DEPARTMENT OF COMPUTER SCIENCE

UNIVERSITY OF OXFORD

Capturing Industrial Information Models with Ontologies and Constraints

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SIEMENS

Smart Factory

Automation

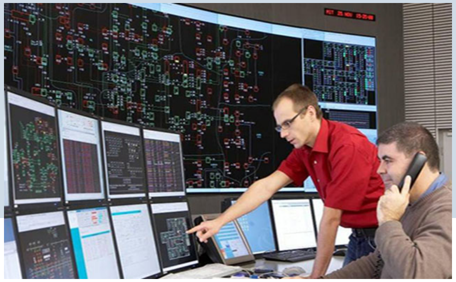
- of various individual processes
  - production
  - warehouse

(Enterprise-wide) integration

- of machines and processes
- factory as one organism

Control

- machines and processes
- monitoring, analytics, and diagnostics



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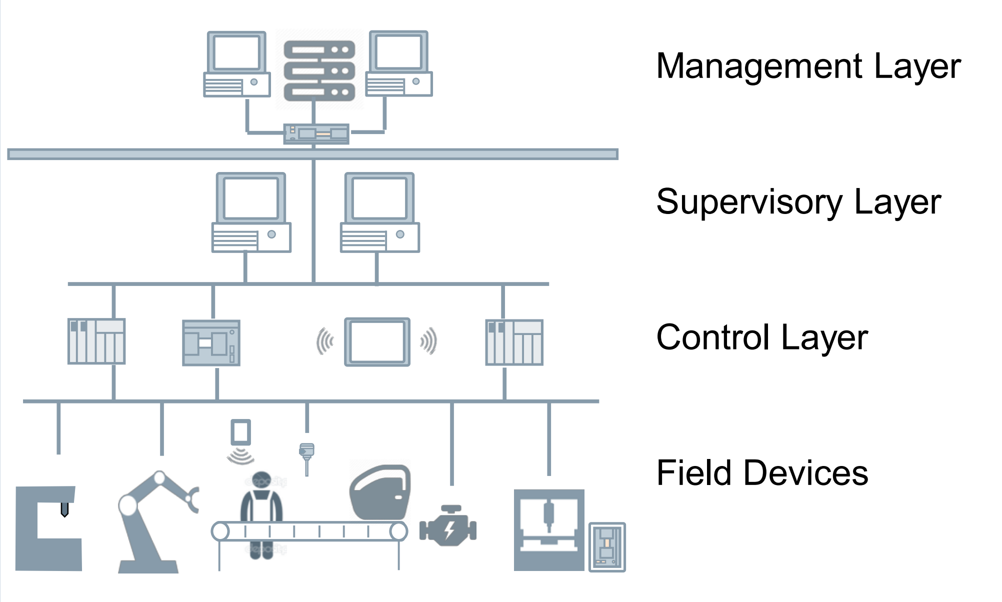
Software View on Smart Factories

Smart factory is

- fully computerized
- software-driven (system)



Software View on Smart Factories

Smart factory is

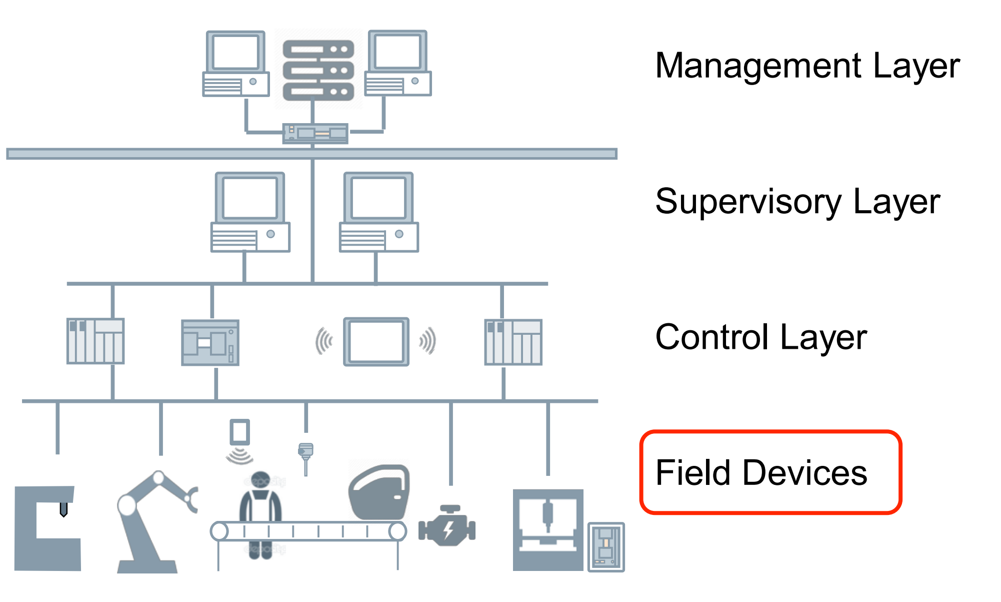
- fully computerized
- software-driven (system)

Software levels

- embedded in machines

Ex: Conveyor belt system

- simple controlling
  - positioning
  - speed
  - safety: emergency stop



Conveyor belt system

Software View on Smart Factories

Smart factory is

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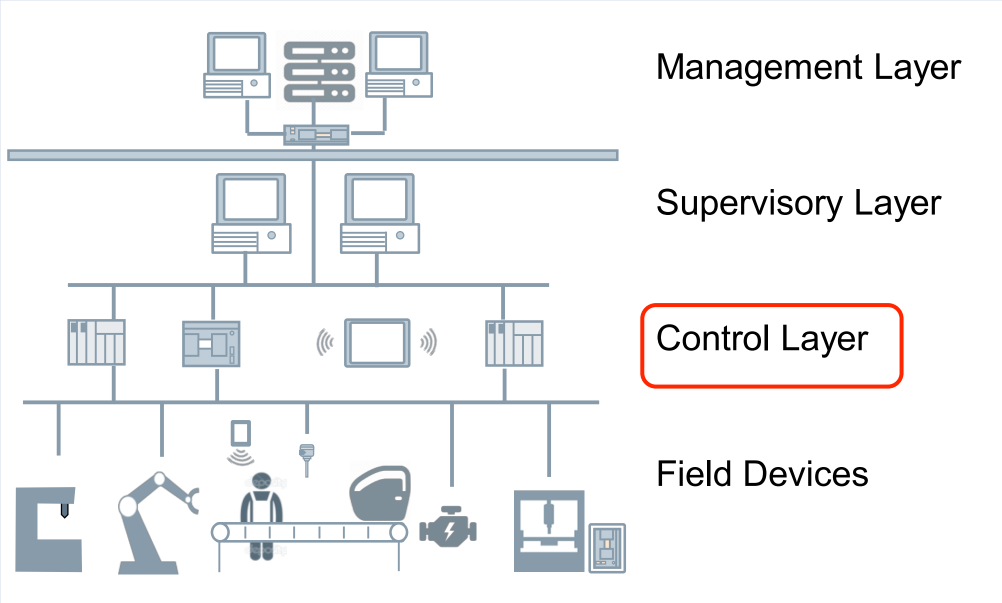
Software levels

