CYBER-PHYSICAL PRODUCTION SYSTEMS – CONCEPTS FOR MANUFACTURING VALUE-ADDING SYSTEMS

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Development Stages of the Digital Transformation
From digital image to an autonomous system

1. Digitalization
2. Virtualization
3. Connectivity
4. Autonomization

Mechatronic Systems → Cyber-physical Systems → Autonomous Systems

Timeline:
- 1950
- 1980
- 1990
- 2000
Vertical Integration
Core elements of the fourth industrial Revolution

**Infrastructure** (physical, digital)

**Cyber-physical System**

**Product Life Cycle** (valuable = personalized + sustainable)

**Interaction**

**Physical Systems** (act, sense, communication)  **Human Beings** (decide, create, communicate)

**Reflection**

**Digital Shadow** (real-time model of everything)

**Transaction**

**Software Service** (machine skills, Apps for humans, platform services)

**Interoperation**

**Cloud-based Platforms** (private, community, public)

**Prescription**

**Analytics** (Big Data/machine learning)

**Communication**

**Internet of Everything** (human beings, services, things)
Horizontal Integration
From B2B and B2C to Business to User (B2U)
10 Design Rules for CPPS
ARENA2036 – Stuttgart Research Campus
Active Research Environment for the Next Generation of Automobiles

- PPP
- 15 years
- Research factory as integration platform
10 Guidelines for the Value-Adding System of the Future
How Industrie 4.0 will change automotive production

- **Guideline 1:**Merge production- and logistic system into one value-adding system  
  Production and logistics systems act as integrated entity for reaching the enterprise goals.

- **Guideline 2:**Dissolve line and tact depending on product variety and work flow complexity  
  Granularity of structures and processes is adapted to the complexity of the product programs and frame conditions.

- **Guideline 3:**Set-up processes and structures mobile and scalable  
  Value-adding structures can be re-designed dynamically and economically when needed.

- **Guideline 4:**Design intelligent systems  
  Self-regulated subsystems contribute with their self-healing abilities to an entire robust system.

- **Guideline 5:**Make support processes value-adding  
  All support process (i.e. logistics) are either transformed into adding-value support processes or eliminated.

- **Guideline 6:**Replace material flow with information flow  
  Information is used effectively to reduce waste and stock and to support a downstream customization.

- **Guideline 7:**Shift process complexity to where it can be handled most efficiently  
  The value-adding systems’ boundaries are flexible, integrating customers and supplier as value-add partners in the value-adding system.

- **Guideline 8:**Represent system elements and processes continuously in a digital shadow  
  Accurate prediction and evaluation of upcoming events is made possible.

- **Guideline 9:**Optimize production based on data science  
  In complex systems correlation is more important than causality.

- **Guideline 10:**Focus the human role on design and optimization  
  Humans use their skills to enhance the value-adding and thus optimize the total system.
Guideline 1: Merge Production and Logistic System into one Value-adding System

Production and logistics systems act as integrated entity for reaching the enterprise goals.

- Decoupled optimization of production and logistics
- Competing target systems
- Optimization of production results in higher complexity and higher costs in the logistics
- Separated production and logistics functions to ensure transparency

- Global optimum instead of individual optimization
- Transparency by self-descriptive systems
- No separation of productive and logistics areas
- Changeable productive and logistics structures
Guideline 2: Dissolve Line and Cycle-time depending on Product Variety and Work Flow Complexity

Granularity of structures and processes is adapted to the complexity of the product programs and frame conditions.

**Fixed production today**
- fixed chain of singular plant technology
- strict organizational split of section, lines and line sections
- fixed line balance
- fixed just in time sequence
- high efforts in control
- low possibility to adapt during product life cycle
- changes interrupt the whole production

**Changeable production tomorrow**
- universal process modules
- interconnection of modules adapted to the situation
- system-inherent routing flexibility
- self-similar systems-of-systems architectures
- dynamic reconfiguration subsystems
- no separation of body, paintwork, interior assembly
- no dissection of the overall organization
All Objects in a Factory will be Mobile as Far as Possible
Example: Audi R8 – freely navigating AGV (navigation as a service)
Guideline 3: **Set-up Processes and Structures Mobile and Scalable**

Value-adding structures can be re-designed dynamically and economically when needed.

