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Implementing cyber-physical production systems in learning factories

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Abstract

Rapid development in ICT and production engineering and the subsequent joining of both fields result currently in the creation of cyber-physical production systems. With these new technologies innovative didactic concepts are required to cope with new arising tasks on the job and in the development of such systems. Learning environments have proven to be effective instruments for developing competence in manufacturing training and education. To enable development of competence on cyber-physical production processes and systems a design approach for implementation in learning environments is presented. A case study illustrates the proposed implementation framework in a real learning factory.

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1. Introduction

Rapid development in ICT and production engineering led in combination to the creation of cyber-physical production systems (CPPS). This is recognized as major future trend in industry as well as research and referred to among others as *fourth industrial revolution, industry 4.0* [1] or *(direct) digital manufacturing* [2]. Undoubtedly this development requires new skills for workers. Learning environments such as *learning factories* have proven to be effective instruments for developing competence in manufacturing training and education [3].

As with all new technologies there are social and technological barriers connected to its implementation to industrial reality [4]. By utilizing learning factories most of these barriers can be overcome through early contact with the new technology. This helps to minimize the possible fears of workers and managers especially in the context of demographic changes in industrialized countries. For these countries a rise of the average age of the workforce is predicted in several

studies. In a survey amongst German human resource managers the highest ranked influence on recruiting was the demographic change [5].

Thus it is most important for universities and companies to impart knowledge and practical skills on CPPS. For this a holistic approach for didactic concepts is required covering all elements of CPPS. The outlined approach implements action based learning strategies which are promising high learning success in occupational qualification and academic knowledge transfer [3].

2. Cyber-physical production systems

2.1. Appearances of CPPS

The term “cyber-physical system” describes a technology containing computational and physical capabilities combined with the possibility of human machine interaction [6]. Through the connection of the “real” physical world with the corresponding “virtual” cyber representation a great potential

of applications is made possible. Not only improvement in dynamically optimized controls of complex physical systems is enabled by the introduction of cyber-physical systems; a whole new set of innovative technologies and applications can now be developed employing this concept.

For production systems the implementation of elements from cyber-physical systems technology leads to cyber-physical production systems (CPPS). As shown in the production system itself consisting of a physical component (e.g. machinery, tools,...) as well as a virtual component (e.g. simulation model, data analysis,...) is in the production context connected to the employee. This concept allows - among other advantages - an increase in productivity, production efficiency and/or product quality. Further applications of CPPS are in condition monitoring and in predictive maintenance. The connection of the physical and cyber world is relying on data acquisition from physical to cyber and a feedback from cyber to physical.

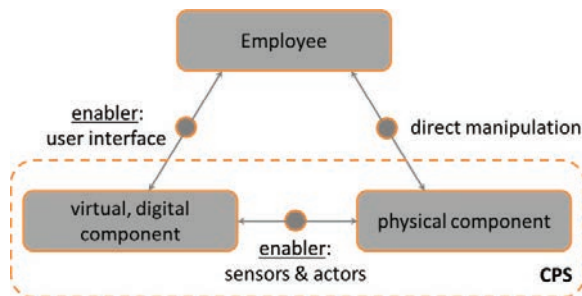


Fig. 1: CPS in production and its components in interaction with employees [7]

The introduction of CPPS in any production system promises economic, social and even ecological benefits. On the other hand, these implications need to be considered against possible disadvantages or social and economic introduction barriers of new technology and the demands of adjusted work flows for employees as stated in the introduction of this paper. Ensuring safety and security of underlying ICT-systems are also of great concern for companies. For the practical implementation several guidelines and frameworks are being developed with one example being the 5C architecture for implementation of cyber-physical system proposed by LEE et al. [8].

2.2. CPPS in education

In recent times learning factories are more and more established in academia and industry. Numerous approaches mostly tailored for the specific needs of a company or educational institution have been developed and examined [9][10]. Cyber-physical systems themselves are deployed in recent years to enhance teaching and learning experiences [11].

