Cyber-Physical Production Systems: A Teaching Concept in Engineering Education

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***Abstract*—Highly flexible production systems as well as increasing complexity and individuality of products lead to changing parameters in industrial environments. The ongoing digital transformation of the production sectors demands not only a rethinking of management and decision-makers, but also a reform of academic teaching. First, the paper focuses on the analysis of requirements and key qualifications students are to be taught essentially with the advent of smart factories. Therefore, a wide-ranging course draft giving a comprehensive insight on overall coherence in Cyber-Physical Production System is developed. Finally, a second focus lies on the theoretical evaluation of the outlined concept referring to its didactical structure to impart application knowledge in engineering education.**

***Index Terms*—Industry 4.0, Academic Education in Engineering, Cyber Physical Production Systems, Problem Based Learning**

I. Introduction

The future of production, in particular within the context of the so-called fourth industrial revolution (Industry 4.0), is strongly connected with the integration of IT technologies on all levels of the factory [1]. Within this ongoing evolution, the factory of the future becomes 'smart', which leads to new requirements for engineers on the one hand the field of production systems, but on the other hand regarding their individual skills. Customer specific requirements are realized by communicating machines in a flexible and adaptive production, thus enabling the shift from static cycles to individual production [2]. Autonomous robotic systems will be added increasingly to previously fully automated production systems in order to allow a more dynamic handling e.g. regarding product tolerances or errors [3].

These few examples already show that the product as well as the production systems itself exist not only as a physical entity, but also have a virtual representation. Both aspects are combined in *Cyber-Physical Production Systems* (CPPS) that allow the integration of production data (e.g. machine parameters or data from quality checks) and sensor data gathered by autonomous agents in the production in a virtual representation of the product. This data can be analyzed to get deeper insights on the manufacturing process on the one hand for the human as the process expert and on the other hand for the machines as autonomous entities on the shop floor.

With the focus on technical tasks the evolving role of engineers, whether as designers of manufacturing lines or products, requires new skills. To utilize the benefits of the smart factory, the skill set of engineers has to be evolved by integrating topics like data acquisition, integration and analysis into the engineering curriculum. This paper presents a teaching concept that is based on aspects of the fourth industrial revolution and transfers these aspects in engineering education to meet future requirements.

II. Demands on Engineers in Smart Factories

A. State of the educational landscape in Industry 4.0

The concepts and technologies of automation technology are well understood and expert knowledge is widely available. Courses on automation technology are a fixed part of engineering education as well in undergraduate as in graduate level courses. There are also a bunch of courses held on the topic of Cyber-Physical Systems and Internet of Things (IoT). The scope of these courses is the design of IoT or CPS devices and their interaction on the embedded devices level and the protocol level [4], [5]. Such courses, as well as courses on big data and machine learning, are often addressed in the curriculum of computer science. On the opposite, in the area of mechanical and electrical engineering many courses considering automation technology like control systems engineering are widely available [6].

We aim to bring all the needed basic skills described before together in one course on CPPS. Starting with the physical sensors and devices over the data they produce and the storage of the data until the machine learning area. Students will get a good overview which will enable them to recognize problem statements and possible solutions when they start working in a smart industry.

B. Weakened boundaries of the automation pyramid

With the development of Industry 4.0 and CPPS, the boundaries of the automation pyramid become indistinct as industries demand on vertical integration gets bigger [3]. Of course, the different levels will not disappear, as each level addresses a different view on the production process, nevertheless, the distinction between them will fade. They will probably fade even more with climbing the pyramid because of the possibility to read the data from its origin directly without using specialized databases and interfaces.