- embedded in machines
- controlling several machines



Ex: Manufacturing conveying sub-system

- combines
  - Conveyer belt system
  - Routing system
  - Storage system
- orchestrated by complex controllers

Mechatronics Sub-System with Siemens PLC

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Software View on Smart Factories

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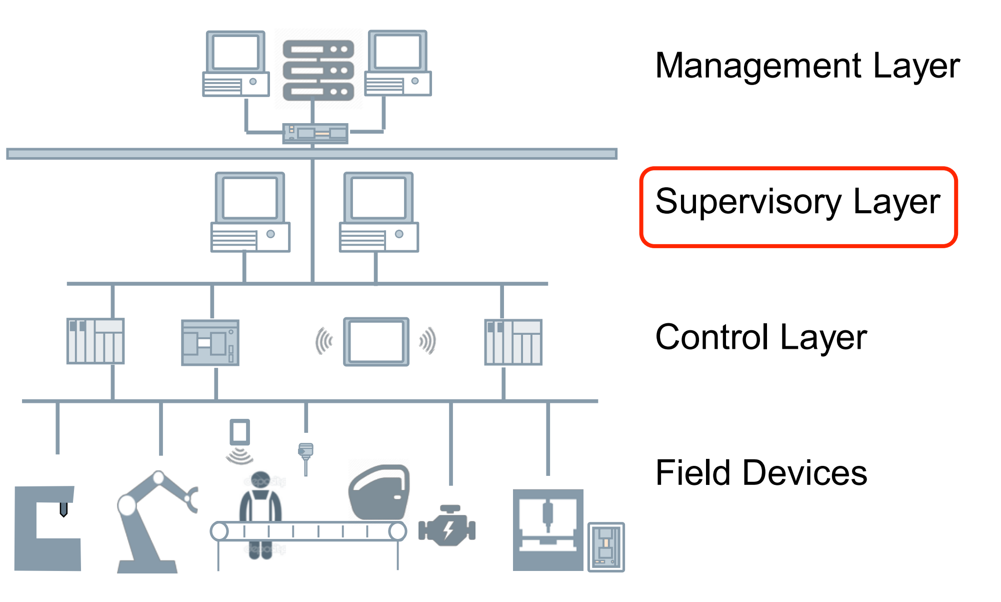
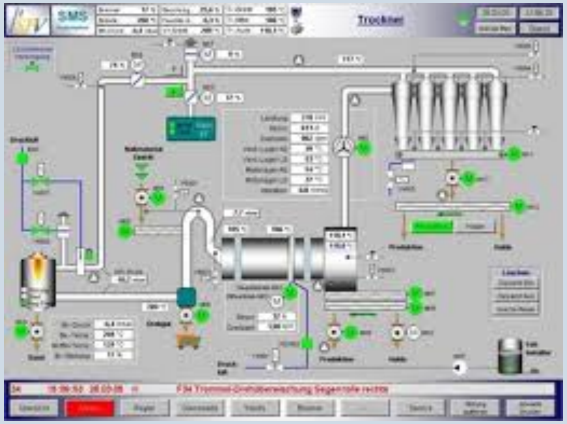
Software levels
- embedded in machines
- controlling several machines
- controlling the whole plant



Supervisory level
- plant-wide
  - integration
  - orchestration of processes
- plant-wide
  - monitoring
  - diagnostics of machines and processes



SCADA computer system

Software View on Smart Factories

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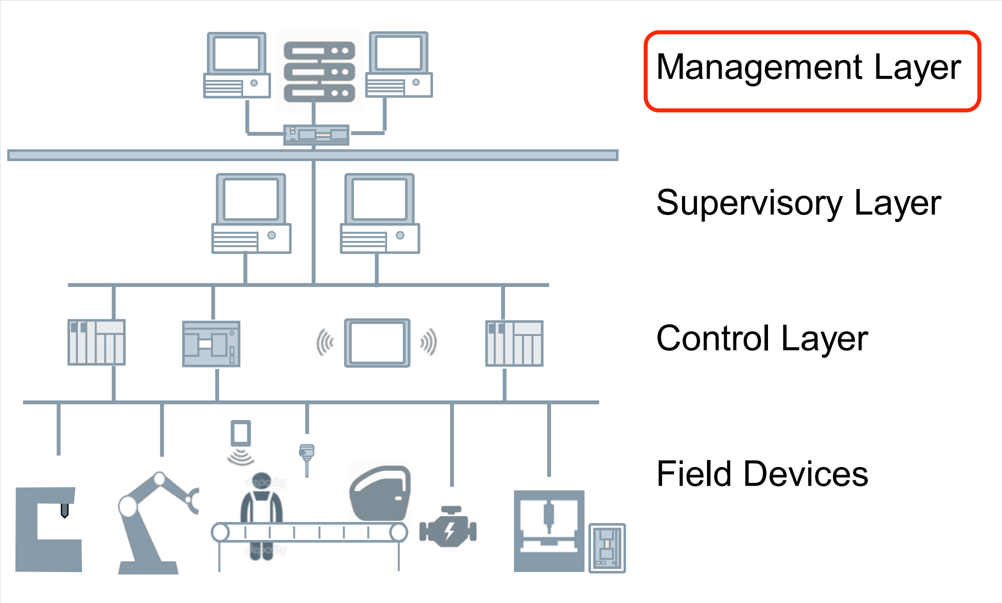
Software levels

- embedded in machines
- controlling several machines
- controlling the whole plant
- management level software
  - ERP
    - Manufacturing resource planning
    - Finance
    - Human resources