CPPS are seen as major future trend. A significant rise in training and teaching demand is to be expected and already noticeable on this topic. There are learning environments

focussing on this topic dedicated to SME [12] as well as there are ones dedicated to both university teaching and industrial training [cf. 9]. A concept for the combination of work-based learning with industry 4.0 has been proposed by SCHUH et al. [13].

The Learning factory “Die Lernfabrik” at TU Braunschweig consists of the three parts *Research Lab*, *Experience Lab* and *Education Lab*. Whereas the *Research Lab* is mainly focussed on research and industrial projects and the *Education Lab* on occupational training, the *Experience Lab* is utilized as learning and training area for university student and professional training and education. One main approach in the Experience Lab is research- and action-based learning which has proven to lead to higher individual learning motivation and success [14]. A concept for designing learning environments for energy efficiency through model scale production processes was already successfully implemented [15]. This work stands in the line of these developed approaches.

3. Implementing CPPS in learning factories

3.1. CPPS assessment framework

As indicated before, educating cyber-physical production systems is of increasing relevance. As alternative or addition to theoretical frontal presentation, practical experiences in learning factories in either model or real scale are a promising didactic approach. Therefore, the question arises whether a certain production process or system is suitable for educating CPPS. It should not just give a selective perspective but include all elements of a CPPS as described above. Even more, a suitable education oriented CPPS should show all technical aspects and allow to experience related benefits but also challenges. Against this background, an assessment procedure is proposed to enable 1) the assessment of a given production machine or system towards its suitability for CPPS related education but also vice versa, to provide 2) a guideline to systematically build up a CPPS which is usable in learning factories. The structure and flow of this assessment procedure is shown in Fig. 2. Derived from the CPS definition, four main elements – *physical world*, *data acquisition*, *cyber world*, and *feedback/control* - need to be distinguished. Each element includes three levels that determine the degree of fulfilment whereas superior levels include lower ones. Going through all those elements and determining the levels allows to derive a score which reflects the suitability for CPPS related education in learning factories.

3.2. Assessment levels per CPS element

Within the *physical world*, the system physically performs its designated task. Thus, resulting key performance indicators (KPI, e.g. time or energy demand per piece) are determined. Defining appropriate KPIs is the base level (I) for CPS here since they are the purpose respectively objective for analysis and improvement. State variables (e.g. electrical power

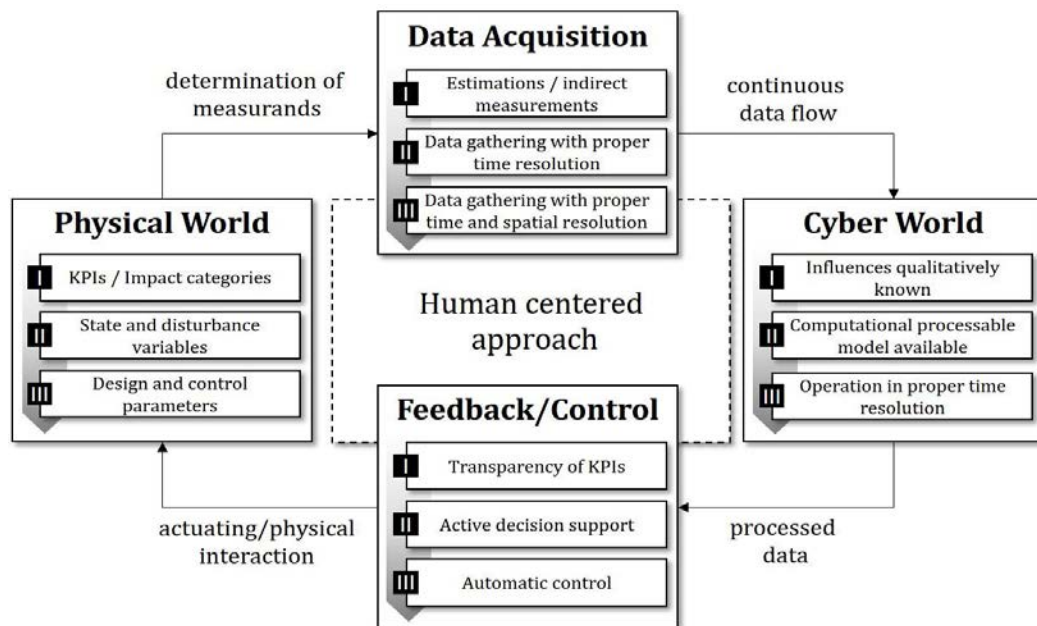


Fig. 2: Structure and flow of assessment procedure for analysis and development of CPPS