Each level of the pyramid implies its own challenges and specialties, but as the boundaries start to disappear, the ability to 'think outside the box' becomes more important. When,

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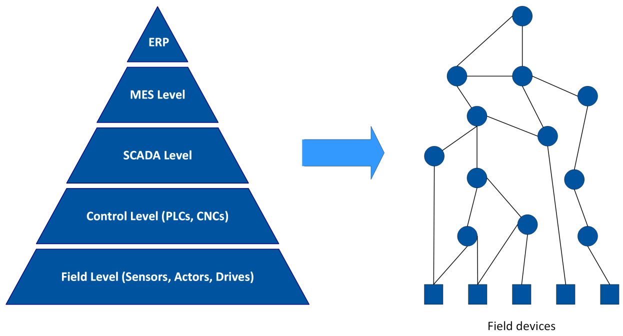

Fig. 1. The weakened boundaries of the automation pyramid [7]

for example, higher level systems directly communicate with field level devices, one will need basic skills from both fields to understand the challenges involved and to be able to communicate with the experts of the single domains [8].

To figure out which skills are needed in this upcoming environment, we take a closer look at the single levels of the classical automation pyramid.

1) In the field level, known as level 0, the scope lies on sensors and actors and their interconnection. Only a small amount of data is generated by each sensor or actor, typically from only a single bit, e.g. a simple on/off signal to a few couple of bytes, e.g. shaft controllers. However, this small amount of data is transferred with low latencies and under hard real-time conditions.
2) Level 1, the control level, describes the controllers needed to utilize the sensors and actors of level 0. *Programmable Logic Controllers* (PLCs) are highly specialized systems designed to react quickly and deterministically to changing input signals. They are not designed for any other form of data processing and often allow only very limited access to themselves.
3) The supervisory control and data acquisition level, referred to as level 3, interfaces with the different PLCs. At this level, supervisory personal has the chance to interfere with the main process. The process data is visualized at terminals where operating staff can change parameters and has the possibility to interact with the PLCs of the control level.
4) The MES level addresses the production planning for a complete shop floor. This is where decisions are made regarding which machine will run which task and how the whole production process interacts.
5) The higher level of ERP is a purely information driven level. The main focus here lies on the enterprise view for the back office. Data is consolidated and preprocessed to allow an enterprise domain view on it. Direct view of the production data is no longer of special interest.

In the last years the rise of machine learning and artificial intelligence has led to an increased interest in these topics, not only from a scientific point of view, but especially by industrialists. Trends like predictive maintenance, individualized control, and intelligent robotics resulted in an increased interests and a high expectation regarding optimization potentials. Many manufacturers today already work with highly automated machinery and have a demanding need of well trained personal with knowledge in the topics mentioned above.

Experts on the lower level of the pyramid often have a background in mechanical or electrical engineering, but are usually not familiar with data integration or data analysis. These fields are typically tackled by computer scientists who in turn are often not familiar with the constraints of the systems in level 0 and level 1. The gap between these historically separated fields needs to be filled.

C. Challenges in Industry 4.0 education

Subsequent, the qualifications needed in a fully Industry 4.0 enabled production environment are lined out.

1) Integration of PLC controlled field devices: At first, vertical integration of field devices requires knowledge about the physical connection of the field devices. Today many different automation buses exist. There are, for example, Actor-Sensor Interface (AS-i) and IO-Link that directly connect sensors and small actors and at the same time provide power to them. In addition, there are more powerful buses like ProfiNet, EtherCat or Sercos III, all based on Ethernet, but with modifications to enable real-time data transport [9].

All these buses are not designed for heavy data exchange, but their scope is to exchange only the portion of the data that is crucial for the control process. Therefore, flexibility is not available. All the data that needs to be transferred is configured when the machine is built and not changed after commissioning of the machine. An engineer of CPPS needs to be aware of these limitations and special requirements.

Understanding the interaction of the different sensors and actors within a machine to form a working machine is another needed skill. PLCs work in fixed computing cycles, reading the inputs, computing the output values and writing the output values, to guarantee real-time reactions [10]. PLCs do not allow direct user input and they are not to be seen as any standard computer because usually there is no possibility to run any other program than the control software on a PLC.

