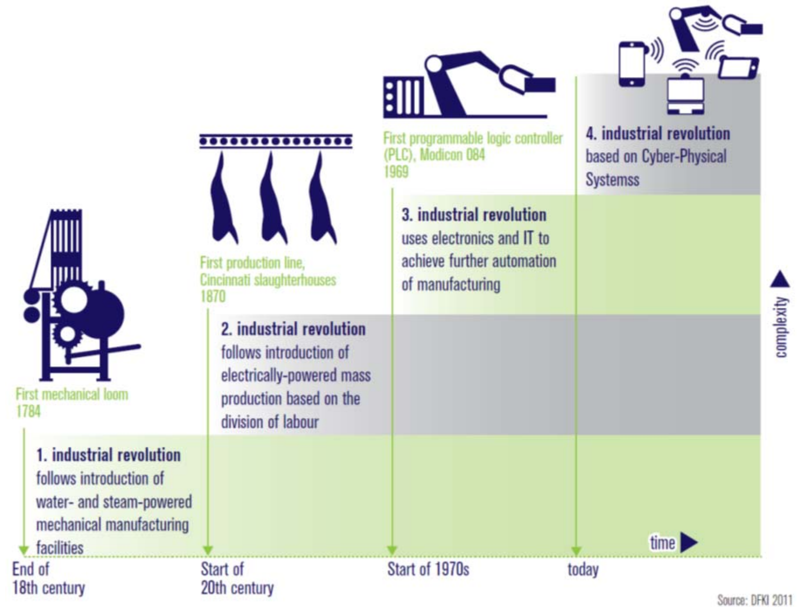
Outline

Cyber Physical Production systems / Industry 4.0- challenges in research and industrial application)

1. **CPPS and Industrie 4.0 in Germany**
2. Agent technology to enable CPPS
3. Myjoghurt
   - Production changes due to malfunctions
   - New products
   - Maintenance support
4. xPick & Place unit plus COCOME an open I 4.0 demonstrator (PP 1593)
5. Metrics for CPPS and Industrie 4.0
6. Open Research issues

Univ.-Prof. Dr.-Ing. Birgit Vogel-Heuser
Full professor and head of Chair Automation and Information systems (AIS)
Faculty of mechanical engineering, Technische Universität München
41st IEEE IECON

Four stages of industrial revolution



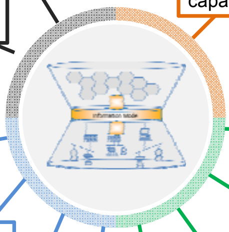
Characteristics of Cyber-Physical Production Systems (CPPS) – Industrie 4.0

Data processing for humans

- **Assistance systems for Engineering**
- **Data processing and integration for humans**

Communication and data consistency

- **Appropriation of necessary data** for configuration, production, negotiation
- **World wide distribution** of data, **high availability, access protection**
- **Data consistency** about different „stakeholders“ in different engineering phases and crafts
- **Digital networks** and interfaces for communication (between machine, human and plant, plant and plant)



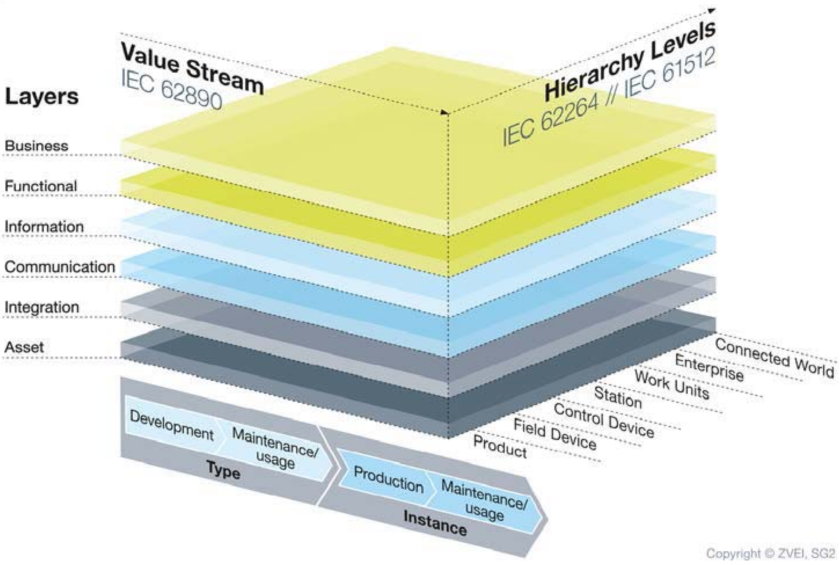
Architecture models (reference architecture) for a category of aggregation/modules related to properties, capabilities, interfaces…

Intelligent products and production units

- Production units with **inherent capabilities**
- **Data analysis** of process and alarm data and connection with engineering data
- **Flexible production units**, **adaptable** to modified product requirements, allow also structural changes
- **Description of product and operating resources**, e.g. ontology, for independent analysis, presentation, organization and execution of a production process

Source: B. Vogel-Heuser, G. Bayrak, U. Frank: Forschungsfragen in "Produktautomatisierung der Zukunft". acatech Materialien. 2012.

Reference Architecture for Industrie 4.0



Source: VDI/VDE-Gesellschaft Mess- und Automatisierungstechnik: Statusbericht; Industrie 4.0; Wertschöpfungsketten. Düsseldorf: VDI e.V., April 2014.