demand, forces, vibrations) describe system behaviour which is also affected by internal and external influencing variables. Knowing those variables in context of the specific application can be seen as level II since they have major influence on later steps. Finally, identifying the means of actively influencing the considered system through system design or control parameters defines Level III.

Another crucial element of CPS is the (continuous) *data acquisition*. Therefore, one or more appropriate measurand(s) need to be selected which will typically be state or disturbance variables as identified in the step before. For Level I at least good estimations or indirect measurements (e.g. estimation of state variable value through interpretation of other measured value) should be available. Level II is achieved through direct measurement of the measurands in proper time resolution. This does not mean that the sampling rate needs to be as high as possible – it should have a good fit with the dynamics of the given application. If the data should serve as base for dynamic machine control, real-time capability is certainly an important issue. In case of user oriented decision support for the operation of rather inert systems (e.g. ovens) lower sampling rates can be absolutely fine. With Level III the spatial perspective comes into play. CPPS are often related to decentralised applications, e.g. in context of autonomous smart product agents or distributed sensor networks [16]. But also for a single machine, measuring the same type of variable on different spatial spots might be beneficial (e.g. product temperature at start and end of oven conveyor). Thus, Level III is achieved if the necessary spatial resolution is given (which is trivially fulfilled if really just one measuring point is possible and necessary).

The *cyber world* stands for the virtual, model based representation of the production system. Continuous processing of input data flow(s) into meaningful decision

support for rather operative system control is an important distinction towards concepts like the digital factory [17]. For this, influences between state and influences variables as well as KPIs should be at least qualitatively known and described which would allow manual interaction based on input data (Level I). To unfold the full potential in terms of speed and quality, computationally processable models are necessary (Level II). This could include any type of models, e.g. data based (e.g. regressions, decision trees), physical (e.g. equations based on physical laws), numerical (e.g. finite element/FEM or computational fluid/CFD models) or discrete event (e.g. material flows in factories). However, those models strongly differ in terms of computing time which might conflict with production processing time (e.g. CFD simulation of die casting takes several hours, the process itself just seconds to minutes). Thus, Level III requires operating the models in the proper time resolution for the given application.

Finally, the *feedback/control* element ensures the conversion of processed data (from cyber world) into means for interaction (to physical world) while involving the human. With Level I, transparency regarding KPIs is given - the decision for further action has to be taken manually by the human (e.g. worker). Level II provides active decision support, the human is still in charge but rather in an executive role. With Level III, the considered system is controlled automatically. However, the human still should have transparency regarding KPIs and control actions that have been conducted.

4. Implementation Case: Research based learning

On the basis of the outlined guidelines for implementing cyber-physical production processes in learning environments a suitable exemplary process had to be selected for utilization

in a lecture accompanying team project. Following the analysis, a heating process was revised according to the proposed procedure from chapter 3.

4.1. Lecture “Sustainable Cyber-Physical Production Systems”

The lecture “Sustainable Cyber-Physical Production Systems” is held at TU Braunschweig for engineering master students. The newly developed course’s scope is covering all the basics of CPPS and connects these to its potential to foster sustainability in production engineering.

As practical exercise a lecture accompanying team project is set up as compulsory part of the course. In this team project the students divided into groups with three to five members are working mostly self-organized on a given model scale production process with real scale behaviour. The goal of the team project groups is to enhance the sustainability of the process by making it “cyber-physical”. All means of CPPS taught in the lecture can be adopted to the model scale process to enhance the energy demand, processing time and product quality.

