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Stellenbosch, South Africa

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Implications and Future Challenges for Logistics in Cyber-Physical Production Systems at the Example of ESB Logistics Learning Factory

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Abstract
Increasingly volatile market conditions and manufacturing environments combined with a rising demand for highly personalized products, the emergence of new technologies like cyber-physical systems and additive manufacturing as well as an increasing cross-linking of different entities (Industrie 4.0) will result in fundamental changes of future work and logistics systems. The place of production, the logistical network and the respective production system will underlie the requirements of constant changes and therefore sources and sinks of logistical networks have to obey the versatility of (cyber-physical) production systems. To cope with the arising complexity to control and monitor changeable production and logistics systems, decentralized control systems are the mean of choice since centralized systems are pushed to their limits in this regard. This paradigm shift will affect the overall concept under which production and logistics is planned, managed and controlled and how companies interact and collaborate within the emerging value chains by using dynamic methods to generate and execute the created network and to allocate available resources to fulfill the demand for customized products. In this field of research learning factories, like the ESB Logistics Learning Factory at ESB Business School (Reutlingen University), provide a great potential as a risk free test bed to develop new methods and technical solutions, to investigate new technologies regarding their practical use and to transfer the latest state of knowledge and specific competences into the training of students and professionals. Keeping with these guiding principles ESB Business School is transferring its existing production system into a cyber-physical production system to investigate innovative solutions for the design of human-machine collaboration and technical assistance systems as wells as to develop decentralized control methods for intralogistics systems following the requirements of changeable work systems including the respective design of dynamic inbound and outbound logistic networks.

Keywords
Logistics, Cyber-Physical Production Systems, Changeable Work and Logistics Systems

1 INTRODUCTION

Scientist as well as experts and decision-makers from industry agree on the huge potential of the systematic introduction of enabler technologies summarized under the terms “Industrie 4.0” and “Internet of Things” to cope with future challenging globalized market and manufacturing environments [1] [2] [3]. These volatile market and manufacturing environments will be characterized by customized products leading to small lot sizes and the need of changeable production systems which allow a dynamic adjustment of production and logistics processes [4]. Due to their lack of versatility, fundamental changes regarding the technical infrastructure and the required IT-systems for planning, steering and control of changeable production systems are expected. The great significance of logistics in the field of *Industrie 4.0* and the *Internet of Things* is on the one hand based on the rapid technological development and on the other hand highly influenced by technical and social challenges, like the demographic change and urbanization, which are directly or indirectly linked with logistics and a more efficient supply chain management of future value chains [5] [6]. Considering logistics in general, logistics networks including their logistics nodes have to keep pace with changeable production environments, which often excludes the use of conventional logistics infrastructure like statically installed conveyor systems [4] [5]. This evolution to an *Industrie 4.0* implies far-reaching process-related changes as well as substantial investments. Therefore the transition period is expected to last at least one decade and companies will have to develop individual and customized transition concepts in close cooperation with their customers and suppliers [7] [8]. To plan and design these changeable production systems as well as to transfer existing mostly statically designed production into changeable production systems and to develop customized transition concepts specific knowledge and competences are needed [9]. In addition new methods and technical solutions have to be tested and validated in a safe and at the same time practice-oriented factory environment to ensure a smooth transfer into industrial practice. Learning factories, like the ESB Logistics Learning Factory at

ESB Business School (Reutlingen University), offer a wide range of possibilities for research in the field of cyber-physical production systems as well as many options for a practice-oriented education and training of students and professionals in a close-to-reality factory environment. Based on defined maturity levels of the learning factory the participants can be sensitized and trained in the field of cyber-physical systems and at the same time gain specific competences.

2 CYBER-PHYSICAL PRODUCTION SYSTEMS

Future production environments as well as supply chains will be highly influenced by a global crosslinking of all machineries, storage systems and means of production to cyber-physical systems (CPS) respectively cyber-physical production systems (CPPS) [1] [10]. CPPS are networks of at first independent CPS which are creating a comprehensive production system, which is characterized by a high degree of cross-linking of all involved systems representing an independent and intelligent production unit [11]. CPPS also have to be capable of analyzing data in real-time to interact actively with humans as well as digital and physical objects linked to the *Internet of Things* and *Services*. These vertically cross-linked and integrated production systems are a crucial part of the resulting horizontally integrated and real-time optimized value chain networks based on digital consistency of engineering incorporating the product and factory life cycle of entire value chains [9] [11]. Therefore data, services and certain functions will be held, retrieved and executed where the highest benefit, e.g. regarding a flexible and efficient development and production, can be achieved. These places will not necessarily be on the conventional automation levels. This leads to the hypothesis that the today's predominantly existing automation pyramid will be gradually resolved and replaced by interconnected, decentralized systems. In this scenario services, data and hardware components will be spread over various nodes of the emerging network building abstract functional modules which are creating the automation system [12].