2) Data acquisition and data modeling: The sensors, actors and devices in the field and control level generate a lot of data which has to be gathered and stored in a clear and distinct manner to simplify later analysis. In the past, it was a hard task to gather data from the different PLCs inside the factory. Special knowledge of the program structure as well as the construction of the machine were needed to identify, which sensor value could be read from which data offset inside of a PLC. This is why machine data is often only available in the lower levels of the automation pyramid. With upcoming new standards like OPC UA [11] it has become easier to gather machine data and integrate it to upper level databases. Data access is standardized among the different manufacturers. Information is no longer modeled as data blocks and offsets, but can now be integrated into complex information models.

These information models allow enriching raw values with complex data types and additional data like measurement units already in the PLCs. Moreover, relations between data values can be expressed by adding references.

Computer scientists are typically used to think in complex data models, whereas electrical engineers are used to think in electrical connections. Up until today, PLCs are programmed with special languages, which are inspired by electrical connections and do not support complex data types [12]. A basic understanding of both domains will enable engineers to master the transition to Industry 4.0 enabled manufacturing processes.

3) Data storage and data integration: Collected data from the field level has to be stored persistently to allow later data analysis. This is a challenging task, as production systems are heterogeneous and even with upcoming standardization, like OPC UA, this will also be the case in the future. Investment cycles in industry are often long termed and new machines exist together with older ones.

Furthermore, long production cycles in industry require specialized storage concepts. Data storage systems need to be able to store a huge amount of data for a long period of time. Only systems featuring flexibility and scalability can fulfill this requirement.

Understanding the diverse requirements and the different technologies and solutions is a crucial skill, required by future production engineers.

4) Data analysis: Based on the assumption that all the data from level 0 and level 1 of the automation pyramid has been gathered and stored in an appropriate way, the next logical step is to create a benefit out of the data. Due to the increased processing and storing capabilities of modern computer systems, machine learning algorithms can be used to find weaknesses of a production process as well as predicting certain outcomes based on input values.

For example, data analysis can be used inside a production process to identify products that will not pass quality control before they are processed further [13].

Another common example for the usage of production data is 'predictive maintenance', where machine data is analyzed to anticipate an upcoming machine failure and, like the name says, predict maintenance need.

Of course, data analysis and machine learning is a very complex task and not every engineer working in a smart factory has to be a specialist in this area, but every engineer dealing with CPPS has to know about what is possible and how it can be achieved. Only then he or she will be able to support or supervise the data analysts.

III. ENGINEERING EDUCATION IN CYBER-PHYSICAL PRODUCTION SYSTEMS

To prepare students for the presented industrial developments and challenges, it is necessary to highly qualify them on applications and technologies of smart factories. This chapter aims at appropriate approaches to teach smart factory technologies and cause-effect relationships in intelligent production systems in courses at university. A key challenge in academic education is to enable students to gain active knowledge. Studies show, that the majority of students is able to apply 'in vitro' knowledge, acquired at university, only in university analogue contexts (e.g. exams) [14]. In contrast, students are hardly able to transfer in-class acquired knowledge into complex, everyday situations – because they acquired inert knowledge. Inert knowledge can be defined as knowledge which certainly exists but which is not retrievable in problem situations. The difficulty is based on the transfer of scientific, generalist models to complex reality problems in engineering environments [14], [15].

Cognitive constructivism is a scientific field which focuses on ideal information conveyance. Its target is to enable learners to transfer knowledge into everyday situations at the best possible degree – and therefore focuses on problem-orientated learning. Moderate constructivism is one of the most important approaches in educational research because it equally concerns multiple factors of knowledge acquisition, such as learning environment, social and contextual factors of learners. The increasing complexity of future skill requirements within smart fatories, outlined in section II, demands problem-based learning scenarios more than ever. For the latter mentioned reasons, this paper is based on five basic constructivist theses about cognitive learning processes [15]:

1) Learners construct their knowledge actively by themselves. Perception-related experiences always depend on previous knowledge and mental structures.
2) Knowledge cannot be transferred from external references, but must be generated by oneself.
3) The social arrangement of the learning context is fundamental for knowledge acquisition. Therefore, a learning environment should rather allow individual experiences than enforce an objective coaching.
4) It can be assumed that, if the connection between learning contents and resulting advantage to the learner is not perceived, the information given is less important. Learning experiences are always social processes at the same time.
5) Meta cognitive skills are required for the control of the own learning success.