Software View on Smart Factories

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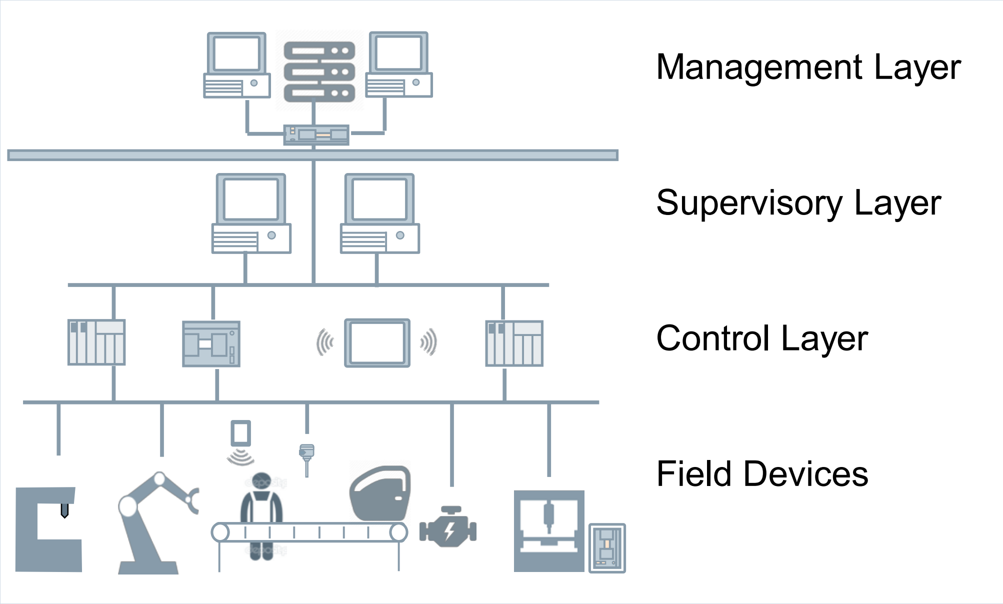
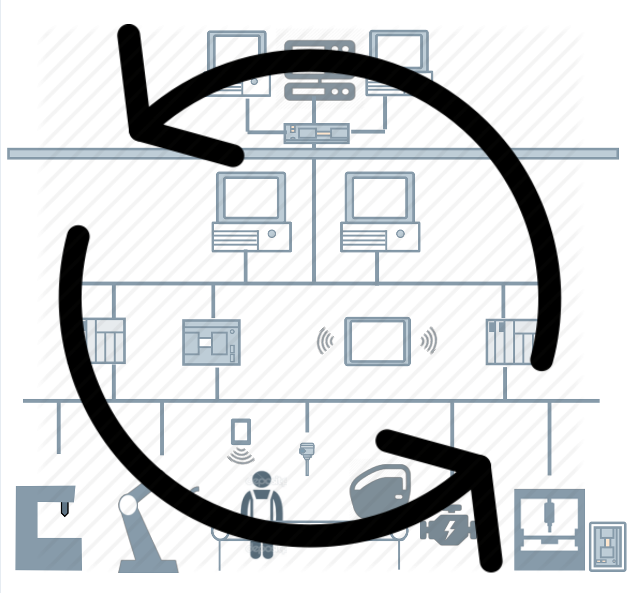


Software Challenges

Smart factory
fully computerized and software-driven



Challenges

- Software development
- Software integration

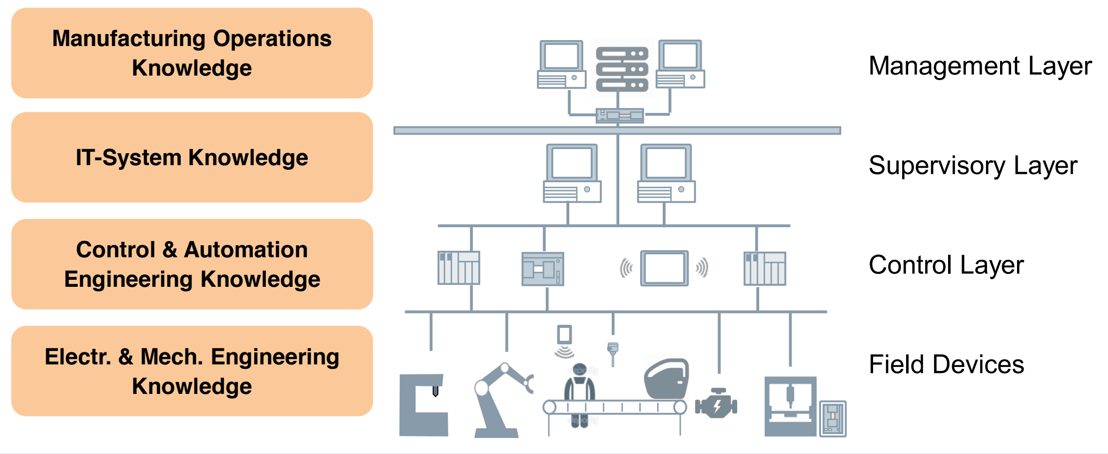
software development: ~40% of the price of manufacturing machines

estimated by Mechanical Engineering Industry Association (VDMA) [2011]

Information Models for Smart Factories

Factory-wide info. models

- address challenges
  - SW development
  - SW integration
- capture knowledge on all SW levels



