Data-Driven Reliability Assessment of Cyber-Physical Production Systems

PhD Project / University of Southern Denmark
Jonas Friederich, Prof. Sanja Lazarova-Molnar
Agenda

1. Introduction to cyber-physical production systems (CPPS) and reliability assessment
2. Current challenges for reliability assessment of CPPS (in manufacturing)
3. Data-driven reliability assessment (DDRA) using process mining
4. Process-centric vs. resource-centric DDRA
5. Validation of data-driven reliability models
6. Application of data-driven reliability models for decision support
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Cyber-Physical Production Systems (CPPS)

“Cyber-World” (digital world)

Planning and controlling
- Self-organization
- Reliability
- Robustness
- Predictability
- Real-time control
- ...

Digital model

Databases

“Physical World” (real world)

Sensors/Interfaces
- Software state
- Part state
- Process state
- Operator state
- Machine state

Environment influences

Imkamp et al. (2016), Challenges and trends in manufacturing measurement technology – the “Industrie 4.0” concept
Reliability Assessment

“Reliability describes the ability of a system or component to function under stated conditions for a specified period of time.” (IEEE, 1990)
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Model Generation Challenge

At the time the physical manufacturing system changes, the model might be out of date.
Model Conformance Challenge

The actual system often does not match the initial system design.
Reliability Assessment Challenges – Overview

Manufacturing systems change frequently due to internal and external drivers (e.g. unwritten rules, demand, price uncertainty)

Manufacturing systems become increasingly complex

Reliability assessment is a labor-intensive and expert-knowledge-driven process

Models are usually static and do not reflect changes in a system

Models lack generalizability

→ need to dynamically generate accurate reliability models for manufacturing systems based on real-time data streams (especially for short-term decision making)
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Data-Driven Reliability Assessment

Manufacturing system → Data → Data preprocessing → Model generation → Simulation and analytics → Decision support

Model Validation & Verification
Process Mining as Enabler for Data-driven Reliability Model Generation

Process Mining is a novel discipline to support the analysis of operational processes based on event logs.

- **Process discovery**: Constructing a process model based on an event log
- **Conformance checking**: Comparing an existing/discovered process model with an event log
- **Enhancement**: Enhancing a discovered process model

![Diagram of process mining steps](fig source: UiPath)

![Graph of publications over years](source: Scopus)
Data Requirements

Material-flow events (Event log)

<table>
<thead>
<tr>
<th>Timestamp</th>
<th>Pr. ID</th>
<th>Resource</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>2020-11-23 16:37:40</td>
<td>2</td>
<td>Resource A</td>
<td>Start</td>
</tr>
<tr>
<td>2020-11-23 16:37:44</td>
<td>2</td>
<td>Resource A</td>
<td>End</td>
</tr>
<tr>
<td>2020-11-23 16:37:47</td>
<td>2</td>
<td>Resource B</td>
<td>Start</td>
</tr>
<tr>
<td>2020-11-23 16:37:51</td>
<td>2</td>
<td>Resource B</td>
<td>End</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

Resource state changes (State log)

<table>
<thead>
<tr>
<th>Timestamp</th>
<th>Resource</th>
<th>State</th>
</tr>
</thead>
<tbody>
<tr>
<td>2020-11-23 16:37:40</td>
<td>Resource A</td>
<td>WORK</td>
</tr>
<tr>
<td>2020-11-23 16:37:44</td>
<td>Resource A</td>
<td>IDLE</td>
</tr>
<tr>
<td>2020-11-23 16:37:45</td>
<td>Resource C</td>
<td>FAIL</td>
</tr>
<tr>
<td>2020-11-23 16:37:46</td>
<td>Resource D</td>
<td>REPAIR</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