<table>
<thead>
<tr>
<th>Fixed production today</th>
<th>Changeable production tomorrow</th>
</tr>
</thead>
<tbody>
<tr>
<td>fixed allocation of products to resources and to production tasks</td>
<td>individual coordination of sequence and operation</td>
</tr>
<tr>
<td>fixed layout</td>
<td>scalable automation</td>
</tr>
<tr>
<td>safety fences between humans and machines</td>
<td>human-robot-cooperation</td>
</tr>
<tr>
<td>fixed and investment-intensive automation</td>
<td>scaling and flow-orientation layout-adaption to daily production schedule</td>
</tr>
<tr>
<td>resources dedicated to one specific operation</td>
<td>system adaption according to availability of resources</td>
</tr>
</tbody>
</table>
Output-oriented Configuration of Process Modules
Example: Assembly of a door module with HRC in ARENA2036

1 operator

1 operator, robot screws

2 operators

2 operators, 1 robot screws at 2 stations

4 operators at two stations

takt [sec]:

107

74

55

37

28

1 station

2 stations

more than 2 stations
Guideline 4: Design Intelligent Systems

Self-regulated subsystems contribute with their self-healing abilities to an entire robust system.

**Fixed production today**
- centralized planning, controlling and optimization
- incorrect master data
- selective operating data recording
- manual commissioning, programming and optimization
- uncertain planning data
- planning based on experience

**Changeable production tomorrow**
- intelligence shifted to decentralized entities
- plug-and-produce of system-elements into systems of higher complexity
- self-description of CPS: always up-to-date information base
- cloud-based self-control
- changeable functional range of system elements
- virtual commissioning
- automated, self-optimizing operation planning
Everything as a Service (XaaS)

Use case Virtual Fort Knox – integration platform

AppMES, AppERP, eApp, ...

Devices

mOS AppStore

APP 1

APP 2

...

APP Development Kit

Private or Public Cloud

Virtual Fort Knox

mOS

S1 S2 S3 S6 S4 S5

AS1

AS2

Manufacturing Service Bus (ESB++)

S1 S2 S3 S6

IS1 IS2 IS3

Equipment

CPS1 CPS2

Service, AS Aggregated Service, IS Integration Service, mOS Manufacturing Operating System, SOA service-oriented architecture

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Cyber-physical Production Systems
Example: Bin-picking as a cloud services

**Advantage**

- externalization of skills, services, maintenance
- lean robot workcell (»Lean Client«)
- centralized collection of data
  - optimization by statistical learning
- best practice solutions accessible
- displayed at HMI 2015
## Guideline 5: Make Support Processes Value-adding

All support process (i.e. logistics) are either transformed into value-adding support processes or eliminated.

<table>
<thead>
<tr>
<th>Fixed production today</th>
<th>Changeable production tomorrow</th>
</tr>
</thead>
<tbody>
<tr>
<td>fix installation of massive material flow systems</td>
<td>innovative parallelization of assembly and logistics</td>
</tr>
<tr>
<td>complex supply chain network</td>
<td>flexibility enabled by flexible material staging</td>
</tr>
<tr>
<td>long-lasting planning horizon (forecast)</td>
<td>no material areas in production</td>
</tr>
<tr>
<td>high safety stock level</td>
<td>commissioning on tour</td>
</tr>
<tr>
<td>material staging area is the bottleneck</td>
<td>assembly on AGV</td>
</tr>
<tr>
<td>low time-share of value-add activities in total throughput time</td>
<td>»best-fit« to avoid adjusting processes</td>
</tr>
</tbody>
</table>

Changeable production tomorrow

- Innovative parallelization of assembly and logistics
- Flexibility enabled by flexible material staging
- No material areas in production
- Commissioning on tour
- Assembly on AGV
- "Best-fit" to avoid adjusting processes
Robots will be Mobile, Flexible and Safe
Example: SEW Eurodrive – freely navigating DTS (carries the robot for bin picking)

- 3D-camera system: ensenso N20
- Magnetic gripper
- Cut-pieces
- Point cloud
- KUKA Agilus
- Bin with cut-pieces
- Mobile platform – Inductive power transmission

source: IPA
Guideline 6: Replace Material Flow with Information Flow

Information is used effectively to reduce waste and stock and to support a downstream customization.