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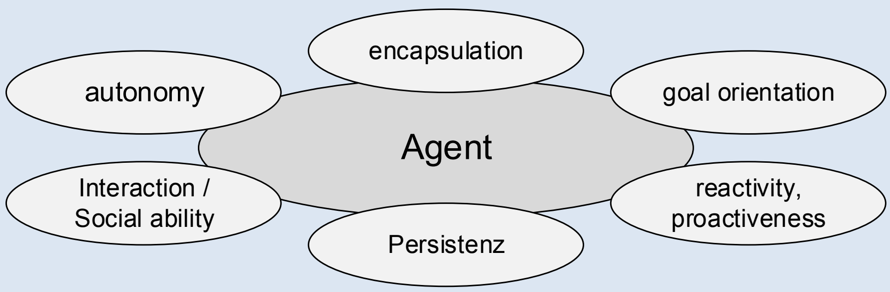
Properties of software agents

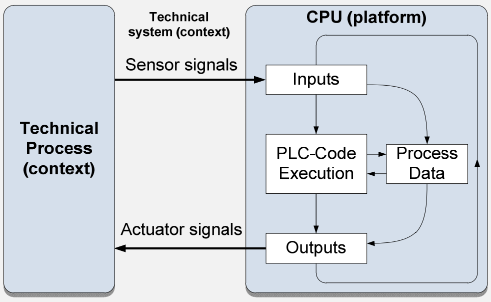


[Wooldridge & Jennings, 2000]

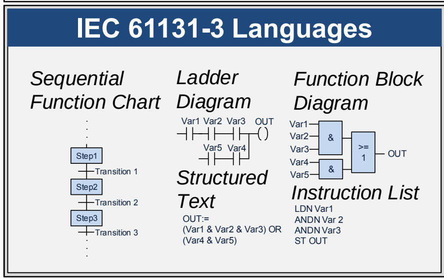
A **technical agent** is an **encapsulated** (hardware/software) entity with **specified objectives**. An agent endeavors to reach these objectives through its **autonomous behavior**, in **interacting** with its **environment** and with **other agents**.

Source: VDI-Standard 2653 Sheet 1, 2010

Technical Constraints of the Automation System



- Real-time requirements of aPS
  → hard real-time for the platform (PLC)
- Cyclic behavior of the platform (1µs – 1s)
- Classical PLC as well as Soft-PLC (PC-based) programmed in IEC 61131-3 Languages
- Increasing amount of IPC and C, C-derivatives
- ***Online change is mandatory***



IEC 61131-3 Programming Languages

- Proprietary programming languages: Structured Text (ST), Ladder Diagram (LD), Instruction List (IL), Sequential Function Chart (SFC), Function Block Diagram (FBD)
- **Upcoming: C**

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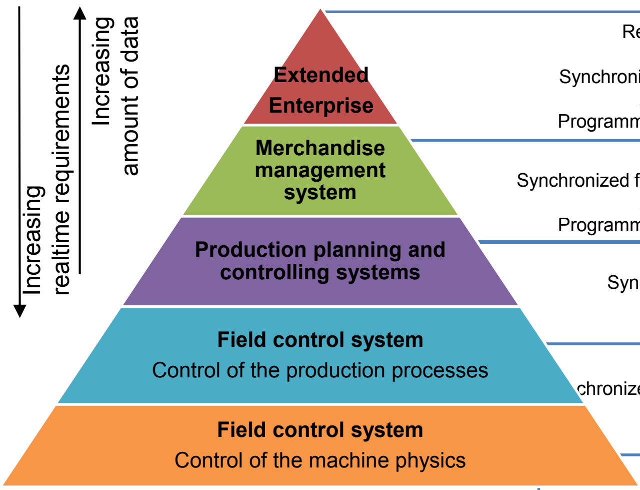
Fields of application



Reaction time: 8 hours < x < 1 week
Synchronized frequency: 1 hour < x < 1 day
Any agent systems are applicable
Programming languages: C++, C#, Java, …

Reaction time: 1 hour < x < 1 day
Synchronized frequency: 60 seconds < x < 1 day
Any agent systems are applicable
Programming languages: C++, C#, Java, …

Reaction time: 1s < x < 60s
Synchronized frequency: 1s < x < 60s
Need for multi-agent systems
IEC 61131, C++, C#, Java

Reaction time: 10ms < x < 1s
chronized frequency: 100 µs < x < 100ms
Realtime Agents on RT-Java
Mostly IEC 61131 and C

Reaction time: partly < 1ms
Synchronized frequency: partly < 1µs
Need for multi-agent systems

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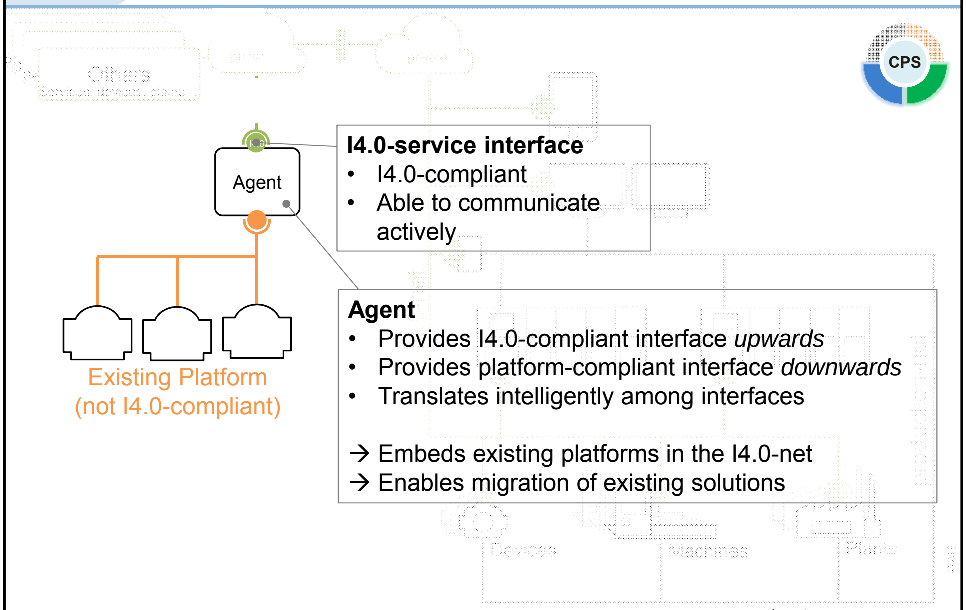
Compare: Lüder, A. Möglichkeiten und Grenzen Agentenbasierter Steuerungssysteme; 2006

Agents as Interfaces for Platform Industrie 4.0



Source: ABB AG / Plattform I4.0

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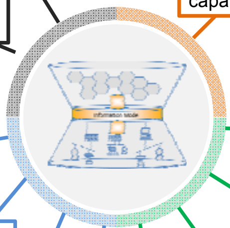