Condition monitoring data

<table>
<thead>
<tr>
<th>Timestamp</th>
<th>Resource</th>
<th>Sensor Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>2020-11-23 16:37:40</td>
<td>Resource A</td>
<td>0.43</td>
</tr>
<tr>
<td>2020-11-23 16:37:41</td>
<td>Resource A</td>
<td>0.89</td>
</tr>
<tr>
<td>2020-11-23 16:37:42</td>
<td>Resource A</td>
<td>0.9</td>
</tr>
<tr>
<td>2020-11-23 16:37:43</td>
<td>Resource A</td>
<td>0.84</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

Friederich et al. (2022), Process Mining for Dynamic Modeling of Smart Manufacturing Systems: Data Requirements
C:\Projects\curioustoday_partnertomorrow>python twocell.py
Log Replay
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**Process-centric vs. Resource-centric DDRA**

### Process-centric DDRA

- Suitable for simple flow-lines
- 1:1 relationship between resources (e.g., machines) and activities
- Material flow/Manufacturing process is of interest
- Sequence of activities for each production order in event log is used to discover process model

### Resource-centric DDRA

- Suitable for more complex production lines
- m:n relationship between resources and activities
- Resource connectivity is of interest
- Sequence of resources used for each production order is used to discover process model
Process-centric DDRA

Friederich & Lazarova-Molnar (2022), Data-driven Reliability Modeling of Smart Manufacturing Systems using Process Mining
Reconfigurable Manufacturing System
Extracted resource-centric reliability model

Friederich et al. (2023), Equipment-centric Data-driven Reliability Assessment of Complex Manufacturing Systems (in review)
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Validation of Data-driven Reliability Models

- Data-driven reliability models need to be validated continuously
- Both input-output transformations (IOT) and historical input data (HID) can be used
- Extracted Petri nets are simulated using discrete-event simulation
- Key-performance indicators:
  - Production volume
  - Throughput
  - Cycle time
  - Resource downtime
  - System downtime
  - Resource utilization
  - …

Friederich et al. (2023), Equipment-centric Data-driven Reliability Assessment of Complex Manufacturing Systems (in review)
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# Application of Data-driven Reliability Models

- Extracted and validated models can be used to support decisions of various kind, for example:

<table>
<thead>
<tr>
<th>Decision type</th>
<th>Decision</th>
<th>Description</th>
<th>Adjustments in reliability model</th>
</tr>
</thead>
<tbody>
<tr>
<td>System configuration/purchase decisions</td>
<td>Resource efficiency</td>
<td>Increasing/decreasing resource efficiency</td>
<td>Adjust distribution of resource activity transition</td>
</tr>
<tr>
<td></td>
<td>Resource reliability</td>
<td>Increasing/decreasing resource reliability</td>
<td>Adjust distribution of resource failure transition</td>
</tr>
<tr>
<td></td>
<td>Equipment redundancy</td>
<td>Adding/removing a resource</td>
<td>Duplicate existent resource sub-model in reliability model</td>
</tr>
<tr>
<td></td>
<td>Routing</td>
<td>Increasing/decreasing utilization of equipment</td>
<td>Adjust firing probabilities that represent routing decisions</td>
</tr>
<tr>
<td>Maintenance</td>
<td>Preventive maintenance</td>
<td>Introduce preventive maintenance</td>
<td>Reset delay of resource failure transition after specified time</td>
</tr>
<tr>
<td>Maintenance staffing</td>
<td>Better maintenance staff</td>
<td>Better maintenance staff</td>
<td>Adjust distribution of equipment repair transition</td>
</tr>
<tr>
<td>Maintenance scheduling</td>
<td>Prioritization of repairs</td>
<td>Prioritization of repairs</td>
<td>Add model components that represent maintenance crew as limited resource</td>
</tr>
<tr>
<td>Scheduling</td>
<td>Order scheduling</td>
<td>Improving order schedules</td>
<td>Replace distributions of arrival transitions with pre-defined schedule</td>
</tr>
</tbody>
</table>
Exemplary results
Thank you for your attention

Q&A