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Information Models for S

Factory-wide info. models

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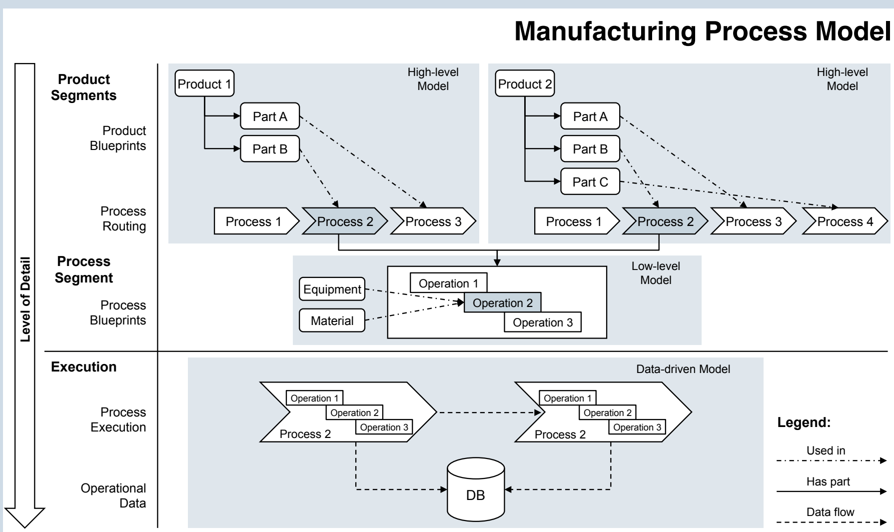
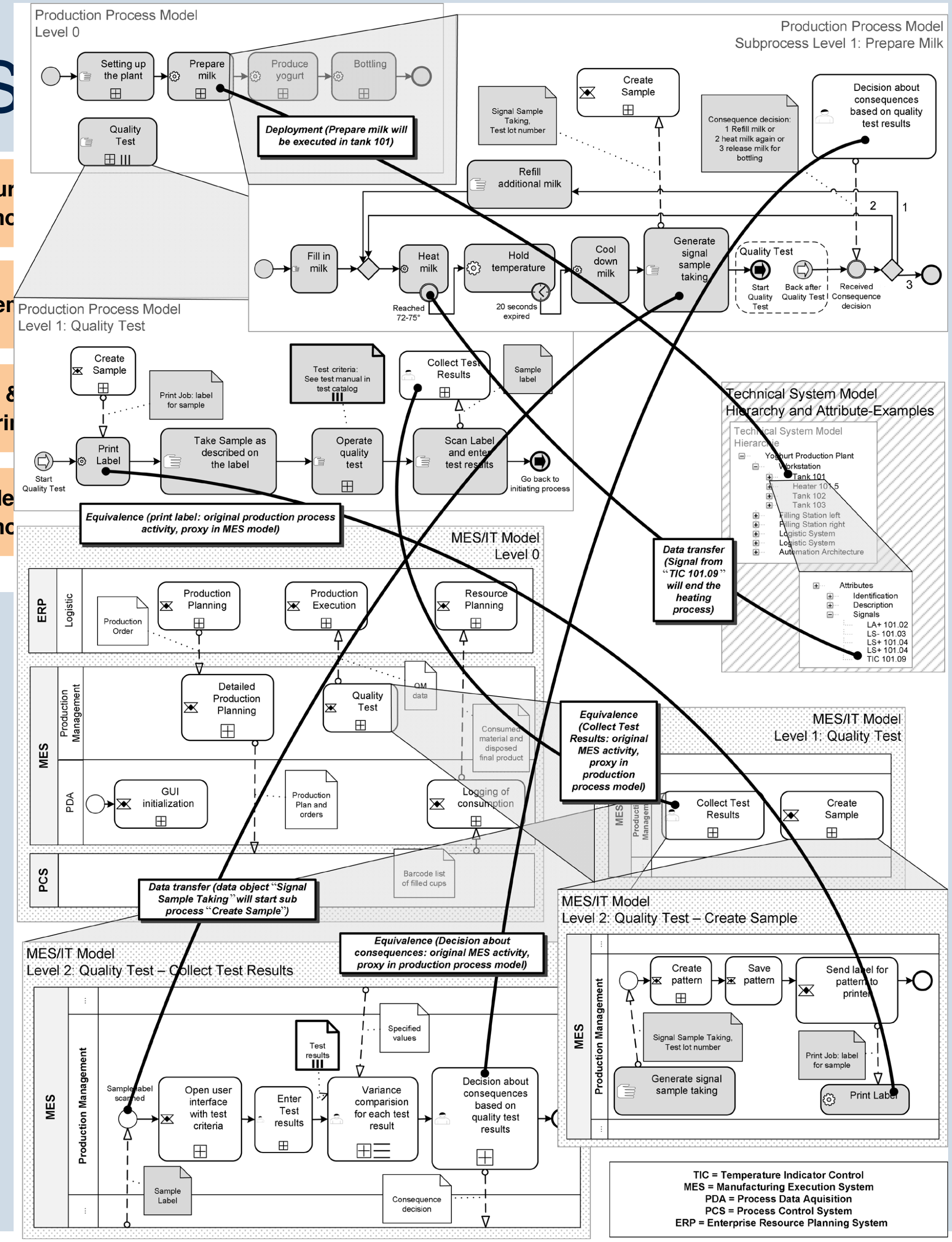
Manufactur Kno

IT-Syster

Control & Engineerir

Electr. & Me Kno





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Information Models for Smart Factories

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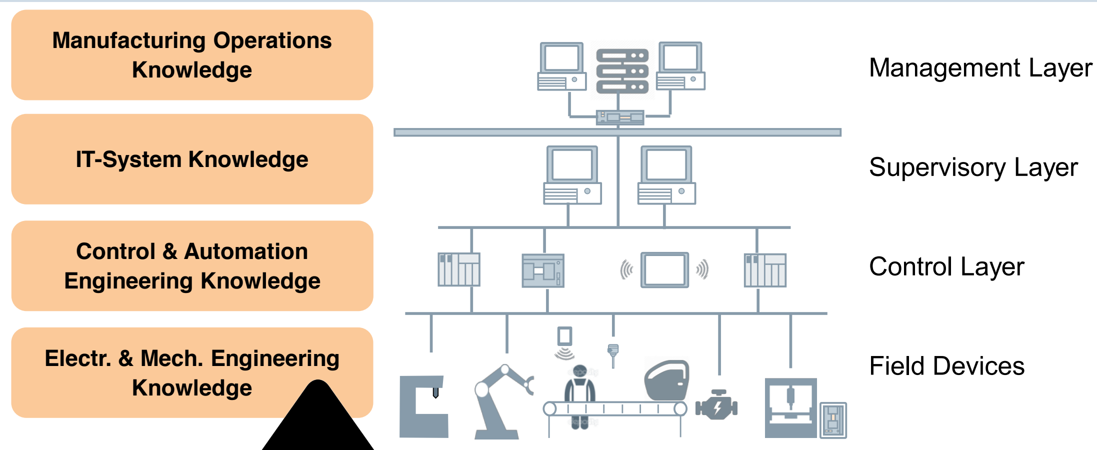
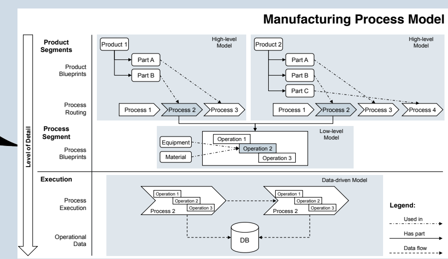
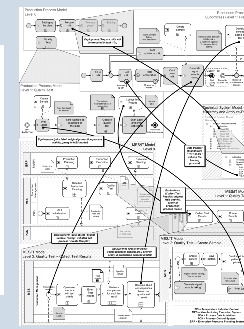


Industrial standardisation is critical

- ensures: safety, security, robustness, …
- sets “good practices” for industrial automation
- bases for industrial information models





International Organization for Standardization

INTERNATIONAL ELECTROTECHNICAL COMMISSION

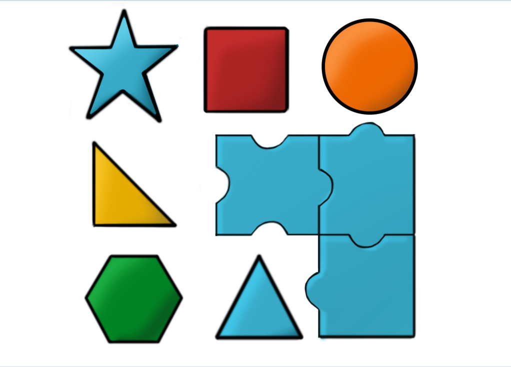
IEC connector type	Diagram of connector type
IEC 60320 C13 / C14	
IEC 60320 C19 / C20	

How well these models solve the problems?