Out of the five listed basic theses, three instructional approaches for teaching concepts have been developed [15], [16], [17] to avoid inert knowledge: the approach of *Anchored Instruction*, of *Cognitive Flexibility* and of *Cognitive Apprenticeship*. The approach of Anchored Instruction addresses the design of courses within authentic problem situations. An authentic situation within the learning context is of significant importance to the students learning effort as well as personal relevance of taught contents [17]. Therefore, a realistic storytelling format which allows an identification with the learning situation is essential. Realistic, problem-orientated scenarios allow an explorative, open learning environment in which personal relevant experiences can be made.

The approach of Cognitive Flexibility demands a high level of multi-perspectivity in learning situations to make new knowledge retrievable even in new and complex everyday situations. To induce flexible, multiple representations of knowledge, it is necessary to consider the same concept at different times from different points of view [15]. Thus, it is important to enable non-linear learning processes in which learners can individually switch to contents of interest or rather need of information similar to the concept of hypertexts.

The approach of Cognitive Apprenticeship focuses on implicit, strategic expert-knowledge which is clearly to be distinguished from easily to expatiate knowledge. It is to be mentioned that this approach is particularly used in practical situations like internships or traineeships. Here, while solving the problem, the expert needs to verbalize own cognitive processes to transfer implicit knowledge to a novice. A well-known methodology to transfer implicit knowledge to novices, especially within companies, are triad talks described by [16]. In this approach, a layman leads an interview between an expert and novice to extract and assure the transformation of implicit knowledge to the novice.

In result, beyond the technical requirements mentioned in section II, the following six constructivist requirements have to be taken into account in order to design a concept to prepare the topics of the smart factory for academic teaching. [15], [17]:

- Authenticity and situatedness of the learning process
- Confrontation with multiple contexts for transferable knowledge for other problems
- Multiple perspectives to construct transferable knowledge for other situations
- Social context which allows collaborative learning in a situated problem solving
- Teaching content needs to be open to allow individual and active learning by the students referring to previous knowledge
- Scope of action needs to be recognized by the students to make them benefit from it

In general, all learning units are constructed following the learning cycle of experimental learning by Kolb [18].

Experimental learning approaches aim at processes whereby knowledge is created through the transformation of experience [18]. Here, concrete experience, abstract conceptualization, reflective observation and active experimentation are set into a recursive process that is responsive to the learning situation and what is being learned [18]. Experimental learning offers the ideal fundament for collaborative problem solving within classes. By only imparting basic knowledge and demanding study groups to solve extended tasks, we encourage the transfer of new information into application know-how. Teamwork allows the discussion of a problem from many points of views and the evaluation of diverse solution approaches. Competition settings especially motivate a maximum of situatedness and individualized thinking approaches (within a scope of action) to find the best option to optimize processes and to prevail against competitors. In terms of triad talks [16] section IV will show a teaching concept to prepare education at university for contents of Industry 4.0 - regarding the aforementioned six constructivist requirements. This way, we want to meet demands of industrial employers [3]. Universities need to prepare students for interdisciplinary aspects in the fields of future factories. Due to the goal of a course imparting active knowledge, we regard it as necessary to teach an overarching concept of all relevant parts of Industry 4.0. It is certain that a university course cannot meet the requirement of preparing learners for all imaginable use cases of later employment. However, by creating practical knowledge during learning experiences on Cyber-Physical Production Systems, we want to assure that the skill set of future engineers meets the requirements of future industrial problems. This can be achieved by teaching problem solving attitude as well as fundamental expertise in the huge, wide-ranging field of Industry 4.0. To provide a maximum of experience-based learning, all learning modules identified in section IV are characterized by a minimum of basic input and a maximum of knowledge application — learning content is to be experienced by the students themselves.