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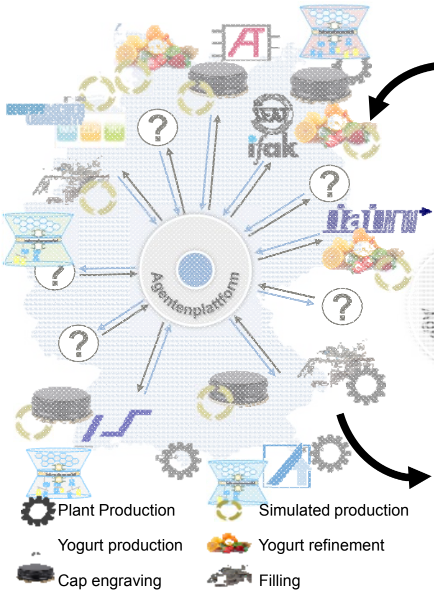
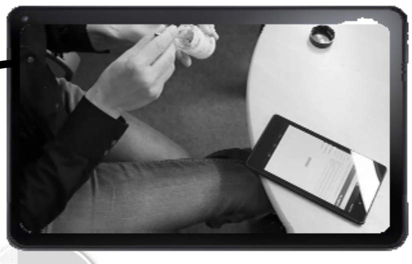
Intelligent networked production systems – myJogurt how it all began





Website: http://www.ais.mw.tum.de/myjoghurt/

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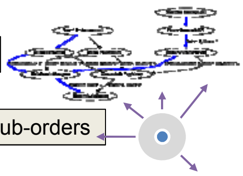
Procedure of production control

CPS

- Customer places order
- Splitting orders into sub-orders
- Collecting charges and deadlines for sub-orders of system
- Determine (new) schedule
- Contracting (new) sub-orders
- Production monitoring (operator and customer)
- Automatic troubleshooting
- Send status report

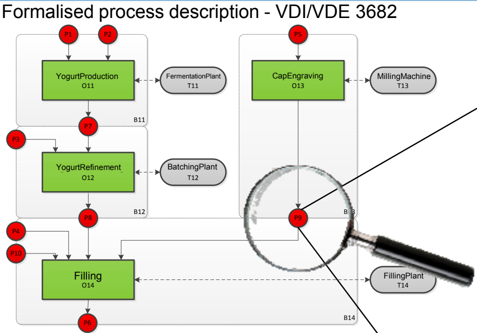
e.g.



Models for classifying product, process and resource

Formalised process description - VDI/VDE 3682

CPS



Product
↑
Handling and Conditioning, …
↑
Packing materials
↑
Bottles
↑
Caps or Tops
↑
Engraved lid

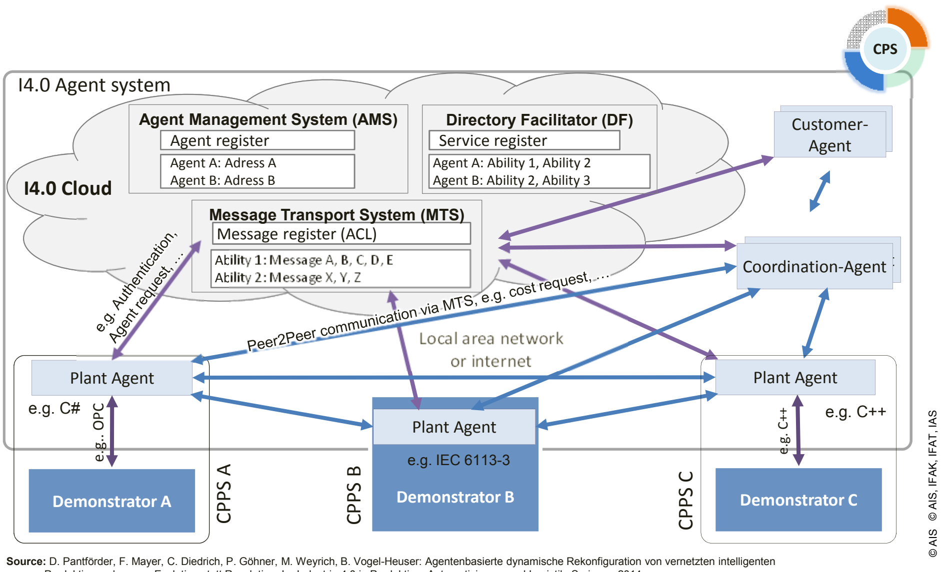
According to UNSPSC

Gap/Weaknesses

- Is Automation ML "enough" for **process** and **resource** description and its variations and versions?
- "rich" classification of not standardized or custom-specific products missing (more than UNSPSC necessary)

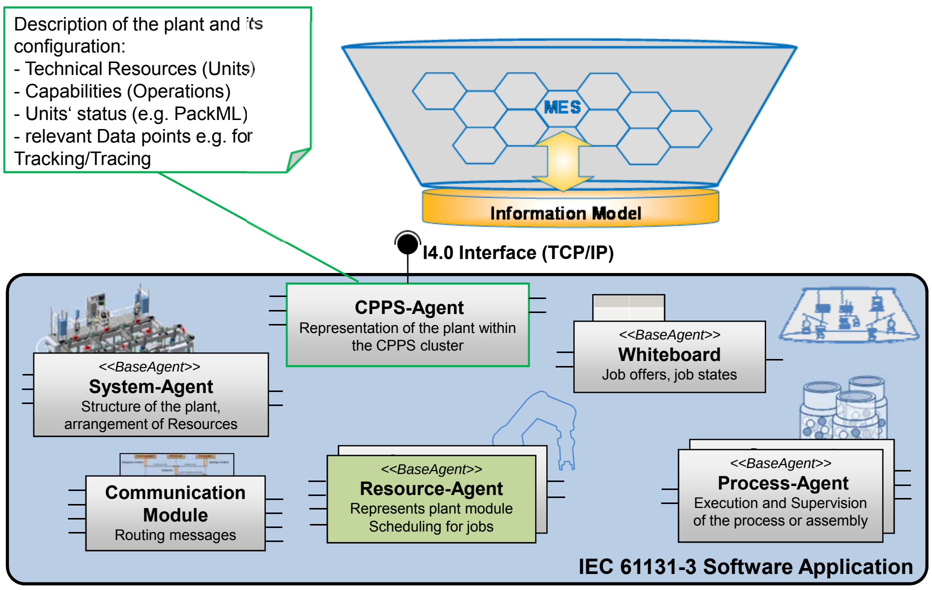
Source: Diedrich C, Fay A, Grützner J, Göhner P, Vogel-Heuser B, Weyrich M, Wollschlaeger M (2013) Automatisierungstechnischer Forschungsanlagenverbund für Industrie 4.0. Markt&Technik. Summit Industrie 4.0, München

