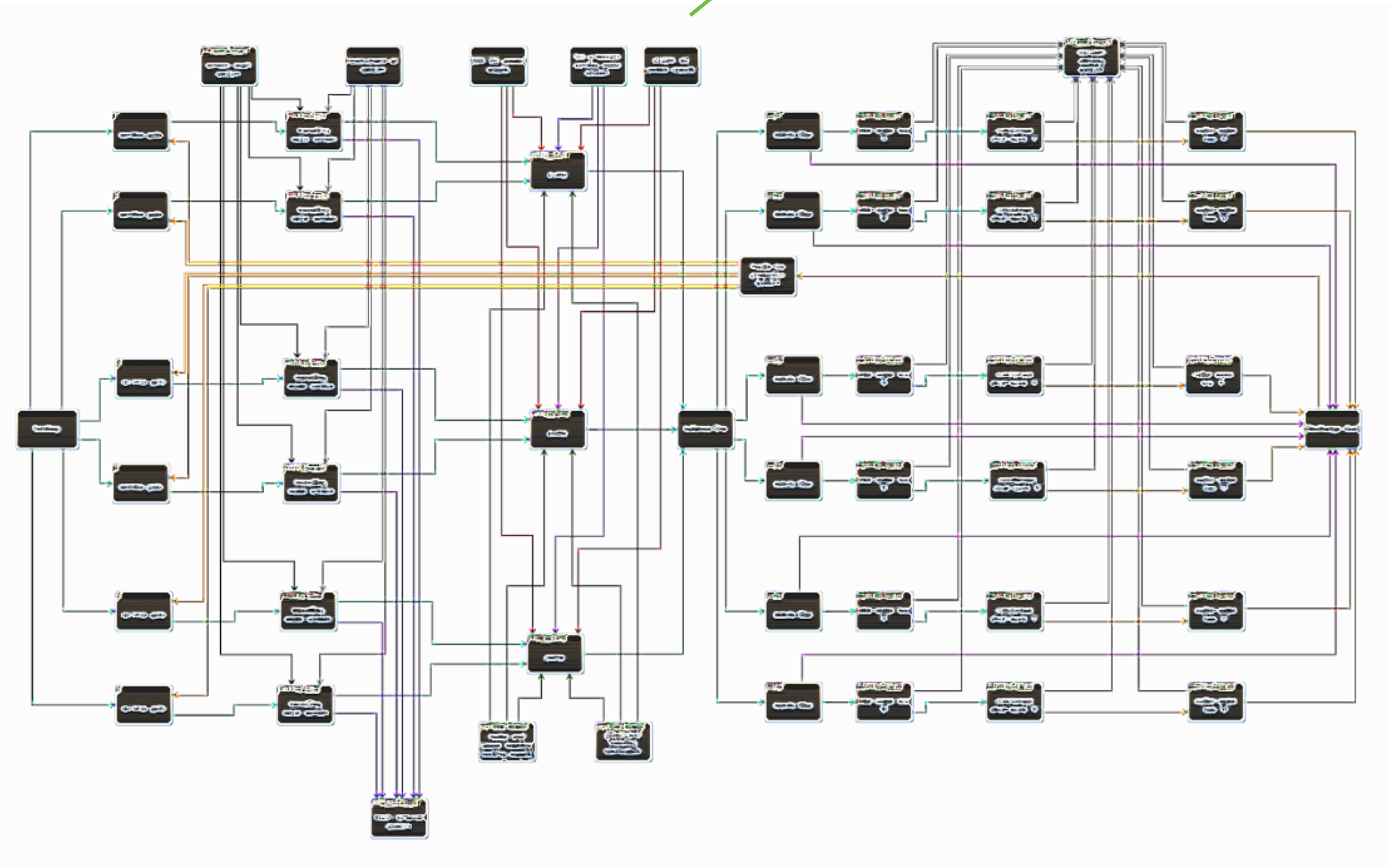
Data is not enough!



