Building a Rigorous Foundation for Performance Assurance Assessment Techniques for “Smart” Manufacturing Systems

Utpal Roy, Yunpeng Li and Bicheng Zhu
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Motivation/Background

- Manufacturing System and Goal
  - A production Plant
  - 4 equivalent product lines: L1, L2, L3 and L4

- Basic Indicators: Local Performance

- Aggregated Indicators: Global Performance

- Challenging Job

Nature of non-uniqueness

Bad Indicators give long term effect on the company: Inertia
Nature of non-uniqueness

- Non uniqueness of choice of basic indicators
  - L1, L2, L3 and L4
  - Goal: low defectiveness

\[ I_1 = "\text{number of rejected parts}\" \]
\[ I_{1*} = \min\{I_1(L1), I_1(L2), I_1(L3), I_1(L4)\} \]

\[ I_2 = "\text{number of defects detected}\" \]
\[ I_{2*} = \min\{I_2(L1), I_2(L2), I_2(L3), I_2(L4)\} \]

<table>
<thead>
<tr>
<th></th>
<th>I1</th>
<th>I2</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>35</td>
<td>43</td>
</tr>
<tr>
<td>L2</td>
<td>25</td>
<td>39</td>
</tr>
<tr>
<td>L3</td>
<td>17</td>
<td>45</td>
</tr>
<tr>
<td>L4</td>
<td>21</td>
<td>25</td>
</tr>
</tbody>
</table>
Nature of non-uniqueness

- Non uniqueness of choice of aggregated indicators

- L1, L2, L3 and L4
- Goal: best production line

(1) Weighted sum => L2 is best, assuming same weightage

(2) Borda’s Approach: Sum of every line’s rank and Pick the one with lowest value

=> L1 is best

\[ I_{agg}(L1) = 2 + 2 + 1 = 5 \]
What we learn?

Finding:
- KPAI > Indicator
- Selection of KPAI is difficult.

Proposal:
- Ontology based Case reasoning approach for selection
- Simulation based testbed for evaluation

Focus in this paper:
- A preliminary PA Ontology and KPI ontology, Data Driven Simulation Testbed
Overall Framework

Step 1: Process specification
Step 2: Performance goals or standards specification
Step 3: Retrieval of KPAI
Step 4: Collect data
Step 5: Analyze/report actual performance
Step 6: Compare actual performance to goal/standard
Step 7: Definition of corrective actions
Framework For KPAI Selection

KB & Training Data Pool

<table>
<thead>
<tr>
<th></th>
<th>Meta Level</th>
<th>Upper Level</th>
<th>Domain Level</th>
<th>Application Level</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mereology</td>
<td>Topology</td>
<td>System</td>
<td>Performance Assurance</td>
</tr>
<tr>
<td></td>
<td>Data Structure</td>
<td></td>
<td></td>
<td>Supply Chain Performance Assurance</td>
</tr>
<tr>
<td></td>
<td>Supply Chain</td>
<td>Manufacturing</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Using KB & Training Data Pool

<table>
<thead>
<tr>
<th>Case</th>
<th>f1</th>
<th>f2</th>
<th>f3</th>
<th>...</th>
<th>KPAI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>Xx</td>
<td>xx</td>
<td>xx</td>
<td>...</td>
<td>K1</td>
</tr>
<tr>
<td>Case 2</td>
<td>xx</td>
<td>xx</td>
<td>xx</td>
<td>...</td>
<td>K3</td>
</tr>
<tr>
<td>Case 3</td>
<td>xx</td>
<td>xx</td>
<td>xx</td>
<td>...</td>
<td>K3</td>
</tr>
</tbody>
</table>

Using output KPAI
“Hyper Cube” Model

- Represent high-dimensional information
  - x-axis: Product
  - y-axis: Process
  - z-axis: System Intelligence
  - Each cell: a physical system
    - Entities, processes, and data inputs/outputs

\[ \text{ManufacturingSystemModel} = f(\text{Product, Process, System Intelligence}) \]
## Terms in "Hyper Cube" Model