2.1 Value networks

Future value chains will be affected by a dynamic and horizontal integration of value networks which organize themselves ad-hoc. Also the intelligent product, which knows its own processing status and possible irregularities of previous processing steps, supports the production process actively, knows its customer and also controls the required logistical processes to its final customer [13]. Therefore a cross-functional digitalization and link-up of value networks is of vital importance. For example in this *Industrie 4.0* scenario the purchasing department will have to track inventories in the own company as well as in the supply network in real-time to keep production running, while the customer will be able to keep track of the degree of completion of his individualized product. So the field of view of companies will have to change from their own factories to the whole value network involving all processes and partners from the engineering, sourcing, production up to the delivery of the final product to the customer [14]. This will also include new methods and processes regarding the use of big data to identify customer needs, predictive maintenance for machineries, the use of open-innovation principles and collaborative engineering to produce products which meet the customer needs and new methods how value chains are designed, organized and costs and earnings are allocated within this dynamic value chains [15] [16].

2.2 Intralogistics systems

The planning and controlling of highly dynamic and changeable material flows of CPPS requires new methods and systems, since a regulation and reconfiguration of the material flow will be required at any point of the material flow system [5]. Today's centrally controlled material flow systems using centralized material flow computers are not capable of accommodating future requirements of tailor-made products, decreasing batch sizes and volatile sales and procurement markets, because these system rely on complex, centralized controller architectures which are neither flexible nor changeable [17]. The combination of changeable production systems and conventional control approaches based on predefined processes would result in a tremendous increase of complexity and a continuous programming effort of central control units like material flow computers [18]. In addition small production batches up to batch size 1 are leading to an increasing number of transport orders which have to be processed and a high complexity of the control systems [19]. The development of decentralized control concepts for automated material flow systems combined with the theories of the *Internet of Things* offer great potential to solve the previously mentioned weaknesses of centralized control systems regarding changeable application scenarios in context with *Industrie 4.0* [18]. The basic units of the *Internet of Things* are cooperating functional units (entities) of conveyor modules, transport units and (software) services which define every automated material flow system [18] [20]. So the goods which have to be transported, route themselves autonomously through the logistical system by using the transport services of the conveyor modules to reach their destination and can be identified and localized anytime within the material flow system. By refraining from the use of centralized material flow computers the complexity of the system can be reduced while the versatility and responsiveness of the material flow system can be highly improved. In addition the solving of arising interruptions and blockades as well as an automated replanning and rescheduling of transport processes and routes are becoming inherent functions of the material flow system [17][18]. Multiagent systems, which consist of autonomous and cooperating software programs (agents) solving specific tasks based on defined behavior patterns, are often serving as a base technology for the realization of these decentralized material flow control systems. So each conveyor module uses one or more of these agents for a dynamic processing of different tasks like order management and order allocation or route planning depending on the current situation and condition of the logistics system [20]. The control functions formerly found in a centralized, hierarchically structured automation pyramid are transformed into a non-hierarchical material flow system composed of cooperative, intelligent and autonomous entities in *the Internet of Things*. By means of their agents these entities are capable of contacting other conveyor systems, transportation entities and services, are able to exchange and process information and finally to organize and control the material flow autonomously in an optimized manner [17][18]. Conveyor systems, like the FlexConveyor system from the company Gebhardt Fördersysteme GmbH [21], which are following this modular concept mechanically as well as regarding their control systems, are already in industrial application and allow a fast reconfiguration of the conveyor system according to recent requirements.