System MBSE Modeling

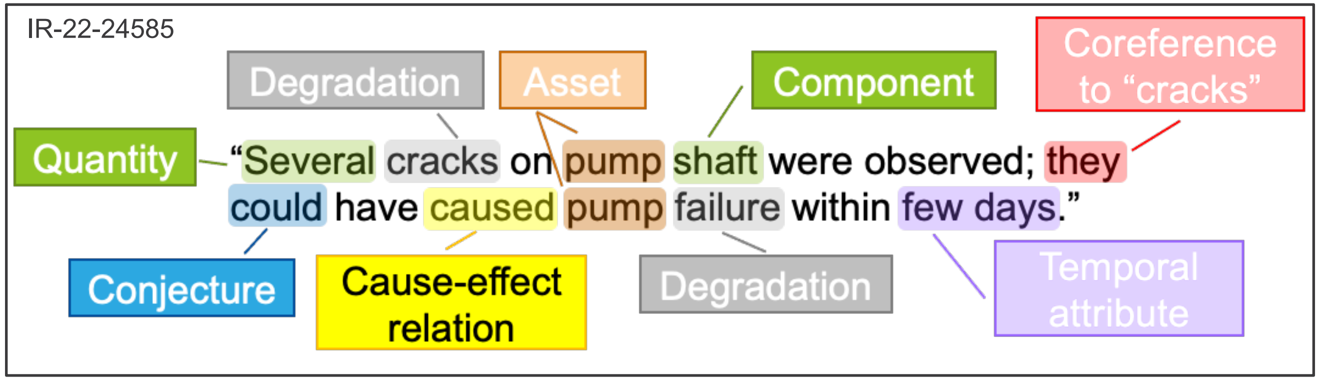
- **MBSE model structure**
  - Form (i.e., which elements are part of the structures, systems, and components)
  - Function (i.e., how systems and assets interact with each other, and which functions they support)
- **CWS model** (LML) includes
  - All major CCW assets
  - Most of CCW minor components
  - Supporting systems
  - Elements of the condenser
  - Link to existing OPM models (pumps)
  - Link to available numeric data

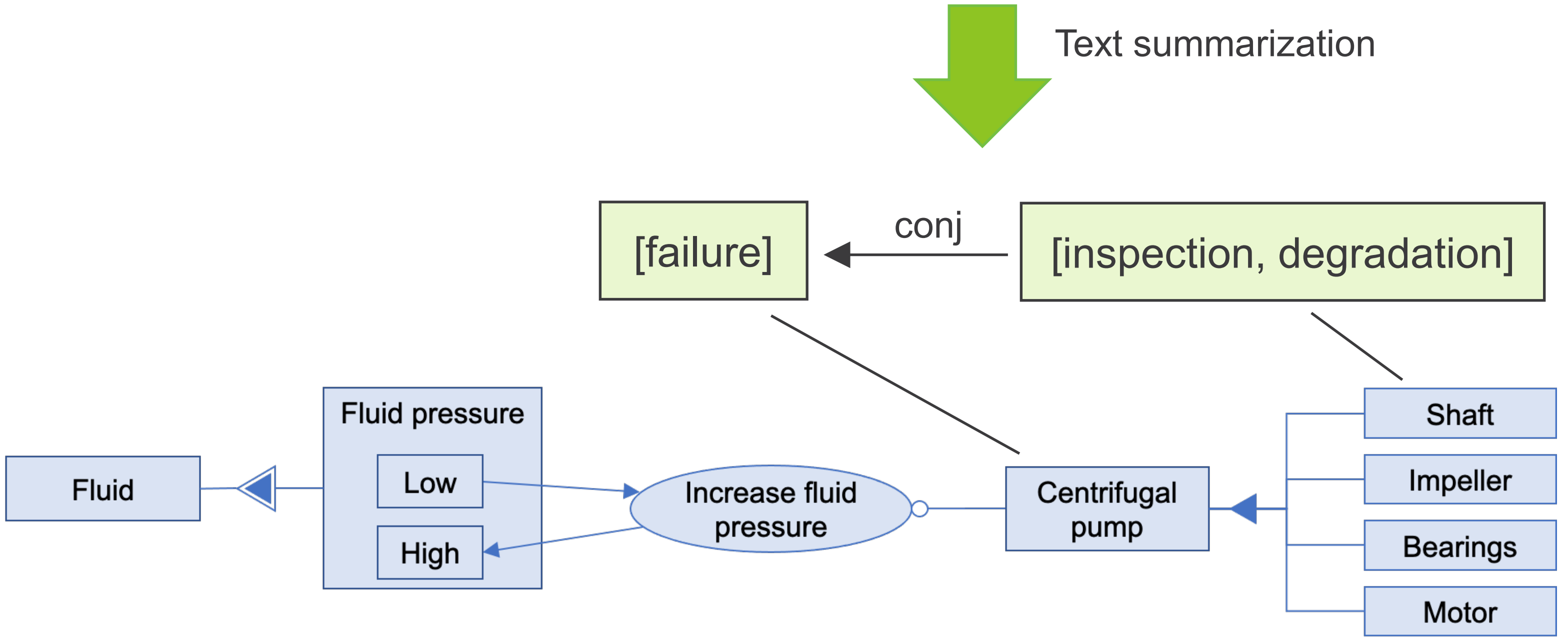
Translated into graph structure (i.e., neo4j)