4.2. Process selection and implementation

For the team project a suitable production process within the learning factory at TU Braunschweig and cyber-physical measures had to be selected and defined. Among the processes in the production line set up from MPS® by the company Festo Didactic with some processes developed according to [15] one single MPS in the line had to be chosen to reduce complexity for the learners according to the approach outlined in section 3 of this paper. The three processes considered in detail were a machining process, a heating process and a handling process. All three processes were rated regarding the approach with the results shown in Table 1.

The heating process achieved the highest score over all categories. On the other side the available handling process lacks any points for the cyber and physical word as well as in the feedback/control category. The milling and heating process both scored a medium rating with the heating process being slightly more cyber-physical. This is due to the knowledge about state and disturbance variables and the more accessible nature of these in the thermal process than in the machining

process. While both processes are equipped with live energy demand measuring systems including an online visualization scoring 2 of 3 in data acquisition there was a lack of CPPS components in the cyber world and in the possibilities for feedback and control resulting in a score of 1 of 3.

To achieve a better fitting cyber-physical production system with more learning elements a graphical user interface was implemented for the heating process. This GUI includes visualization of the process state and recorded product data as well as control inputs for processing time and batch production. The temperatures for the two-point controller are set at the controller itself as is the power for the heating element.

This revised heating process (see Fig. 3) consists of five main components: the heating element, the heating chamber, transport belts with work-piece separators, an RFID temperature measuring system and an PLC with the above described human-machine interface. Two different work pieces can be heated in the process made of aluminium or polyethylene both with a 3D-printed cap made of PLA with an integrated RFID-chip for identification and temperature measurement. The revised process scored according to the rating system an overall score of 10 out of 12 and thus it is a CPPS covering all elements in good to excellent extent.



Fig. 3: Revised heating process in the learning environment with human-machine-interface

	CPPS component				Overall
	Physical World	Data Acquisition	Cyber World	Feedback/Control	
Handling	-	II	-	-	2
Milling	I	II	I	I	5
Heating	II	II	I	I	6
Heating (revised)	III	III	II	II	10

Table 1: Rating of available processes regarding CPPS fulfilment

The team project was scheduled lecture accompanying for the duration of 15 weeks. As milestones were set for all groups:

- **Modelling** of the production process
- **Oral presentation** of conducted modelling approach
- **Validation** of model and improvement
- **Challenge: Measurement** of process timings, energy demand and product quality for four workpieces of predefined but to the learner unknown properties
- Final **poster presentation** of results (Fig. 4)

A set of learning elements was aligned to the milestones for the participants to gain knowledge in:

- Human-machine-interfaces
- Data gathering systems
- Data Analytics Methods
- Modelling approaches
- Simulation behaviour
- Data visualization
- Human-machine-interfaces
- Decision modelling

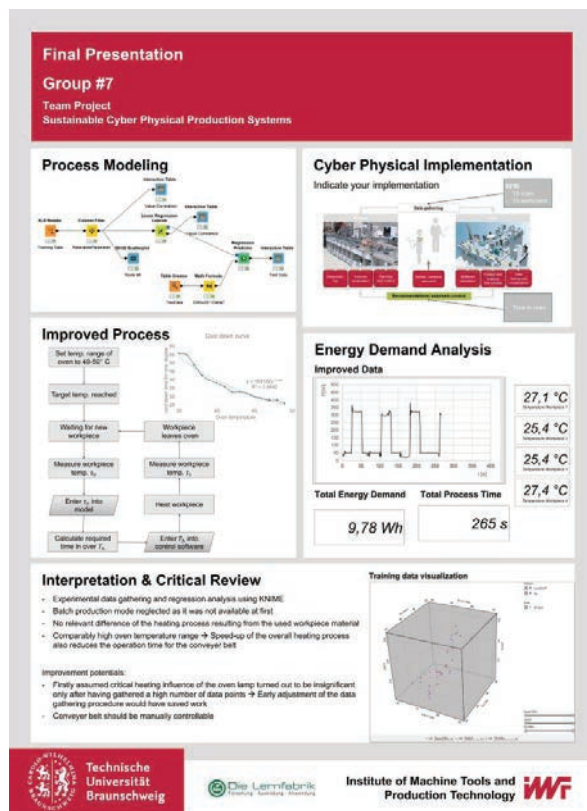


Fig. 4: Poster presentation of final team project results by one student group (2015/2016)