Communication within CPPS

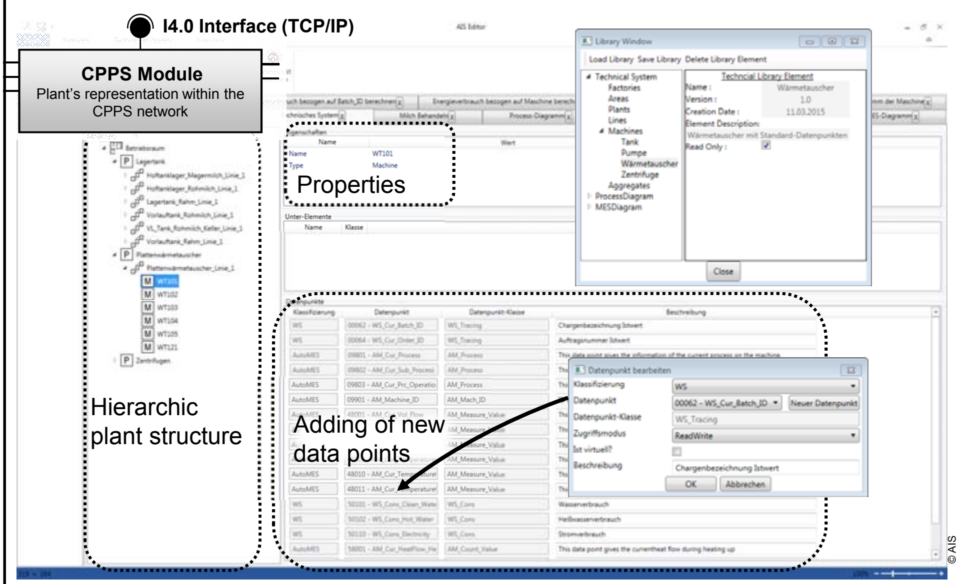


Source: D. Pantförder, F. Mayer, C. Diedrich, P. Göhner, M. Weyrich, B. Vogel-Heuser: Agentenbasierte dynamische Rekonfiguration von vernetzten intelligenten Produktionsanlagen – Evolution statt Revolution. In: Industrie 4.0 in Produktion, Automatisierung und Logistik, Springer, 2014.

Intelligent Industrie 4.0 – Plant's Agent System



Description of the Technical System using MES-ML



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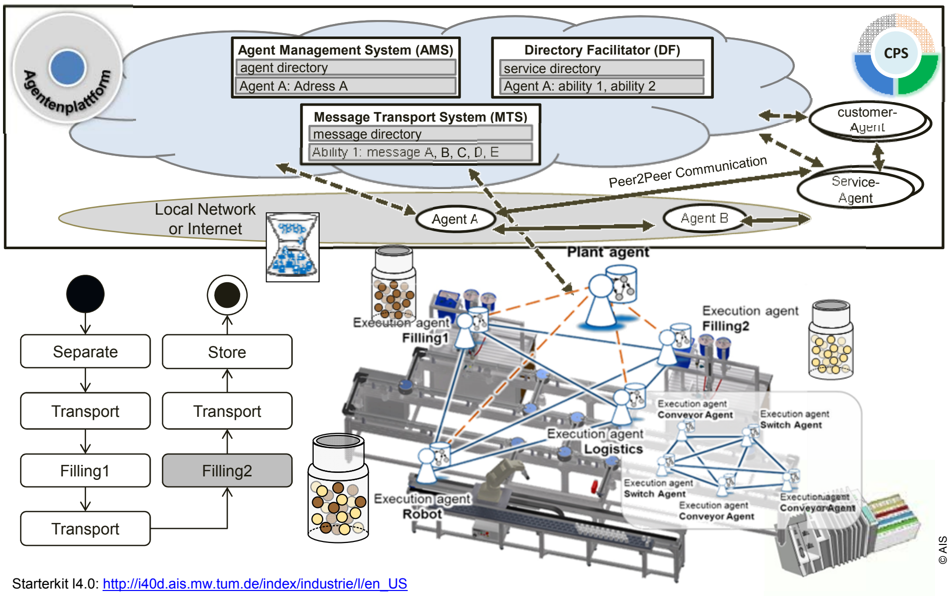
Self-adaptation of an automated production system



Starterkit I4.0: http://i40d.ais.mw.tum.de/index/industrie/l/en_US

Source: B. Vogel-Heuser: Herausforderungen und Anforderungen aus Sicht der IT und der Automatisierungstechnik. In: Industrie 4.0 in Produktion, Automatisierung und Logistik, Springer, 2014.

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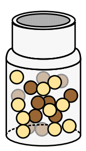
Mapping technical system and process description by means of ontologies

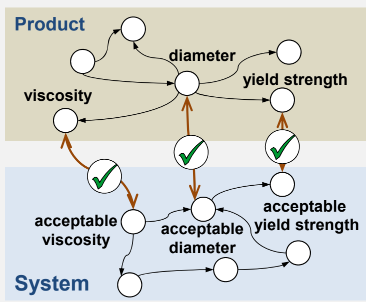


Product description
- **Name**: White chocolate balls
- **Viscosity**: 2.5 Pa*s
- **Yield strength**: 20 Pa
- **Diameter**: 0.5 cm
- **Aggregation state**: solid

System description
- **Name**: Filler
- **Acceptable viscosity**: 1..3 Pa*s
- **Acceptable yield strength**: 10..30 Pa
- **Acceptable diameter**: 0.2..1 cm
- **Functionality**: separate single solid

Ontology
- Formal knowledge representation
- Provides the means to flexibly process knowledge

→ Basis to identify whether **filler** can manufacture yoghurts with **white chocolate balls**



Mapping of **technical system**'s characteristics with **requirements from product** and **production process** by means of ontologies