Analysis of Textual Data

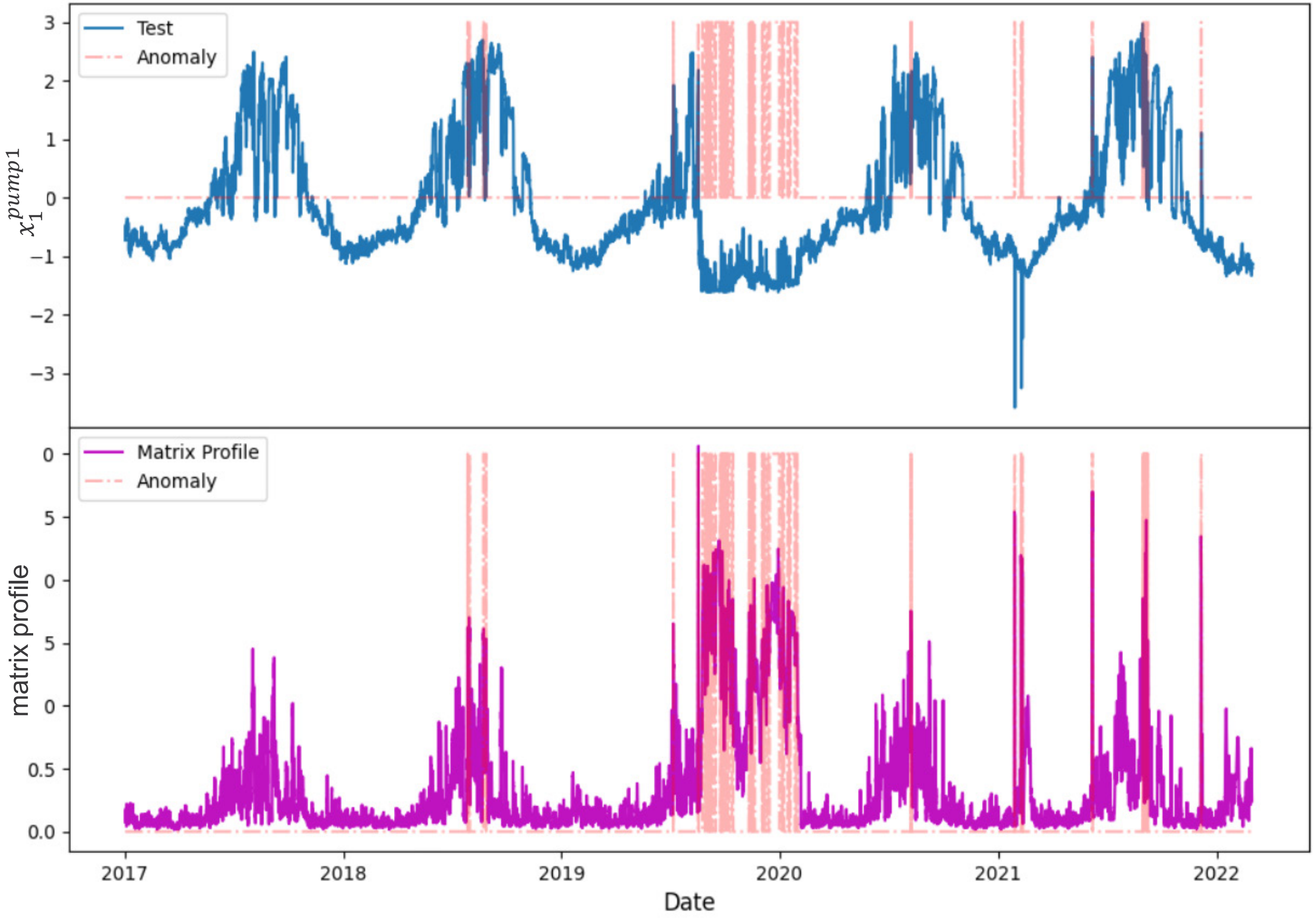
- **Technical Language Processing (TLP)** methods
  - From text to knowledge
- **Developed functionalities**
  - Spell check and abbreviation handling
  - Identification
    - Nuclear related keywords
    - Temporal and location attributes
    - Measured quantities
  - Assessment reported event
    - Event nature (e.g., inspection, maintenance)
    - Component health assessment
    - Cause-effect relations
  - Link data to MBSE model entities