Challenges with Existing Information Models

Reality of Information Models

- many types of models co-exist in one factory
- often incompatible models
  - independently developed
  - use different (often incompatible) formats
  - come from different types of proprietary software
  - may not come with a well-defined semantics
  - specification can be ambiguous



Consequences

- applications
  - ad hoc customization for various models
  - loosely integrated
- model management is a nightmare
  - development
  - maintenance
  - integration

Can Semantic Technologies make life easier?

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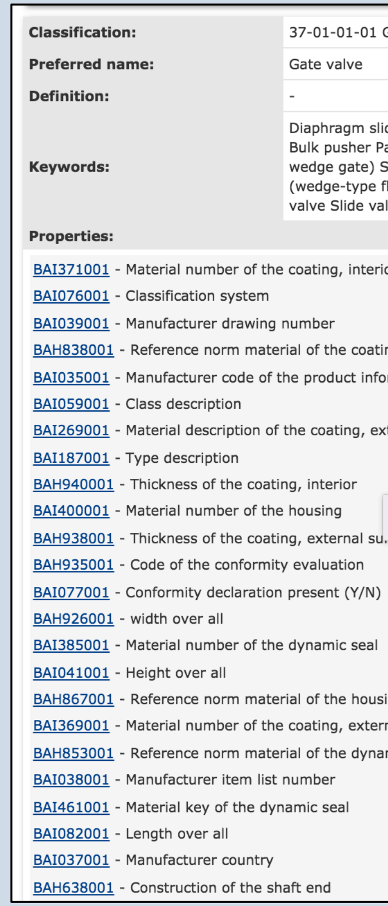
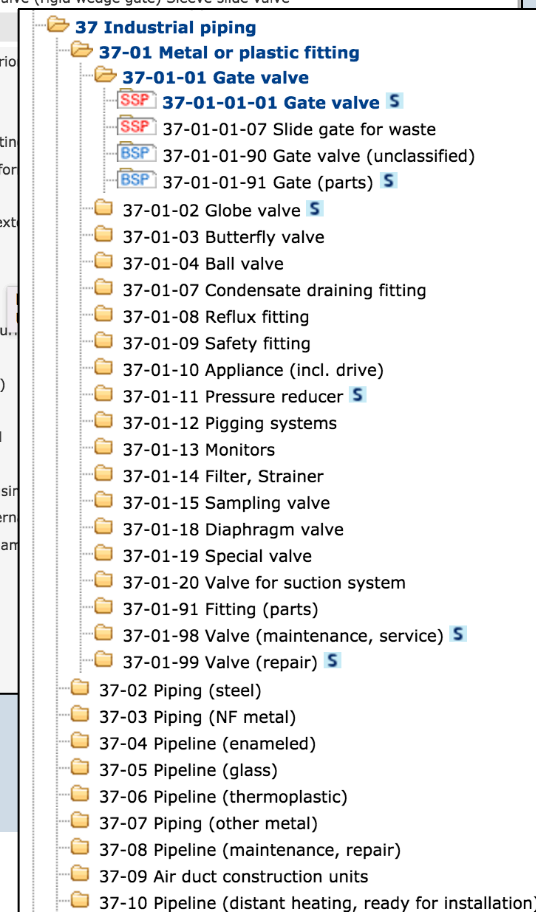
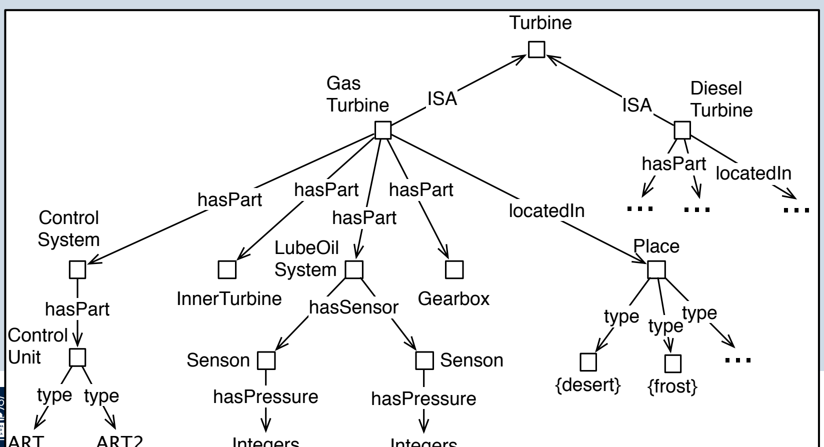
Ontologies as Information Models

Industrial Adoption of Sem. Tech.

- A lot of research
- Industry started adapting Sem Tech
  - Statoil, Aibel, Siemens
- OWL 2 and RDF Benefits
  - W3C standard
  - a lot of tooling
  - clear (machine process.) semantics
  - flex. data standard: storing, exch.







Outline

Intro

- Smart factories and the role of software
- Industrial information models to facilitate smart factories
- Ontologies as industrial information models

Our project

- goals
- achievements

Capturing
Industrial Information Models with
Ontologies and Constraints

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Our Project Goals

Goals
1. Onto language for IIM
2. Concrete ontologies
3. Modelling methodology and tooling

1. Ontology language for industrial info. models
- better understanding
- set foundations for ontologies capturing
  - master data ~ industrial standards
  - domain specific model ~ concrete factories
- study
  - expressiveness
  - management tasks: ontology and data oriented
  - algorithms: to efficiently accomplish the tasks