2.3. Human-Machine Collaboration

Within CPPS employees, machines and resources will communicate and collaborate similar like in a social network, since CPPS will still require the competences and skills of humans as an input as well as employees and executives must be still informed. Therefore the respective roles of employees in line with the technological changes within the production systems will undergo substantial changes regarding the job and competence profiles of the employees [1] [10]. The future role of employees will especially involve their natural capabilities like intelligence, creativity and empathy which hardly can be automated and will also lead to a higher level of responsibility of employees [22]. For example there will still be employees to supervise the superior production strategy or employees who have to act as a creative and specifically skilled problem solver who deals with occurring issues in the CPPS. To do this, the employee will have to be provided with aggregated real-time information to derive actions or interventions and will be assisted by various flexible, partly mobile human-machine-interaction solutions to intervene in the CPPS [23]. But also in the highly technological field of CPPS will be simple tasks for less qualified employees which will not be automated due to economic or technical reasons [24]. To create less burdening work systems and to cope with the intensifying demographic change, innovative technical assistance systems, like collaborative robots, offer a great potential for these manual tasks. Common automation solutions in work and logistics systems are often inflexible, since they are designed for specific operations and changes lead to high programming and configuration efforts and involve a weighing up of automation or flexibility [25]. Also conventional robot systems are designed for stationary use and often require a protective fence to avoid collisions with humans in the work envelope of the robot which militate against a collaborative work of human and robot. Collaborative, force limited robots with intuitive and fast teaching possibilities and integrated safety features are specially designed for a direct and flexible cooperation with humans.

To investigate the industrial feasibility and potential applications in the fields of assembly and logistics of collaborative robots and to train students and professionals on the implementation of these innovative systems, different collaborative robot systems are in use at ESB Logistics Learning Factory.

3 ESB LOGISTICS LEARNING FACTORY

Learning factories offer wide-ranging possibilities for immersive and industry-oriented research, training education. Learning factories in the narrow sense cover a real value chain with a physical product which allows researchers, training participants as well as students to perform, evaluate, and reflect their own actions in a close-to reality research and learning environment [26].

3.1.1 Production system of ESB Logistics Learning Factory

The general objective of the ESB Logistics Learning Factory (LLF) at Reutlingen University is to train students as well as participants from industry the required competences in the field of the design and optimization of flexible and changeable production systems. The production system of the LLF is focused on the assembly of a multi-variant city scooter including the use of innovative technologies like CPS, collaborative robot systems and additive manufacturing technologies. All workstations are mobile and equipped with wireless communication technology and accumulator batteries enabling an easy change of the factory layout. The workstations are also equipped with mobile tablet-pcs, e.g. to receive orders, to send information back to the planning system, to access multimedia-based work instructions or to analyze specific production processes. The access or feedback of information can take place manually or automatically using different maturity levels of information technology, e.g. by using RFID-technology embedded on the product or by using smart sensor tags on the product which are capable of gathering data and act as an intelligent object in the Internet of Things. These technologies set an important step for the development of decentralized control systems in which the product routes itself through the CPPS.

3.1.2 *Knowledge and competence development*

The overall concept regarding the knowledge and competence development of the LLF is composed of defined learning goals and the corresponding learning contents and methods of work and logistics system design, strategies to achieve action competence as well as the learning environment which covers digital tools for an integrated product and process planning and the physical infrastructure to realize the developed solutions. Within the next years the existing production system should be gradually transferred into a CPPS to investigate innovative solutions and methods for the design of human-machine collaboration with a focus on technical assistance systems as wells as to develop decentralized control methods for intralogistics systems following the requirements of changeable work systems. To accomplish a holistic understanding of value networks of CPPS the dynamic design of inbound and outbound logistic networks will also be integrated into the learning factory environment.

3.2 Digital planning environment

The LLF is composed of a digital planning environment and the physical learning factory environment which are interconnected to realize changeable production scenarios (see figure 1).