4.3. Application results

The seven groups took very heterogeneous approaches for the team project assignments. four groups went for a *data-based modelling* approach, two groups decided to follow a *physical modelling* approach and one group built up a predictive simulation with *products modelled as agents*. All student groups manipulated the parameters *processing time* and *temperature* based on recommendations of their simulation model. For this they utilized the live data gathered for each specific product going into the process.

Based on the challenge - the measurement of process timings, energy demand and product quality for four workpieces of predefined but unknown properties – the group’s

results emerged diverse as shown in Fig. 5. The recorded energy demand of the process was recorded from as low as 6.68 Wh up to 13.71 Wh. The processing time and the output product quality also depended on the modelling approach taken by the individual groups. It could be observed that groups taking more time for their modelling and validation of the created models achieved better results than others while working in the wide set boundaries resulted in a wide spread solution space. This was also recognized by the students.

The team project received a very positive feedback in student evaluation. It was evaluated to be very helpful for gaining and securing practical knowledge about CPPS. Not only the implementation of the elements of CPPS taught in the lecture were received positively but also engineering soft skills like team work and project organization. As for many open formulated assignments rarely a lack of guidance during the team project was noted by the students. Very well experienced was also the human centred process design which allows the students to carry out as many elements as possible by themselves like applying the recommendations of the modelling to the process controls. This emphasises the benefits of action based learning in this field as understanding was reached by doing.

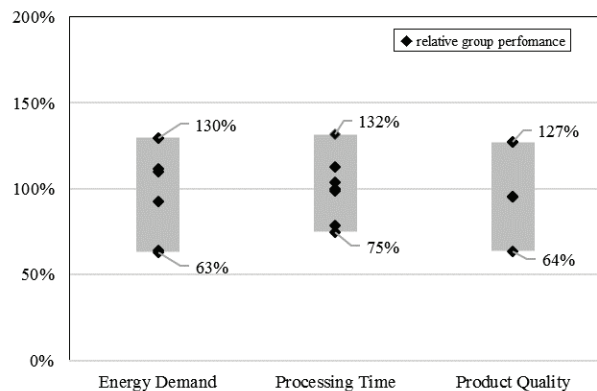


Fig. 5: Relative group performance in the team project case study (normalized values)

5. Conclusion and Outlook

Derived from the rising demand for learning environments on cyber-physical production systems a generic approach for analysis and implementation of appropriate production processes and systems is developed in this paper. As cyber-physical production systems will become more and more apparent in manufacturing, education and training will present key factors for successful implementation for companies. Utilizing a simplified rating system with categories adapted to the components of a cyber-physical system, a tool is created allowing the purpose driven application in learning environments on this topic. The approach is in alignment with corresponding industrial scale processes and systems and their respective required skills for development and operation

The outlined approach was validated by the application in a lecture accompanying team project at university in a post-graduate module in engineering. A model-scale process yet with realistic behavior was chosen among others and enhanced to fit the learning objectives previously set. The predefined learning elements were supported by milestones for the student's groups.

A next step is to consolidate and enhance the corresponding educational contents as the presented approach can be used as a foundation for developing and implementing specific learning methods and concepts fitting curricula of academic and occupational education. With positive evaluation a continuous improvement process is conducted at the learning environment "Die Lernfabrik" with the mid-term goal of deploying the process in different learning situations and in the long-term rolling it out to further learning environments. The modularity for simple implementation of new developed technology and methods needs to be made sure of considering the highly dynamic development of cyber-physical production systems at the moment and in the near future.

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