2. Concrete ontologies
- to show modeling capabilities and practical benefits for industry

3. Modelling Methodology and Tooling
- cost efficient for creation & management of IIM – w/o SWeb background

Our Achievements

Ontology language for IIM

- expressiveness
- algorithms

Concrete ontologies

- 2 ontologies
- experiments

Modeling methodology and tooling

- SOMM systems

Goals

1. Onto language for IIM
2. Concrete ontologies
3. Modelling methodology and tooling

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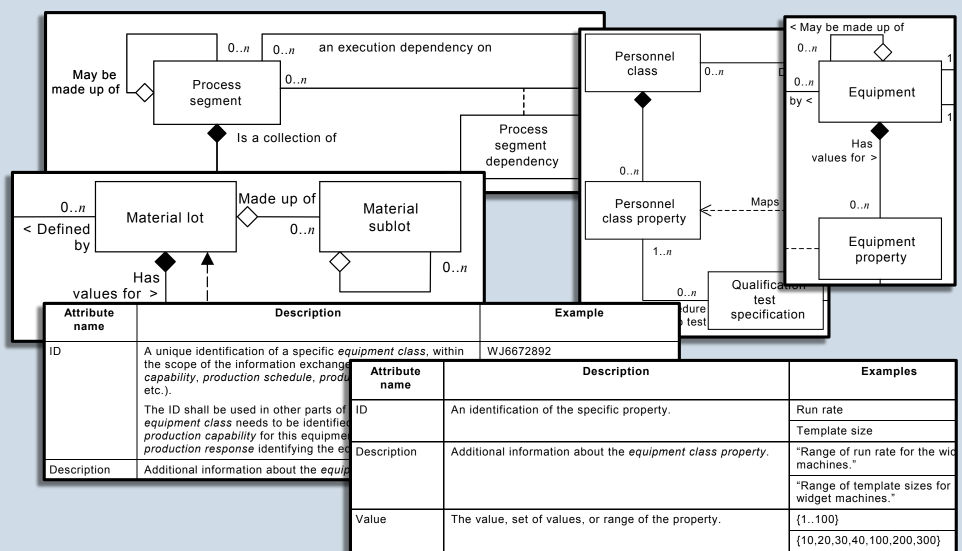
Ontology Language for Industrial Info Models

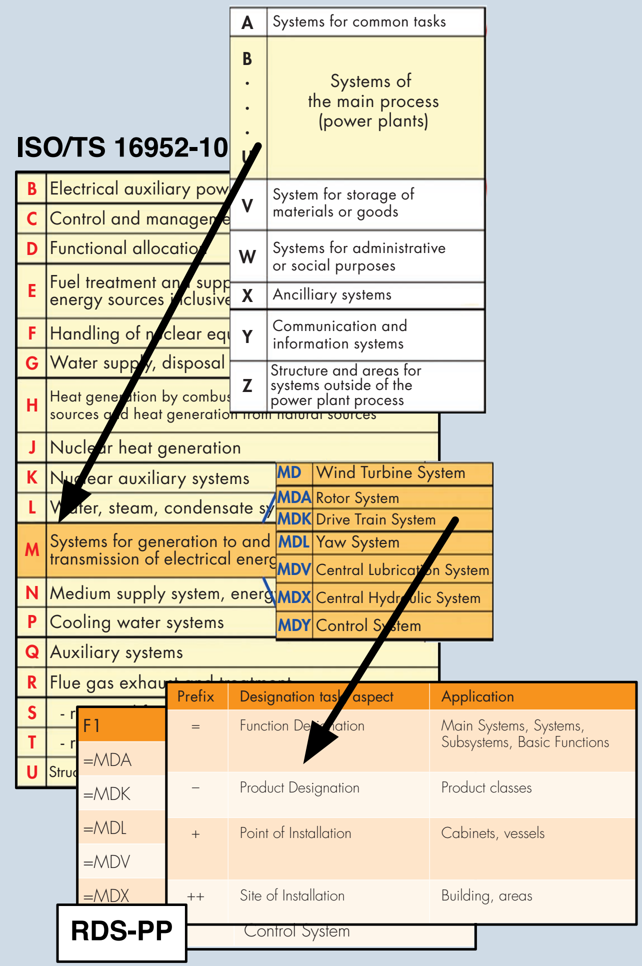
Analyzed two (sets of) industrial standards

- Manufacturing
  - IEC 62264 → ISA 88 and ISA 95
- Energy
  - IEC 81346 → ISO/TS 16952-10 → RDS PP and KKS
- Consolidated modeling requirements

ISA 88/95



IEC 81346



Ontology Language for Industrial Info Models

Axioms

- assigning (relevant) properties to classes
  - If-Then by default (A-quantifier)
  - influence type of inheritance
  - domains and ranges of properties

SubClassOf($Turbine\ Equipment$)
SubDataPropertyOf($hasRotorSpeed\ hasSpeed$)
TransitiveObjectProperty($hasPart$)
InverseObjectProperties($hasPart\ partOf$)

SubClassOf($Conveying$
ObjectAllValuesFrom($followedBy\ Packaging$))

Data Constraints

- Compulsory and default values
- # of compulsory values
- functional properties
- encoded as annotated standard axioms

SubClassOf($Turbine$ SomeValuesFrom($R\ B$))
SubClassOf(A HasValue($R\ b$))
SubClassOf(A MaxCardinality($n\ R\ B$))
SubClassOf(A MinCardinality($n\ R\ B$))
FunctionalProperty(R)

SubClassOf($Turbine$ ObjectSomeValuesFrom($hasPart\ Rotor$))
SubClassOf($TwoRotorTurbine$ ObjectMinCardinality($2\ hasPart\ Rotor$))
SubClassOf($TwoRotorTurbine$ ObjectMaxCardinality($2\ hasPart\ Rotor$))

Boris Motik, Ian Horrocks, Ulrike Sattler:
Bridging the gap between OWL and RDBs. JWS'09

Algorithms: Reasoning, Data Validation

Separate axioms and constr.

- using annotations
- axioms: reasoning
- constraints: data validation

Encode in Datalog

- gives a unified framework for axioms and constraints

Choose the right system

- triple store or rule inference system
- supporting
  - Datalog reasoning and
  - stratified negation-as-failure
- IRIS, RDFOx, etc

OWL 2 Axiom	Datalog Rules
SubClassOf(A B)	$B(?x) \leftarrow A(?x)$
SubPropertyOf(P_1 P_2)	$P_2(?x,?y) \leftarrow P_1(?x,?y)$
TransitiveObjectProperty(P)	$P(?x,?z) \leftarrow P(?x,?y) \wedge P(?y,?z)$
InverseObjectProperties(P_1, P_2)	$P_2(?y,?x) \leftarrow P_1(?x,?y)$ and $P_1(?y,?x) \leftarrow P_2(?x,?y)$
SubClassOf(A AllValuesFrom(P B))	$B(?y) \leftarrow P(?x,?y) \wedge A(?x)$