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Term</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product</td>
<td>Artifact</td>
<td>Part or Product</td>
</tr>
<tr>
<td>Plant</td>
<td>Resources</td>
<td>(materials, machines, fixtures, handling equipment, and labors) required to transform raw materials into a finished product.</td>
</tr>
<tr>
<td>Organization</td>
<td>Functional units</td>
<td>(R&amp;D, manufacturing, sales, service, etc.)</td>
</tr>
<tr>
<td>Supply Chain</td>
<td>System of organizations</td>
<td>(people, activities, information, and resources involved in moving a product or service from suppliers to end customers)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Process</th>
<th>Unit Process</th>
<th>the minimum collection of a set of Activities: e.g. drilling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process Group</td>
<td>a set of Unit Processes in the same category. e.g. machining steps</td>
<td></td>
</tr>
<tr>
<td>Production</td>
<td>different Process Groups to transform the raw material to the finished product. e.g. process plans</td>
<td></td>
</tr>
<tr>
<td>Distributed Production</td>
<td>A decentralized manufacturing process located across a network of geographically dispersed manufacturing facilities. e.g. distributed process plan</td>
<td></td>
</tr>
</tbody>
</table>
## Terms in “Hyper Cube” Model

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Term</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>System Intelligence</td>
<td>Data Collection</td>
<td>Data gathering, data fusion, and data cleaning</td>
</tr>
<tr>
<td></td>
<td>Data Analytics</td>
<td>statistical inference, simulation, machine learning, data mining, and advanced data analytics.</td>
</tr>
<tr>
<td></td>
<td>Scenario Analysis</td>
<td>domain knowledge that governs the scenarios generation, evaluation, comparison and optimization.</td>
</tr>
<tr>
<td></td>
<td>Decision Making</td>
<td>making decisions based on the data analytical results, corporate strategies, and external regulations.</td>
</tr>
</tbody>
</table>
The Hypercube for a Sustainable Manufacturing Scenario

Model: Sustainable Manufacturing System
- Product KPI: Functionality, Quality, Manufacturability
  - Production KPI: Batch Yield, Material Efficiency, Energy Efficiency, OEE
- System KPI: Asset Utilization, Agility, Sustainability

Space: Design for 'X', LCA, ...
- Quality Function Deployment
- Design for Assembly Rules
- Design for Machining Rules
- Design for Injection Molding Rules
- Design for Die Casting Rules
- Life Cycle Inventory Data
- Life Cycle Assessment Model
- Regulation Rules

Pt: Plant
- Raw Materials
- Part/Assembly (Shape, Material, Tolerance)
- Plant Layout
- Machines, Fixtures
- Handling Equipment, Assembly Line and Robotics

Sustainable Manufacturing Plant

System Intelligence
- Decision Making
- Scenario Analysis
- Data Analytics

Decision Tree:
- Distributed Production
- Production
- Process Group
- Unit Process
- Artifact (1,0)
- Plant (2,0)
- Organization (3,0)
- Supply Chain (4,0)
Ontological Formulation of PA Information

- Assurance_Provider
- Recipient
- Assurance_Scope
- Goal
- Level of Action
Ontological Extension for KPAI

**KPI: K1**

- **hasName**: String: Availability
- **useIn**: Machining System 1
- **hasGoalValue**: Double: 0.95
- **isDefinedBy**: MTTF/(MTTF + MTTR)
- **hasDimension**: Null
- **feedTo**: Null

**KPI: K2**

- **hasName**: String: MTTF
- **useIn**: Machining System 1
- **hasGoalValue**: Double: 1000h
- **isDefinedBy**: 1/(tIn(Reliability))
- **hasDimension**: Time
- **feedTo**: K1