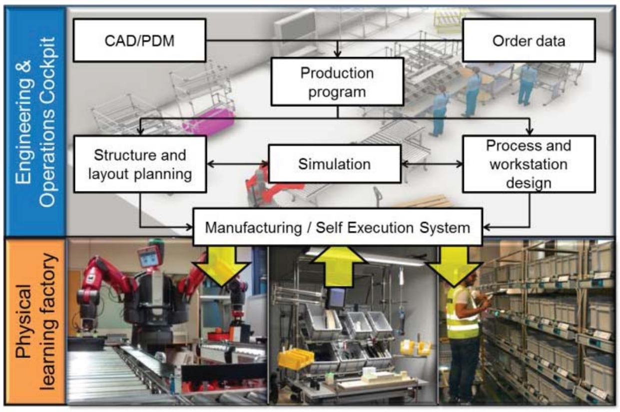

Figure 1 - Digital planning environment and physical learning factory

By using different tools of the software company Dassault systèmes in the so-called "Engineering and Operations Cockpit (EOC)", like ENOVIA for product data management, CATIA for computer-aided design and DELMIA for process and resource planning and simulation, most of the overall required data and functionalities are integrated in the same platform and different production scenarios can be planned and validated with low effort within a short period of time. Customer orders are generated through an online shop, processed by the manufacturing execution system (MES) and finally allocated to the respective resources and workstations in the physical learning factory environment. The information flow is designed bi-directionally to allow the supply of information from the digital planning environment to the physical factory environment as well as vice versa to enrich the planning with current information from the shop floor level. The gathered information is aggregated, analysed and interpreted to optimize und restructure the production system within the EOC to validate improvements digitally before the changes are executed in the physical environment. In addition this digital environment can be used to initiate rescheduling actions or to introduce turbulences (e.g. additional high priority customer orders, malfunction of infrastructure etc.) which have to be solved manually by the participants or automatically by the employed planning and control systems of the EOC. For an improved support of future changeable production scenarios using decentralized control structures and CPS a cloud-based so-called "Self-Execution System (SES)" has been developed and pilot tested in cooperation with a local IT company. The SES has been developed based on an event-oriented concept enriched with a specific cloud data-storage structure for central entities (like employee information) and a digital product memory on every product, for example to allow a decentralized production control and a bi-directional exchange of information between the physical factory and the digital planning environment. Since the SES is still in the proof-of-concept phase and different majority levels should be captured, also a conventional MES is in use to compare the planning and control results of both systems. In a next step also logistical inbound and outbound processes will be integrated into the digital planning environment to simulate the interaction of the learning factory with external value networks to gain an even more realistic learning factory environment and to enable further research in the area of ad-hoc designed value networks in context with *Industrie 4.0*.

3.3 Intralogistics systems

Besides manual pallet trucks and transport trolleys, different kinds of autonomous guided vehicles (AGVs) as well as an intelligent continuous conveyor system are used for material transport. The AGVs can be implemented as both tractors for tugger trains and as a platform for shooter racks to automate the material supply. The routing and navigation of the vehicles is based on optical tracks or laser-based navigation to allow flexible factory layouts. The modular and entirely locally controlled conveyor system, "FlexConveyor" provided by the company "Gebhardt Fördersysteme", is a perfect example of CPS implementation for intralogistics [27]. By means of the plug-and-play functionality and decentralized control units in each conveyor module, the modules can be combined to user-defined conveying lines without the need of a central control entity.

To investigate the potential for automation and/or collaboration in material supply for future CPPS Reutlingen University is going to develop a collaborative tugger train system in cooperation with industry partners in a project funded by the Federal Ministry of Education and Research. The overall aim of the project is the development of an interactive, collaborative and autonomous tugger train transport system including the respective manipulator technology which can navigate through complex factory environments, handle different goods autonomously and can be integrated into the changeable production system of the LLF. To tow the trailers of the tugger train and to manipulate goods a mobile robot platform equipped with a collaborative articulated-arm robot will be used. So the advantages of tugger trains, automation of material supply and human-machine collaboration should be combined. In accordance with the event-oriented and cloud-based concept of the SES a decentralized control method for the tugger train system, based on the approach described in chapter 2.2., should be designed and interlinked with the SES. Based on the knowledge gained within this project, the designed control method will be further developed into a generic method for an autonomous and decentralized control of changeable hybrid intralogistics systems by a dissertation project. So in the long run an autonomous and decentralized control method for changeable production environments should be developed and validated within the LLF which allows the goods to route themselves autonomously through the intralogistics system of the LLF by using different transport systems in an optimized manner.

4 SUMMARY AND OUTLOOK

The global cross-linking of different entities within the respective value networks will result in fundamental changes of future production systems. To reduce the overall complexity of the design and cross-linking of CPPS, reference architecture models like described in [14], which are based on existing standards, are essential to define further fields of research and standardization for a successful transition into *Industrie 4.0*.

Within the next years the complete digital and physical infrastructure of the LLF will be transferred into a vertically cross-linked, decentrally controlled CPPS which interacts with a simulated, ad-hoc generated and horizontally integrated value chain network to serve as an education, training, research and demonstration environment for innovative technological solutions in context with the transition into an *Industrie 4.0*. A major research focus of the LLF will lie in the field of intralogistics systems for CPPS to cope with changeable production environments based on decentralized control methods, innovative human-machine collaboration methods and automation solutions for material supply like the collaborative tugger train system which will be developed, tested and validated under close-to-reality conditions in the LLF.

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