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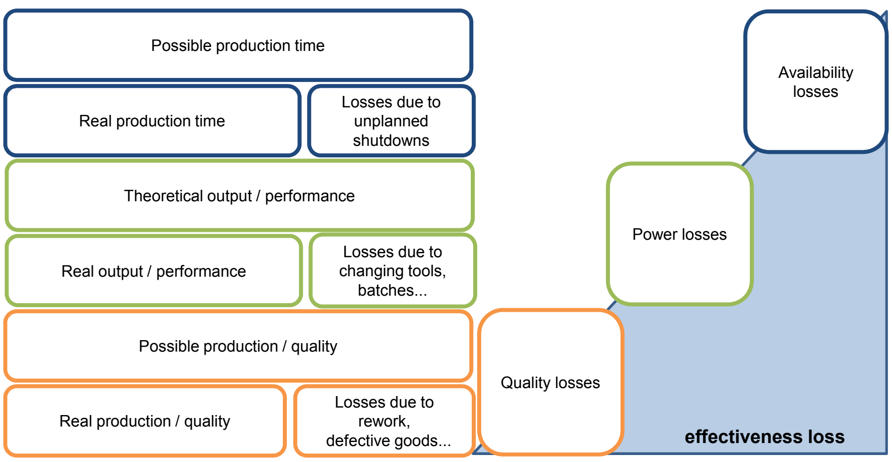
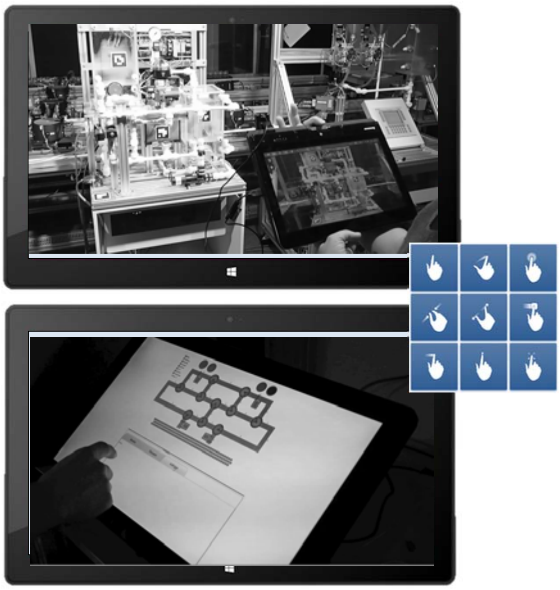
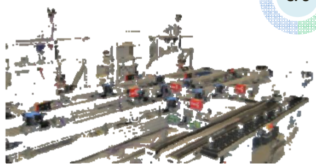
Overall Equipment Effectiveness (OEE)

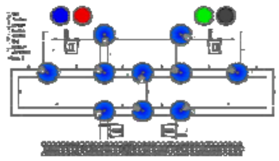


Scenario: Information aggregation for maintenance HMI with AR and touchscreen





- Mobile devices with touchscreen
- Augmented Reality supports optimization and maintenance of industrial plants



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Information aggregation for maintenance (1)

role shift supervisor → shift supervisor undertakes role of mechanic → shift supervisor undertakes role of operator

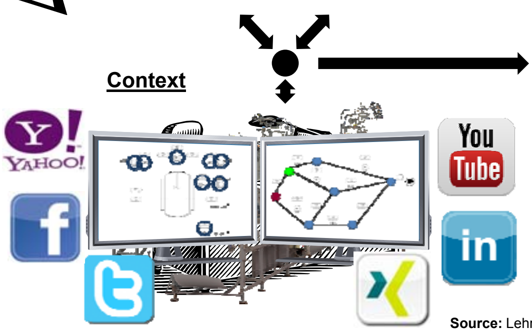
<u>shift supervisor</u>

- Red-green color blindness
- Preferred voice control

<u>role</u>

- shift supervisor
- mechanic
- operator

<u>Context</u>



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Source: Lehrstuhl für Automatisierung und Informationssysteme, TU München

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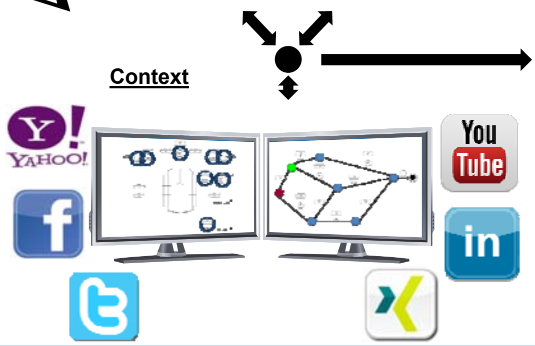
Information aggregation for maintenance (2)

role shift supervisor → **shift supervisor undertakes role of mechanic** → **shift supervisor undertakes role of operator**

shift supervisor
- Red-green color blindness
- Preferred voice control

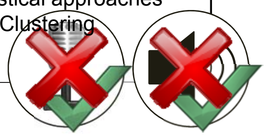
role
- shift supervisor
- mechanic
- **operator**

Context



challenge
- Prediction of critical situations based on analysis of process data and alarm sequences
- recommendations for operator

approach
- Pattern analysis, statistical approaches and Clustering



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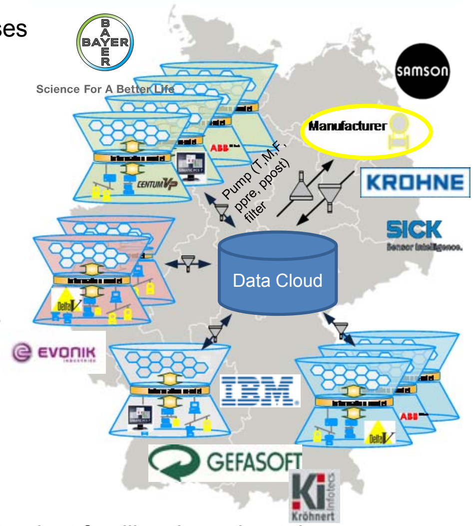
Project: #SmartData2015 / Data Mining in process industry

- Bundle detailed knowledge of processes and plants and include in analysis
- Data logistics
  - Secure provision and transport
  - Secure storage
- Aggregation and analysis of data
  - ➢ Aggregation of data specific to processes and plants with historical data
  - ➢ Identification of unknown correlations in data → make implicit knowledge explicit
  - ➢ Integration of field device manufacturers for improving field devices