**KPI Categories**

- **Financial**: Personnel, Logistics, Learning and Innovation, Supply Chain, Manufacturing, Inventory Logistics, Reverse Logistics
- **Manufacturing**: Product Quality, Quantity, Reliability, Responsiveness, Agility, Costs, Assets, New Product Development Related, Training Related
- **Logistics**: Customer, Staff, Personnel, Logistics, Supply Chain, Reliability, Responsiveness, Agility, Costs, Assets
- **Energy Consumption**: Resource Use, Emission, Waste, Product, Quantity, Quality, Customer, Staff, Learning and Innovation, Supply Chain, Manufacturing, Inventory Logistics, Reverse Logistics
- **Auxiliary Material Consumption**: Energy Consumption, Resource Use, Emission, Waste, Product, Quantity, Quality, Customer, Staff, Learning and Innovation, Supply Chain, Manufacturing, Inventory Logistics, Reverse Logistics

**ValueSets**

- **Recipient**: Level_of_Action
- **String**: hasName
- **KPI**: hasKPI
- **Dimension**: hasKPI, hasGoalValue
- **ValueSet**: 0..* feedTo
- **ProcessLevel**: hasCategory=ProductLevel
- **ProductLevel**: hasCategory=ProductLevel
- **Level_of_Action**: {Artifact, Plant, Organization, Supply Chain}
- **Level_of_Action**: {Unit Process, Process Group, Production, Distributed Production}
## Ontological Extension for KPAI

<table>
<thead>
<tr>
<th>KPI Category</th>
<th>Level Of Action (From PA Ontology)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PRODUCT (Defined in Hypercube)</td>
</tr>
<tr>
<td></td>
<td>PROCESS (Defined in Hypercube)</td>
</tr>
<tr>
<td></td>
<td>Artifact</td>
</tr>
<tr>
<td>Manufacturing</td>
<td>Manufacturing Auxiliary Material Consumption</td>
</tr>
<tr>
<td>Logistics</td>
<td>Reverse Logistics</td>
</tr>
<tr>
<td>Supply Chain</td>
<td>Manufacturing Logistics</td>
</tr>
<tr>
<td>Learning and Innovation</td>
<td>NPD</td>
</tr>
<tr>
<td></td>
<td>Training</td>
</tr>
</tbody>
</table>
System Evaluations: Data-driven Simulation Testbed (DST)

Simulation
- Input
- Process
- Output
- Feedback

Optimization
- Input
- Optimizer
- Output

Data Analytics
- Input
- Analytical Model
- Output

Scenario Manager
- System Parameters
  - Design Variables
  - Objective Functions
  - Constraints
  - Performance Measurements

User Input
Visualization

Repository
- CAD, PLM, ERP, MES, etc.

Model
Scenario
Algorithm
Pt: Artifact and Plant
- Raw Materials (Bread)
- Plant Layout
- Machines
- Conveyor
- Handling Equipment
- ...

Ps: Packaging Production
- Material Handling
- Packaging Process
- Process Planning and Scheduling
- Transportation
- ...

SI: Maintenance Domain Knowledge
- KPAI
- Maintenance Strategy (GMO/RMO/VMO)
- Queuing Theory (FIFO/LIFO/SIRO/PQ)
- Failure Mode
- ...

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Model: Packaging System Maintenance

Production KPI
- Yield
- Utilization
- Average Output Factor
- Cost of Lost Product
- OEE
- ...

System KPAI
- Asset Utilization
- Reliability
- ...

A Bread Packaging Line System
Summary

This paper focuses on:

- Review and Identify the Performance Assurance Challenge
- An Ontology based case reasoning framework has been proposed
- Preliminary Ontology has been developed (hyper cube, PA ontology, KPI ontology)
- A Data-Driven testbed for system evaluation

Future work:

- Testing clustering with some case scenarios using the proposed ontology
- Incorporating existing metric models (SCOR model, SIMA model, etc.) into the proposed ontology