IV. Scenario based teaching concept in four modules

In this section, we propose a teaching concept consisting of four different modules, each dealing with one of the challenges of Industry 4.0 education described in section II. Those modules are designed to impart a vertical section through all industrial information and control layers, starting from sensor level up to enterprise level. By breaking with the classic automation layers, we pursue the goal to help students to gain broad understanding of how data is generated and how to use data to optimize production systems. Each module consists of one or more sessions that contain a short theoretical introduction of the topic and a micro training to let students experience the topic in practice. In contrast to classical lectures, we focus more on the exercises by using the same Industry 4.0 scenario, as well as realistic tasks for all exercises.

A. First module: Integration of PLC controlled field devices

The first module teaches the fundamentals of PLCs and machine level information modeling. This knowledge is required to integrate arbitrary field level devices that can be controlled by PLCs into a CPPS. The first part of the module begins with an input on PLC programming and the related exercise. Students learn how to use PLCs to control devices and generate data. The practical exercise uses configured Raspberry PIs with control boards as PLC units and different sensors that need to be connected and controlled using the Raspberry PI.

The second part of the module deals with information modeling on machine level. The theoretical input of this session creates awareness for the need of a unified information model in the current industry, where every manufacturer uses different interfaces. The module introduces OPC UA as an example approach for a unified information modeling protocol. In the subsequent exercise, students return to their groups and install and setup a basic OPC UA server to access the data generated by the sensors in a unified protocol.

B. Second module: Data acquisition and data modeling

While the first module focuses on controlling single devices using PLCs, the second module deals with connecting those devices and creating the related digital representation to form a CPPS. The introduction of this module gives an overview of how to connect devices using an OPC UA client-server architecture and a messaging system. Afterwards, an exemplary factory scenario is introduced that highlights the challenges of interoperability with heterogeneous systems and proprietary protocols in decentralized work flows. Figure 2 gives an overview of the scenario. The scenario consists of a material storage unit, several production and assembly units and a dispatch unit that ships manufactured products. Robots are used to transport materials and products between those units. The factory receives orders from the manufacturing execution system (MES) but all units coordinate with each other to execute the order decentralized. For the practical part of this module, students once again work in teams that must integrate all the different actors into the given MES. The whole system is simulated, therefore students can examine the result of their work and check if everything works as planned.

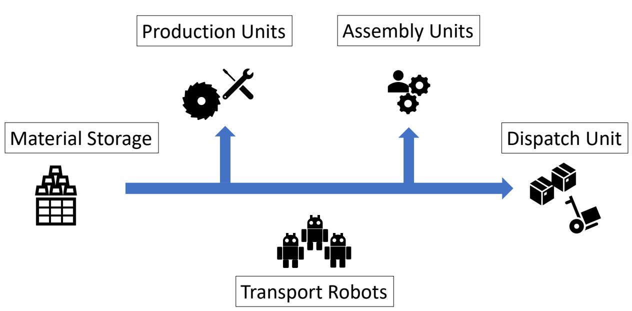

Fig. 2. Scenario of a Cyber-Physical Production System

C. Third module: Data storage and data integration

In the previous modules, students learned how to acquire data and create information models for data. The third module deals with the integration of this data into a central data storage. In the theoretical part of the module, we present different technologies and approaches to create a data storage. Afterwards, we aim to introduce a common industry scenario where the new data storage is used for unified OPC UA data from the current production system and legacy data from old production systems.

The practical exercise addresses the presented problem. Students receive a legacy database and need to create a central data storage for heterogeneous data that contains the data from the scenario of the second module and the legacy data.

D. Fourth module: Perform data analysis to optimize production systems

After the students learned the basics of how to connect systems to form a CPPS and how to integrate acquired data, this module aims at teaching them how to use this data to optimize production systems and support operating staff to understand the current state of the system and make well founded decisions. The third module is split into three small sessions that teach the foundations of data analysis and exercises that let them practice the acquired knowledge in an advanced version of the scenario known from the second module.