Analysis of Numeric Data

- Focus on the identification of abnormal events
- Development of anomaly detection methods
  - Machine learning models
  - Matrix profile (distance based)
- Strong seasonality behaviors
- **Extension to multivariate analysis through a cause-effect lens**
  - Based on MBSE models
  - Pinpoint “patient 0” from a set of anomalies
  - Differentiate between IC- and phenomena-related anomalies

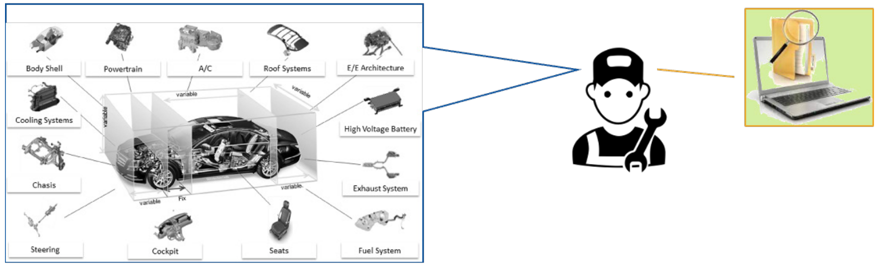


Capturing System Knowledge

- Knowledge is stored in the form of a graph database
  - MBSE graphs are the underlying skeleton
- Data elements are associated and linked to specific MBSE entities
- Data is put into an MBSE context
- Knowledge graph captures system architecture and data
- Machine reasoning: Identification of causal relationships between data elements
  - Requires two conditions: logical and temporal

System architecture

Data



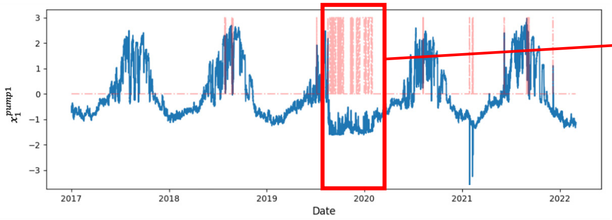
SCR #: D-204

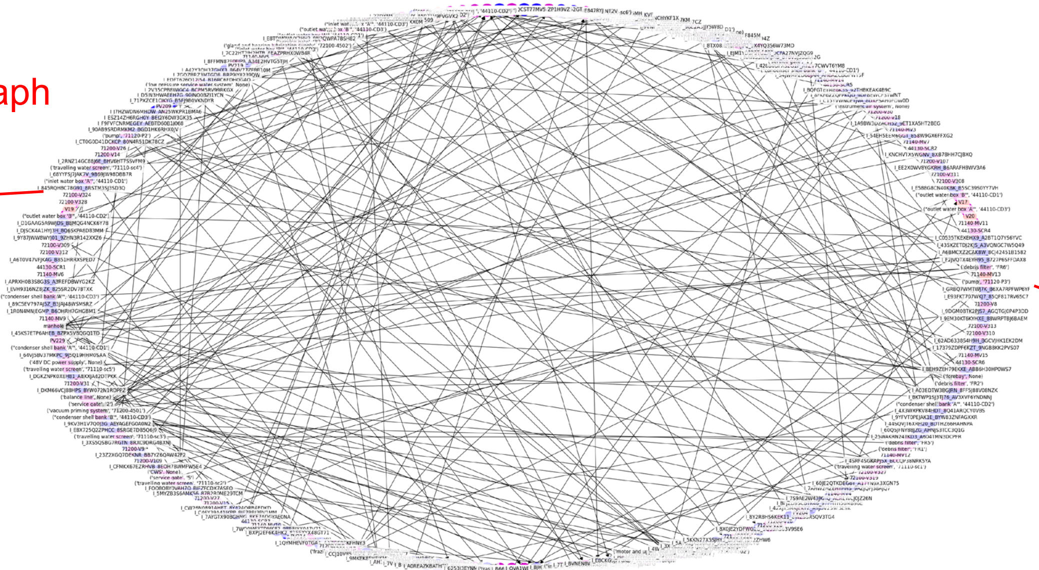
1-20-PM1 was discovered to have water/oil mixture in sight glass. Pump was shutdown.