- Information is inflexibly linked to material flow
- Lagged information flows
- Information Overflow
- High level of buffer inventories to cope with insufficiencies

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Fixed production today

- Real-time information access
- Information flow adapted to actual needs
- Intelligent integration of information
- Simulation based on real-time data
- Product differentiation through software variants
All Objects in a Factory will be Smart
iBin – Intelligent bins order their filling autonomously

Free Access

Open by pushing a button

iBin®-Modul, RFID compatible

push trays for VDA labels

2stage front flap

With an integrated camera combined with its cloud, iBin counts the parts enclosed in it.

source: Fraunhofer IML, Prof. Dr. Michael ten Hompel
Guideline 7: Shift Process Complexity to Where it can be Handled Most Efficiently

The value-adding systems’ boundaries are flexible, integrating customers and supplier as value-add partners in the value-adding system.

Fixed production today

Changeable production tomorrow

- pre-defined products with plenty variants
- complexity of business processes and production must mainly be handled by OEM
- market risks and coordination efforts at introduction of new product designs
- system integration limited to core partners, due to cost and efforts
- many interfaces, partly standardized
- big networks of many small JIS-plants

- active complexity management
- ad hoc configuration of value chains (MaaS)
- complexity of individualization managed by the customer as »Pro-Sumer«
- Open Source, Open Innovation and Co-Creation
- integration of additive manufacturing
- Everything as a service
- Just in Realtime (JIR) delivery
Business Model Innovation
Example Schunk eGRIP

Since 2015 suitable grippers can be ordered at Schunk, based on the CAD-Files of the parts that are transported.

- Reduction of order time and guarantee of high benefit for customers through integration of customers in the development process
- Communication via online-platform
- The partner company Materialise takes over the 3D print

Source: Schunk GmbH; Materialise]
Open Source Communities as Enabler
Example: ROS for Industrial Robotics

Why Open Source?

- more than two million free open source software packages (FOSS) available
- robotics research available as bundled software components brings technology push
- increase of critical mass, quality, transferability etc.
- supports business models, especially for SME
- »rapid prototyping« of technologies
- cost advantage 33 % compared to new development

Example:

Guideline 8: Represent System Elements and Processes Continuously in a Digital Shadow

Accurate prediction and evaluation of upcoming events is made possible.

- unidirectional information flow from planning to »physical« operation level
- production planning and control as sequential processes
- inconsistent and incorrect data
- simulation with historic data
- high effort of planning in different planning phases

- real-time system model for value adding
- automated maintaining of master and dynamic data
- localization, supervision and forecast based on live data
- production planning based on real situation
- transparency on current state makes prediction of future easier
All Entities of a Factory have a Digital Shadow

Example: material-flow-simulation inside a 3D-point cloud of ARENA2036
Basic Technology
Standardized coordinate system for factory and production planning

- The IFF has developed a continuous factory coordinate system for adaptable production systems and implemented it in the learning factory »advanced Industrial Engineering« aIE.

- Merges the digital image of the factory (digital shadow) with the real production process practically in realtime and independent of scale.

- Any decisions that need to be made in the near future can be aided by performing centralized or decentralized simulations with realtime data. This enables systems to be adapted to new restrictions faster and more cost-effectively.

- By comparing the digital shadow with the real production system, any discrepancies are identified immediately, any problems rectified and downtimes reduced even before they arise.
Guideline 9: **Optimize Production, Based on Data Science**

In complex systems correlation is more important than causality.