- Data use
  - ➢ Application of the analytical findings to plant families throughout the company
  - ➢ Supporting the operating personnel in engineering, process management, servicing and maintenance

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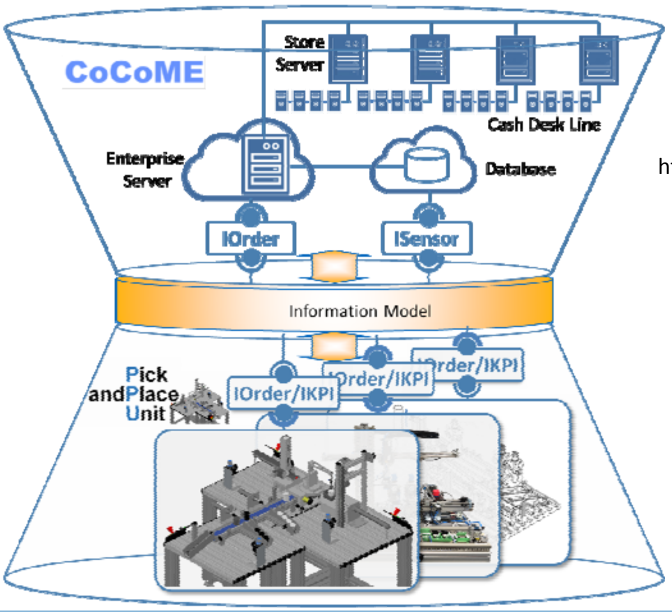
Joined Industrie 4.0 Demonstrator DFG - PP 1593 phase II

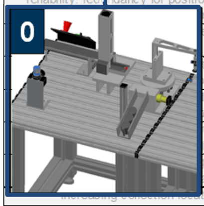


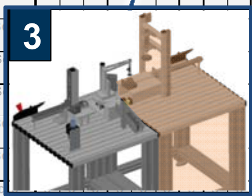
Design For FUTURE
DFG Priority Programme 1593
Design For Future - Managed Software Evolution

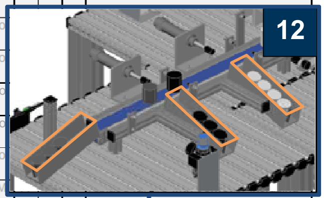
http://www.dfg-spp1593.de

Sequential evolution scenarios

Cause	Scenario	Stack			Crane			Stamp			Ramp			Conveyor			Enabler
		C	P	S	C	P	S	C	P	S	C	P	S	C	P	S	
increasing transportation throughput of work pieces	Sc0	A	A	A	A	A	A	-	-	-	A	A	A	-	-	-	green field: pick and place unit
increasing capacity of output storage	Sc1	o	o	o	o	o	o	-	-	-	M	o	o	-	-	-	Y-shaped ramp
two different products are processed	Sc2	A	A	A	o	o	o	-	-	-	o	o	o	-	-	-	inductive sensor for metal detection
one product has to be labeled	Sc3	o	o	o	M	M	M	A	A	A	o	o	o	-	-	-	stamp unit added
decreasing failure due to sensor pollution	Sc4	o	o	o	o	[illegible]	o	o	o	o	o	o	o	-	-	-	replace crane sensors
reliability: redundancy for positioning ...sors	Sc4b	o	o	o	o	M	M	o	o	o	o	o	o	[illegible]	[illegible]	[illegible]	[illegible]
...eces	S...	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	o	o	o	[illegible]	[illegible]	[illegible]	[illegible]
...eces ...duct	S...	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	o	o	o	[illegible]	[illegible]	[illegible]	[illegible]
... and ...eled	S...	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	o	o	o	[illegible]	[illegible]	[illegible]	[illegible]
...ong) ...ight)	S...	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	o	o	o	[illegible]	[illegible]	[illegible]	[illegible]
...istic ...ation	S...	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	M	M	M	[illegible]	[illegible]	[illegible]	one ramp
increasing collection locations	Sc...	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	o	o	o	A	A	A	additional ramps at conveyor
different logistical locations	Sc11	o	o	o	o	o	o	o	o	o	o	o	o	o	o	M	filling ramps step by step
special sorting that every sorting location has the same WP order	Sc12	o	o	o	o	o	o	o	o	o	o	o	o	o	o	M	defined sorting of work pieces for (similar for each ramp)
increasing the precision of the crane	Sc13	o	o	o	M	A	M	o	o	o	o	o	o	o	o	o	analog sensor for crane positioning
EMC resistance due to electro magnetic influences	SC14	o	o	o	M	A	M	o	o	o	o	o	o	o	o	o	incremental encoder for crane positioning







Legend: A: Added; M: Modified; -: not available at this evolution time; o: no Changes; C: Context; P: Platform; S: Software

Sources: Legat, Christoph; Folmer, Jens; Vogel-Heuser, Birgit. *Evolution in Industrial Plant Automation: A Case Study*. 39th Annual Conference of the IEEE Industrial Electronics Society (IECON 2013), 2013, 4386-4391.
Vogel-Heuser, B.; Folmer, J.; Legat, C.: Anforderungen an die Softwareevolution in der Automatisierung des Maschinen- und Anlagenbaus. In: Automatisierungstechnik (at), Vol. 62, No. 3, 2014, S. 163-174.

Self healing PPU - fault handling @ belt pushers

	customer				
Sc12f	Additional functionality self-healing machine and diagnosis	x	0	x	Additional sensors and software required, automatic mode enlarged

Sc12f: Additional Sensor for Fault Detection, Isolation and Handling

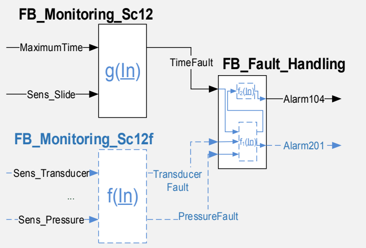
- **Binary Sensors** for discrete front and back position detection
- **Additional analogue sensor** to detect exact position of pusher and redundancy for binary sensors
- Result: work piece jam → self healing mode

fault handling @ belt pushers

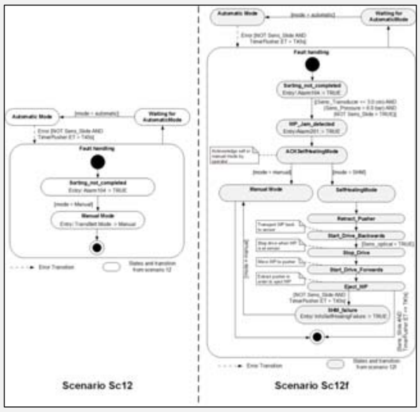
Changes on component list/ sensor level (context)