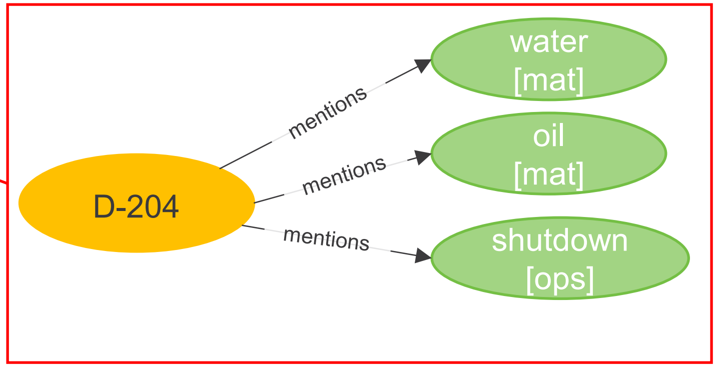
TLP

MBSE-based graph (system architecture)

Anomaly association to knowledge graph



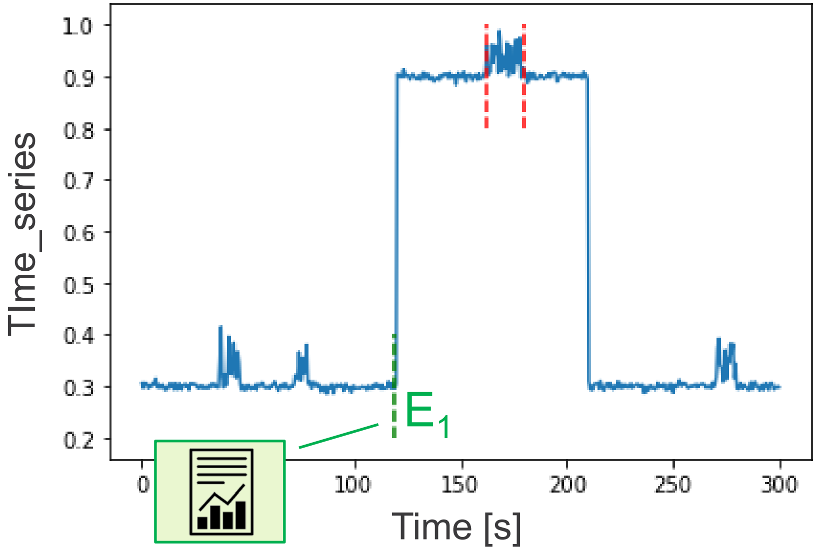




Textual data association to knowledge graph

Temporally Correlation Analysis

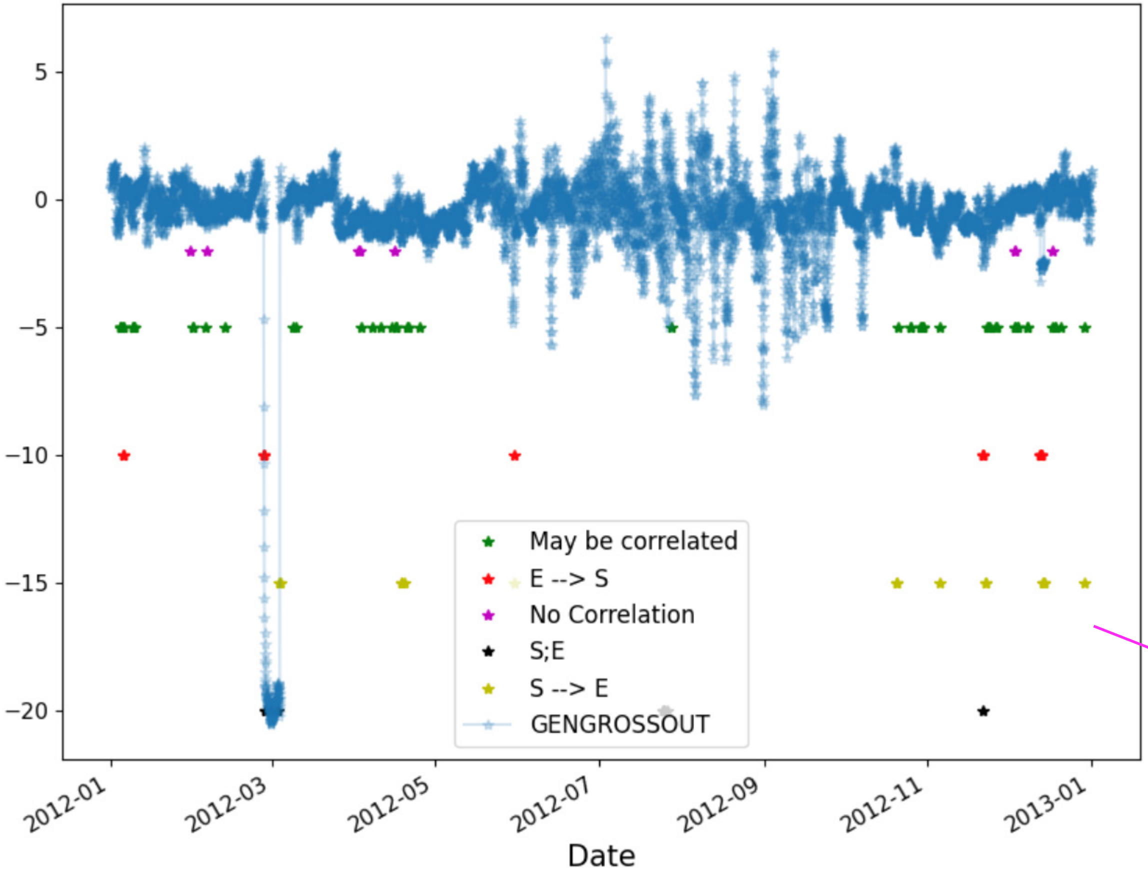
- Correlation between event and time series: Measuring statistical difference