The first small session summarizes the topics from module one and two and leads over to an introduction to analysis methods. In a first exercise, students learn how to build KPIs for the scenario known from the second module. The other two sessions deal with visual analysis and machine learning. Both sessions consist of theoretical input, followed by small exercises that let students practice to apply those methods in a small prepared environment. Those sessions teach students to aggregate and visualize information to support decision making and problem solving. The final exercise concludes the module by requiring the students to apply the acquired knowledge in a small competition. The exercise is based on the scenario from the second module extended by an economic component, adding a gamification character to the scenario. Figure 3 shows a concept graphic of the advanced scenario. Students are once again split into teams that need to use analysis methods to optimize the production of the simulated scenario. Based on real life industry, teams lose virtual currency for storage and production and gain currency for every product that they manufacture. The scenarios production is not optimized and can be controlled by assigning the limited resources like different transport robots and manufacturing stations to specific tasks or by removing inefficient resources from the production. Every change in the factory setting is reflected in the virtual simulation, allowing students to evaluate their decisions and expected results. The student team that manages to make the most efficient use of their resources wins the competition.

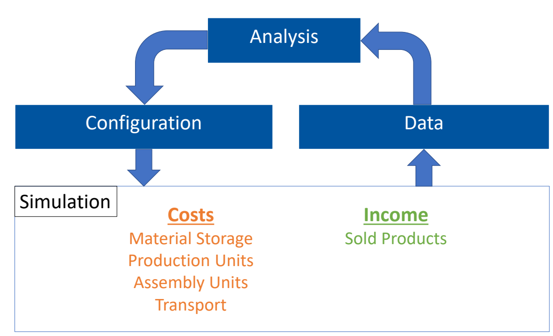

Fig. 3. Scenario with business oriented gamification

V. Theoretical Reflection and Outlook

The concept sketched above is designed within the context of the constructivist approaches and technical requirements outlined in section II and III. First of all, the application of an appropriate, realistic use case scenario allows learning experiences by the example of authentic, industry-related problems and challenges. This, in turn, enables the training of students on multiple complex and interrelated contexts within Industry 4.0. In the presented course concept, learners gain experiences on all levels of the automation pyramid presented in section II. The interaction within challenges of multiple contexts leads students to take multiple perspectives on different levels of the considered organization. The result is the acquirement of new skills and strategies in solving a problem, which makes new knowledge transferable to other situations. Therefore, the course concept aligned in section IV, focuses on control level (collection of data), networking and the analysis (of data) and finally their economic efficiency. The aim is to make interrelations tangible by experiencing the origin, use and evaluation of data. Especially differences between machine-to-machine and machine-to-human interaction are outlined to adopt different perspectives of a system. The implemented competition of module four allows a high situatedness of the learning scenario withing social contexts and a wide scope of action. At present, the term of Industry 4.0 is still under research, which is why the outlined teaching concept needs to be agile and problem-based as well. A steadily growing level of complexity within smart factories requires the use of problem-based learning methods.

Finally, we aim at inviting experts from industry and research additionally to motivate by initial talks and demonstration of strategies in solving course exercises by thinking-out-loud [19] method throughout all of the four modules. In this way it is possible to moderate a talk between experts and novices as a layman and outline implicit knowledge from real-life experiences.

The concept introduced will be implemented and evaluated within the next year. To validate or complement the teaching concept at its content level, we plan to conduct and evaluate expert discussions. A second focus will lie on the evaluation of the didactic concept of the teaching modules. Therefore, we evaluate if the realization of constructivist principles and the use of problem-based learning approaches is appropriate in the context of engineering education in the field of CPPS. Furthermore, we transfer the industrial, competitive scenario during all four modules into Virtual Reality (VR) environments. Previously, a VR approach allowing students to visit remote laboratories was shown in [20]. While in this approach only one student at a time can use the VR environment (1:1 solution), our next goal is to allow a permanent accessibility to a demonstrator (1:n solution), independently from time and space. Here, the central research issue focuses on the question if VR enables students to experience learning contents more immersively and/or if VR improves teaching not in general but under certain predispositions to be figured out (e.g is the learning success depending on prior experiences within the teaching content or even VR games? / How is a manual for the VR demonstrator to be designed to allow an interaction at the best possible degree?). First evaluation results will be presented in a follow-up paper.

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