Group	Device	Function	Location	Device/Signal type	P. supply [V]	Remarks
310	B1.1	pusher is extended	pusher	reed switch DI	24V	mand.
310	B1.4	position of pusher	pusher	distance sensor AI	24V	SHM
…..	…..	….	….	….	….	….
300	B1	pressure sensor	valve node	pneum. meas. AI	0-24V	SHM

Changes on code level (software)



Changes on model level (software)



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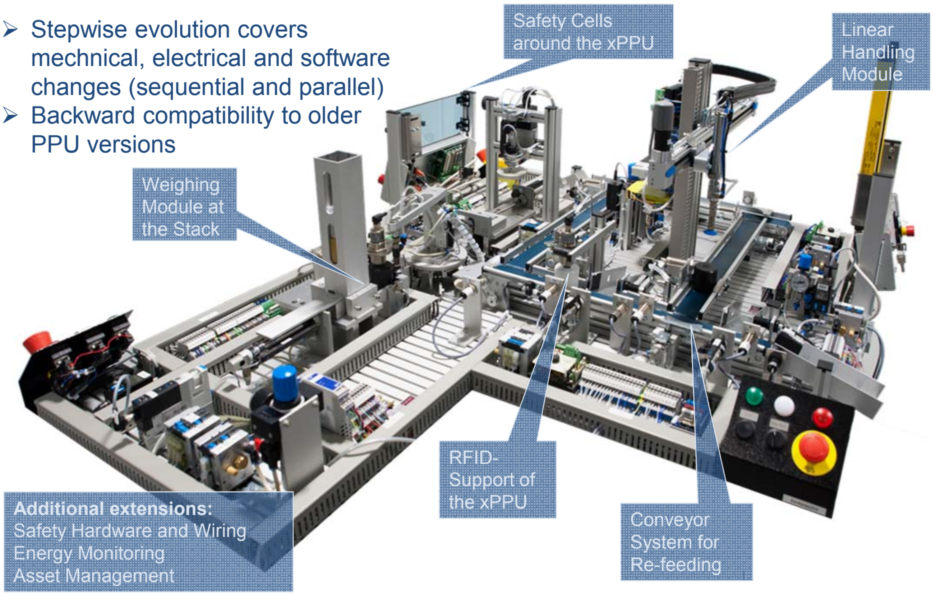
Overview of the xPPU (Pick and Place Unit)

- Stepwise evolution covers mechnical, electrical and software changes (sequential and parallel)
- Backward compatibility to older PPU versions



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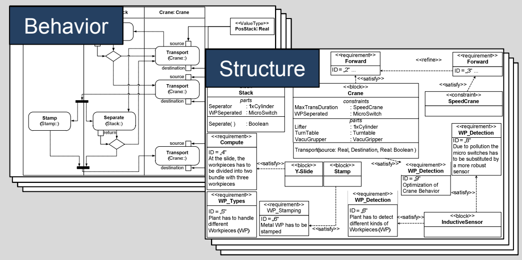
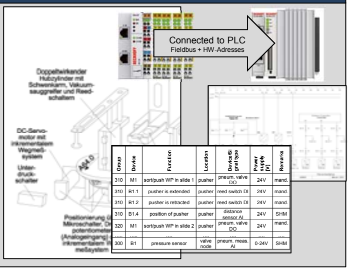
Deliverables from PPU – for each evolution step

16 SysML models with evolutionary changes



Technical Documentations



PLC implementations

Especially for project *Pythia*:
- 45 different IEC 61131-3 Projects
- graphical and textual programming languages

16 PLC implementations each

Based on plcUML

Classical IEC61131

https://mediatum.ub.tum.de/node?id=1208973

Outline

Cyber Physical Production systems / Industry 4.0- challenges in research and industrial application)

1. CPPS and Industrie 4.0 in Germany
2. Agent technology to enable CPPS
3. Myjoghurt
   – Production changes due to malfunctions
   – New products
   – Maintenance support
4. xPick & Place unit plus COCOME an open I 4.0 demonstrator (PP 1593)
5. **Metrics for CPPS and Industrie 4.0**
6. Open Research issues

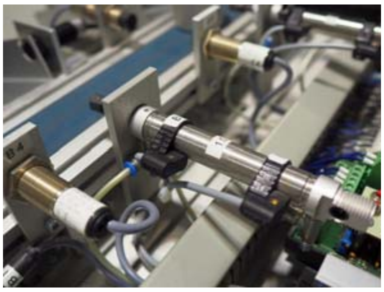
Proposed metrics – adaptivity coverage and realization effort

Fault Coverage Metrics — **Adaptivity Metrics for automated Production Systems** — **Real-time Capabilities Metrics**

BECAI: Basic Event Coverage Adaptivity Index
BENCAI: Basic Event Not Coverage Adaptivity Index
FLCAI$_j$: Fault Level Coverage Adaptivity Index

plcDFAI: PLC-cycles to detect faults
plcIFAI: PLC-cycles to isolate faults
plcSTSAI: PLC-cycles to switch to soft sensor
plcFCLAI: PLC fault compensation latency

Sc12f: Additional Sensor for Fault Detection, Isolation and Handling



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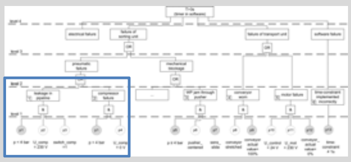
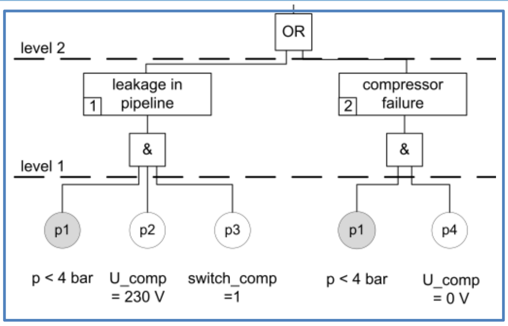
Fault Coverage – Basic Event Coverage (level 1)