between the portions of the time series before and after the occurrence of an event
  - Two-sample hypothesis testing (Maximum Mean Discrepancy algorithm)



TLP

$$(E_1, T_1) \Rightarrow (E_1 \rightarrow TS; T_1)$$

Two-sample testing

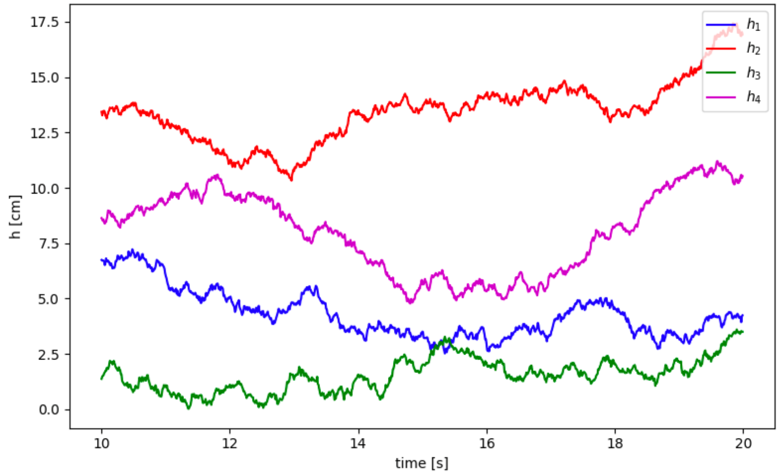


Order, concurrency and coincidence among events and time series are fully captured