OWL Axiom	Datalog rules
SubClassOf(A SomeValuesFrom(R B))	$R\_B(?x) \leftarrow R(?x,?y) \wedge B(?y)$ and $Violation(?x,\alpha) \leftarrow A(?x) \wedge$ **not** $R\_B(?x)$
SubClassOf(A HasValue(R b))	$Violation(?x,\alpha) \leftarrow A(?x) \wedge$ **not** $R(?x,b)$
FunctionalProperty(R)	$R\_2(?x) \leftarrow R(?x,?y_1) \wedge R(?x,?y_2) \wedge$ **not** $owl{:}sameAs(?y_1,?y_2)$ and $Violation(?x,\alpha) \leftarrow R\_2(?x)$
SubClassOf(A MaxCardinality(n R B))	$R\_(n{+}1)\_B(?x) \leftarrow \bigwedge_{1\le i\le n+1} (R(?x,?y_i) \wedge B(?y_i)) \bigwedge_{1\le i<j\le n+1} (\textbf{not}\ owl{:}sameAs(?y_i,?y_j))$ and $Violation(?x,\alpha) \leftarrow A(?x) \wedge R\_(n{+}1)\_B(?x)$
SubClassOf(A MinCardinality(n R B))	$R\_n\_B(?x) \leftarrow \bigwedge_{1\le i\le n} (R(?x,?y_i) \wedge B(?y_i)) \bigwedge_{1\le i<j\le n} (\textbf{not}\ owl{:}sameAs(?y_i,?y_j))$ and $Violation(?x,\alpha) \leftarrow A(?x) \wedge$ **not** $R\_n\_B(?x)$

Our Achievements

Goals

1. Onto language for IIM
2. Concrete ontologies
3. Modelling methodology and tooling

Ontology language for IIM

- formalization
- algorithms

Concrete ontologies

- 2 ontologies
- experiments

Modeling methodology and tooling

- SOMM systems

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Ontologies

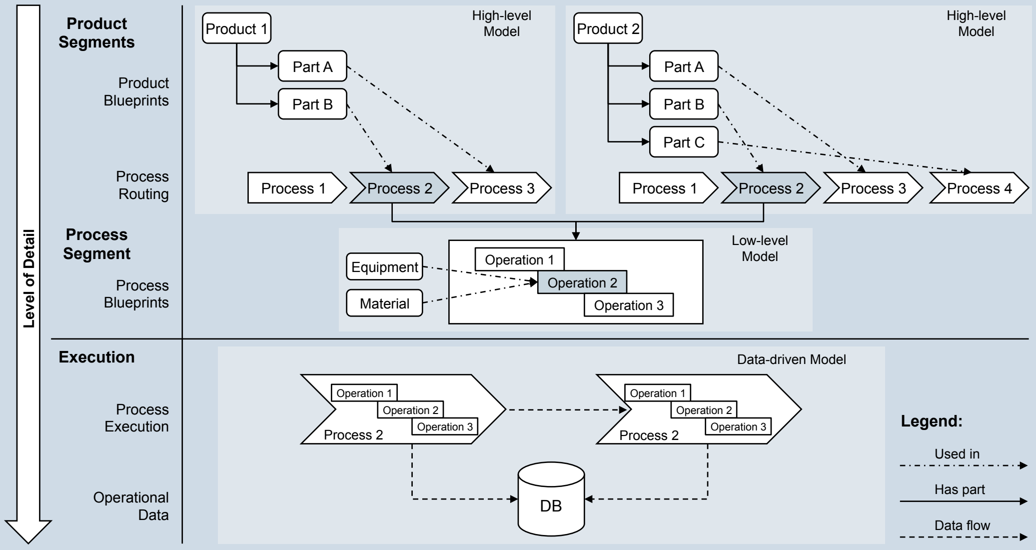
Manufacturing ontology

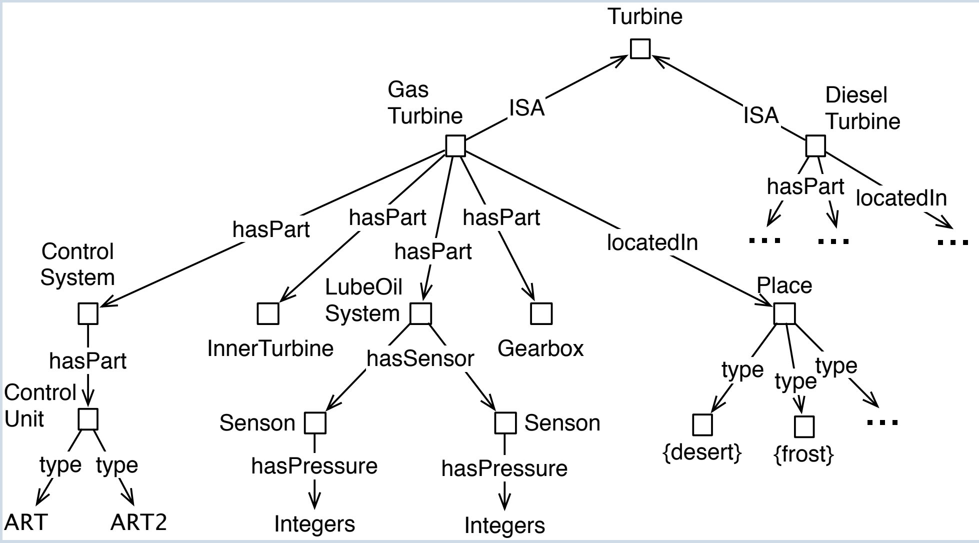
- based on IEC 62264
- 79 standard axioms
- 20 constraints