Fault tree based fault detection





Measured **Basic Events** to detect symptoms of a fault

- values that
  - are measured (grey) or
  - need to be measured (white) to detect level 2 fault
- BECAI - coverage of values that are measured (c) related to all basic events (b)

$$BECAI = \frac{\sum_{j=1}^{k} c_j}{\sum_{i=1}^{n} b_i} \in [0,1]$$

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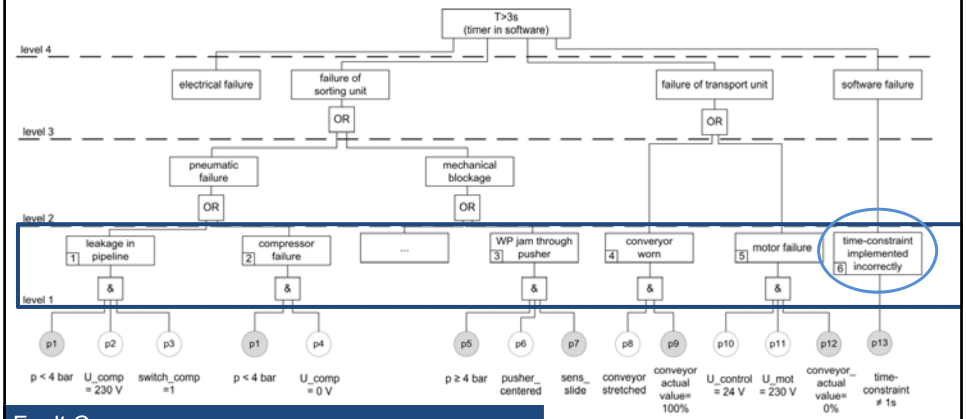
Results for Fault Level Coverage Adaptivity Index (level 2)



Fault Coverage

- indicates a ratio of adaptivity concerning fault robustness of a plant (level 2)
- Fault Level Coverage Adaptivity Index (FLCAI) is used with cf-covered faults and ef-all existing faults

$$FLCAI_2 = \frac{\sum_{n=1}^{k} cf_{(n,2)}}{\sum_{i=1}^{k} ef_{(i,2)}} = \frac{1}{6} = 0{,}167 \rightarrow 16{,}7\%$$

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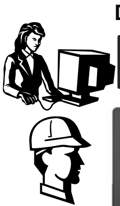
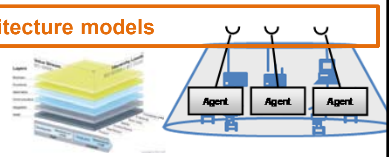
Industry 4.0 - puzzle pieces- open research issues

Data processing for humans

Data processing and integration for humans



Architecture models



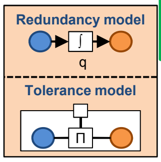
Marketplace of production units

Intelligent products and production units

Reconfiguration, recovery, restart of production units

Data analysis of process and alarm data and connection with engineering data

Production units with **inherent capabilities (Learning)**



Flexible production units, adaptable to modified product requirements, allow also structural changes

Description of product (classification and ontologies) – consistency checking

- ➢ Metrics have to be adapted / further developed for benchmarking aPS designs and operation behavior regarding Industry 4.0
- ➢ Open demonstrators are required to benchmark methods, technologies and approaches for dynamic reconfiguration, restart/recovery and data analysis

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Selected Related Publications

- **U. Frank, J. Papenfort, D. Schütz:** Real-time capable software agents on IEC 61131 systems – Developing a tool supported method. In: Proc. of 18th IFAC World Congress, Mailand, Italien, 2011, S. 9164-9169.
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- **F. Li, G. Bayrak, K. Kernschmidt, B. Vogel-Heuser:**: Specification of the Requirements to Support Information Technology-Cycles in the Machine and Plant Manufacturing Industry. In: 14th IFAC Symposium on Information Control Problems in Manufacturing, 2012.
- **B. Vogel-Heuser et al.:** Model-driven Engineering of Manufacturing Automation Software Projects – A SysML-based Approach. Mechatronics, vol. 24, pp. 883-897, 2014.
- **D. Schütz et al.:** Development of PLC-based Software for Increasing the Dependability of Production Automation Systems. IEEE Transactions on Industrial Informatics, vol. 9, pp. 2397-2406, 2013.
- **S. Ulewicz et al.:** Flexible Real Time Communication between Distributed Automation Software Agents. 22nd International Conference on Production Research (ICPR 2013), Iguassu Falls, Brazil. 2013.
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- **B. Vogel-Heuser, C. Legat, Folmer J., and S. Rösch:** Challenges of Parallel Evolution in Production Automation Focusing on Requirements Specification and Fault Handling. at – Automatisierungstechnik, Vol. 62, Nov. 11, 2014.
- **B. Vogel-Heuser, J. Folmer, C. Legat:** Anforderungen an die Softwareevolution in der Automatisierung des Maschinen- und Anlagenbaus. at – Automatisierungstechnik, Vol. 62, No. 3, pp. 163-174.
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- **Legat et al.:** Interface Behavior Modeling for Automatic Verification of Industrial Automation Systems' Functional Conformance . at – Automatisierungstechnik, Vol. 62, 2014.
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- **M. Kowal, C. Legat, D. Lorefice, C. Prehofer, I. Schäfer, and B. Vogel-Heuser:** Delta modeling for variant-rich and evolving manufacturing systems. 36th International Conference on Software Engineering Workshops (ICSE), 2014, pp. 32-41.
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- **M. Lochau, J. Bürdek, S. Lity, M. Hagner, C. Legat, U. Golz, and A. Schürr:** Applying Model-based Software Product Line Testing Approaches to the Automation Engineering Domain. at – Automatisierungstechnik, Vol. 62, Nov. 11, 2014.
- **B. Vogel-Heuser, A. Fay, I. Schäfer, M. Tichy:** Evolution of software in automated production systems – Challenges and Research Directions. Journal of Systems and Software, Vol. 110, 2015, pp. 54-84.

http://i40d.ais.mw.tum.de

Thank you for your attention.

Univ.-Prof. Dr.-Ing. Birgit Vogel-Heuser
Full professor and head of Chair Automation and Information systems (AIS)
Faculty of mechanical engineering, Technische Universität München