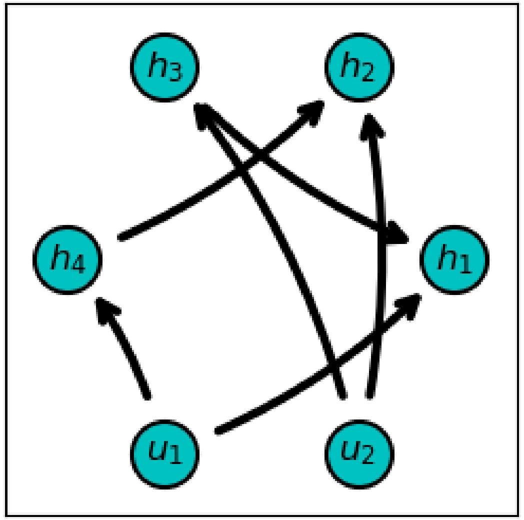
LWRS
LIGHT WATER REACTOR SUSTAINABILITY

Analysis of Numeric Data: Next Step

- Model centric approach to data analytics: Based on causal inference
- Goal: Extract causal information among observed variables
  - Discover and quantify causal relations among observed data
  - Data translated in graphs: Structural causal models



Causal inference



Def. Cause-Effect Relation (A→B).
A physical phenomena such that
a change in A leads to a change in B

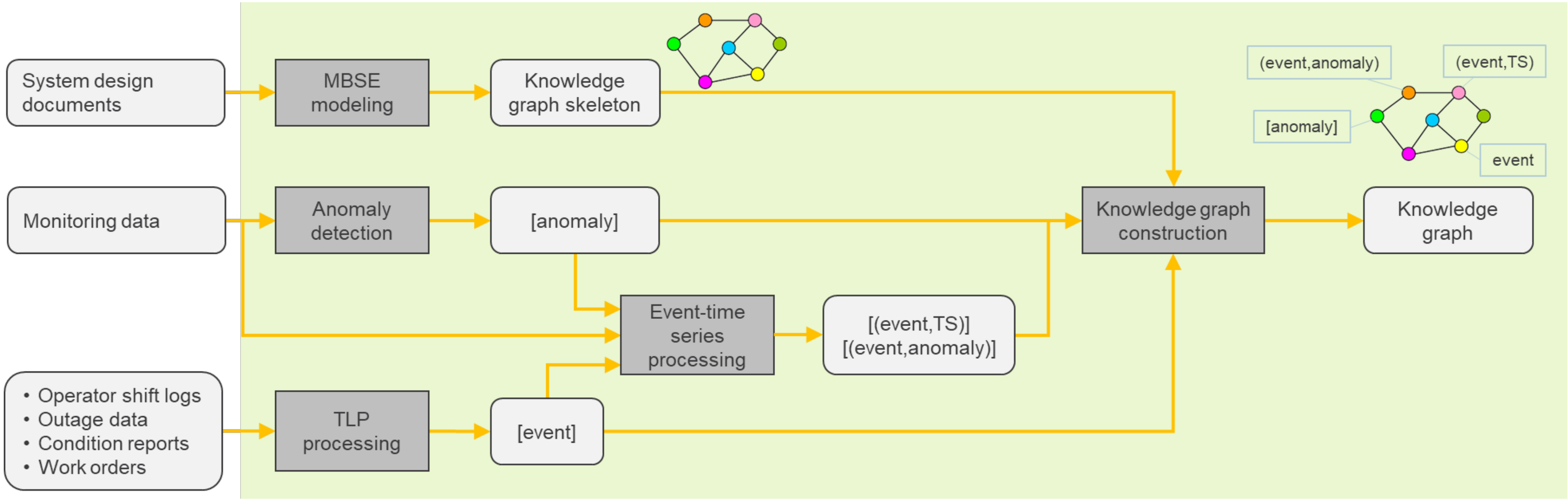
Statistical conditional independence testing

Statistical regression modeling

- Focus on the relations between variables rather rather than the variables themselves
- MBSE models are used to inform the process of causal discovery
- Applications
  - Formulate control profiles
  - Anomaly detection
  - Test hypotheses (e.g., missing edge has emerged)

Summary and Developed Workflow

- **Advanced data analytics methods**
  - Extracting knowledge from textual data
  - Quantifying asset behaviors through causal inference
  - Summarize system performance in an MBSE-based knowledge graph
- **Tool:** Digital Analytics, Causal Knowledge Acquisition and Reasoning for Technical Language Processing (https://github.com/idaholab/DACKAR)



LWRS LIGHT WATER REACTOR SUSTAINABILITY

Sustaining National Nuclear Assets

Diego Mandelli, Diego.Mandelli@inl.go

lwrs.inl.gov