Turbine ontology

- based on IEC 81346
- 121 standard axioms
- 25 constraints

Manufacturing Process Model

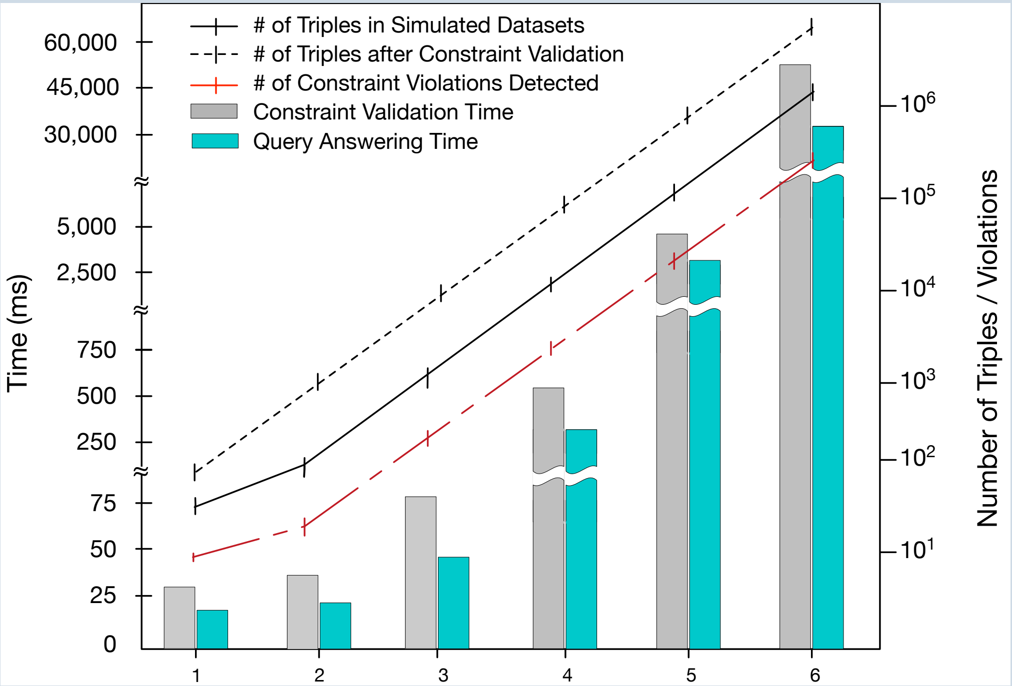




Manufacturing Experiment

Manufacturing data

- simulated
- two types of products
- two configurations
  - manufacturing that violates the model specifications (too much material is used)
  - manufacturing according to specifications
- 6 data sets: 50 → 1x10^6



3 monitoring queries

- Q1: find all products that use material from a given lot
- Q2: find all material lots used in a given product
- Q3: find the total quantity of material in lots of a specific kind

Results

- C. validation, Q. answering is feasible on stock hardware: 87s over data datasets with ~1 million triples

Gas Turbine Experiment

Anonymized dataset

- from 800 real gas turbines
- sensor readings (temperature, pressure, rotor speed and position)
- associated processes (e.g., expansion, compression, start up, shut down)
- converted from a relational DB into RDF
- 25,090 triples over 4, 076 individuals.

3 monitoring queries

- Q1: find all core parts, equipment & current state of all turb. of a given type
- Q2: find all components involved in a compression process
- Q3: find temperature readings of turbines of a given type

Results

- Constraint checking and query answering: < 2s

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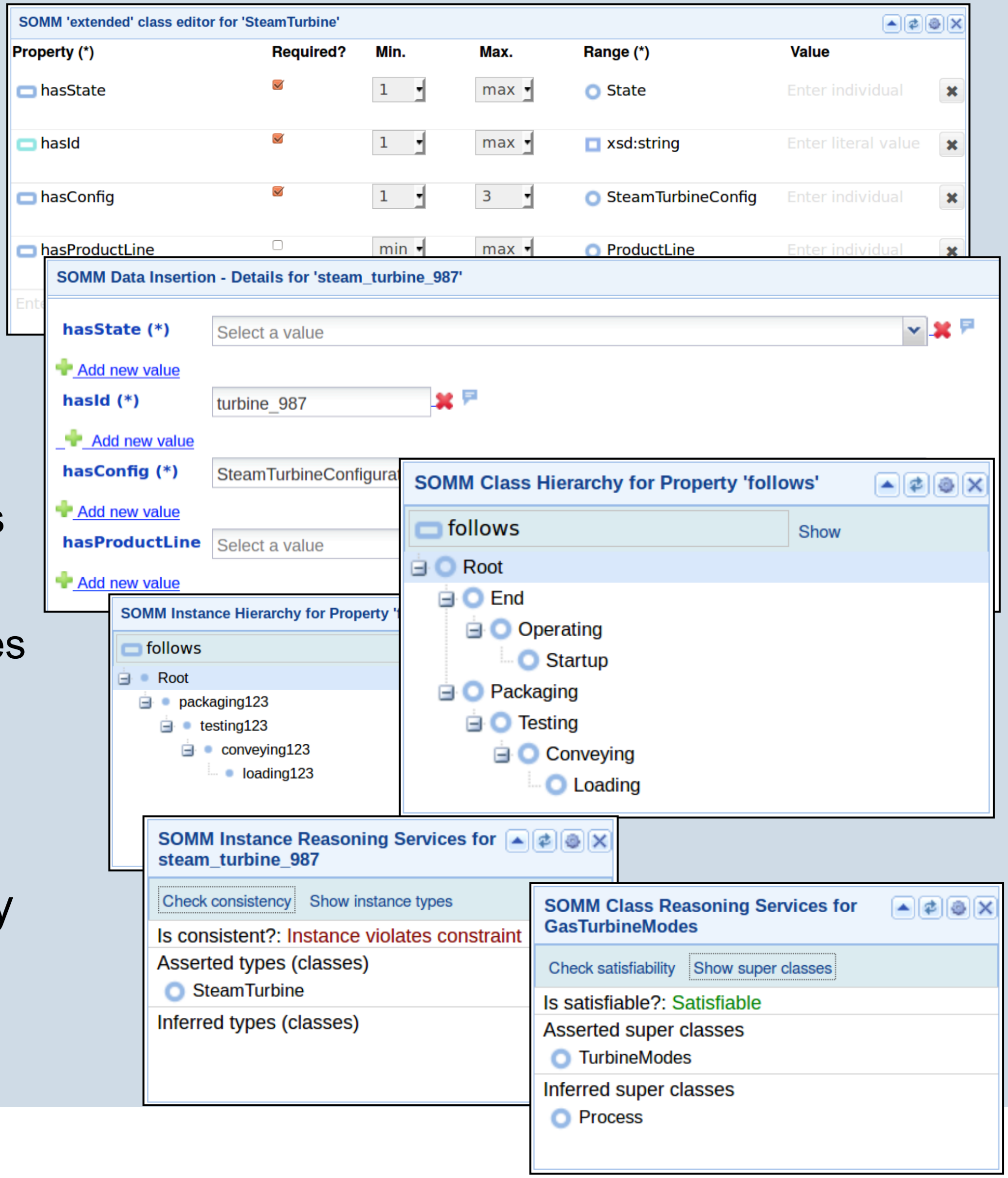
SOMM: Siemens-Oxford Model Manager

Main Features

- WebProtege with new widgets
  - form-based widgets
- Axioms & constraints (A&C)
  - A&C on the same interface, encoded in Datalog
- Auto-generated data forms
  - from prop. assigned to classes
- Extended hierarchies
  - “partonomies” w/ any properties
- Ontology importing
- Reasoning
  - Hermit for ontology reasoning
- Constraint validation and Query answerring
  - Datalog engine with stratified negation (IRIS)



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Summary

Goals
1. Onto language for IIM
2. Concrete ontologies
3. Modelling methodology and tooling

Use case analyses
- Smart factories and the role of info models
- Industrial standards: Manufacturing, Energy

Foundations of ontology language to capture IIM
- Capturing with axioms and constraints
- Algorithms for constraint verification and query answering

Concrete ontologies
- 2 ontologies: Manufacturing, Energy
- experiments

Modeling methodology and tooling
- SOMM system

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