<table>
<thead>
<tr>
<th>Fixed production today</th>
<th>Changeable production tomorrow</th>
</tr>
</thead>
<tbody>
<tr>
<td>lean optimization (Six Sigma) of complicated systems</td>
<td>utilization of structured and un-structured data</td>
</tr>
<tr>
<td>search for root cause (Causality)</td>
<td>analytics with Big Data algorithms</td>
</tr>
<tr>
<td>problem solving by experts</td>
<td>automated pattern recognition</td>
</tr>
<tr>
<td>main question: WHY?</td>
<td>search for recipes (Correlation)</td>
</tr>
<tr>
<td></td>
<td>main question: WHAT?</td>
</tr>
</tbody>
</table>
Automated Detection of Dependencies
Between processes and deriving optimization potential

*Through*
- “minimally invasive” process monitoring via camera without elaborate system integration
- feature-based configuration and recognition of conditions in the videos via adaptive evaluation algorithms

*Benefits*
- near real-time process analysis with direct assignment of the cause for loss
- detection and quantitative evaluation of potential for process optimization
- permanent transparency through forwarding errors and machine condition to operators and planers
Guideline 10: **Focus the Human Role on Design and Optimization**

Humans use their skills to enhance the value-adding and thus optimize the total system.

<table>
<thead>
<tr>
<th>Fixed production today</th>
</tr>
</thead>
<tbody>
<tr>
<td>separation of engineering and operations</td>
</tr>
<tr>
<td>working tact is forced by automated production system</td>
</tr>
<tr>
<td>poor design and optimization autonomy of operators</td>
</tr>
<tr>
<td>routine operations dominating human work</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Changeable production tomorrow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reverse Taylor: merge engineering and operation</td>
</tr>
<tr>
<td>automation of repetitive and standard work</td>
</tr>
<tr>
<td>human intervenes when deviations occur</td>
</tr>
<tr>
<td>design tasks and coordination are dominating human work</td>
</tr>
</tbody>
</table>
Competence Development during value adding
Changing requirements of competence building due to an increase of personalized products

- Development of Taylorism from classical Taylorism to New Taylorism (Digital Taylorism) and leads to rethinking the development of Taylorism.
- The increasing individualization of products and shorter product life cycles lead to an increasing demand on the qualification of the workforce in production.
- This inevitably leads to a reversal of Taylorism, the Reverse Taylor!
- This leads to fluid competence areas in which workers have the respective skills and abilities to master new and unknown situations within the various scopes of the four life cycles.
- This requires defined standards allow workers to decide and act autonomously within certain limits.
Business potential of Integrated Industry (Industrie 4.0)

Specialists expect an increase in overall performance between 30 to 50 % in value creation

Estimation of potential benefits

<table>
<thead>
<tr>
<th>Costs</th>
<th>Effects</th>
<th>Potential</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stock costs</td>
<td>Reduction of safety stocks</td>
<td>-30 to -40 %</td>
</tr>
<tr>
<td></td>
<td>Avoiding Bullwhip and Burbidge effects</td>
<td></td>
</tr>
<tr>
<td>Manufacturing costs</td>
<td>Improving of OEE</td>
<td>-10 to -30 %</td>
</tr>
<tr>
<td></td>
<td>Process control loops</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Improvement of vertical and horizontal staff flexibility</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Use of Smart Wearables</td>
<td></td>
</tr>
<tr>
<td>Logistic costs</td>
<td>Higher level of automation (milk run, picking etc.)</td>
<td>-10 to -30 %</td>
</tr>
<tr>
<td></td>
<td>Smart Wearables</td>
<td></td>
</tr>
<tr>
<td>Complexity costs</td>
<td>Wider span of supervision</td>
<td>-60 to -70 %</td>
</tr>
<tr>
<td></td>
<td>Reduced trouble shooting</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Prosumer model</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Everything as a Service (XaaS)</td>
<td></td>
</tr>
<tr>
<td>Quality costs</td>
<td>Near-realtime quality control loops</td>
<td>-10 to -20 %</td>
</tr>
<tr>
<td>Maintenance costs</td>
<td>Optimization of stock levels</td>
<td>-20 to -30 %</td>
</tr>
<tr>
<td></td>
<td>State-oriented maintenance (process data, measurement data)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Dynamic prioritization</td>
<td></td>
</tr>
</tbody>
</table>

Pilot project at Bosch: Restructuring of complete distribution process based on an in-plant logistics center in an Industrie 4.0 project.

source: IPA/Bauernhansl, Bosch
„Overall connectivity leads us into a highly personalized, highly interactive and very, very interesting world.“

Eric Emerson Schmidt (* 27. April 1955) until April 2011 Executive Chairman (before Chief Executive Officer) with Google. Member of the US President's Council of Advisors on Science and Technology PCAST since 2009.
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