How Virtualization, Decentralization and Network Building Change the Manufacturing Landscape: An Industry 4.0 Perspective

Malte Brettel, Niklas Friederichsen, Michael Keller, Marius Rosenberg

Abstract**—**The German manufacturing industry has to withstand an increasing global competition on product quality and production costs. As labor costs are high, several industries have suffered severely under the relocation of production facilities towards aspiring countries, which have managed to close the productivity and quality gap substantially. Established manufacturing companies have recognized that customers are not willing to pay large price premiums for incremental quality improvements. As a consequence, many companies from the German manufacturing industry adjust their production focusing on customized products and fast time to market. Leveraging the advantages of novel production strategies such as Agile Manufacturing and Mass Customization, manufacturing companies transform into integrated networks, in which companies unite their core competencies. Hereby, virtualization of the process- and supply-chain ensures smooth inter-company operations providing real-time access to relevant product and production information for all participating entities. Boundaries of companies deteriorate, as autonomous systems exchange data, gained by embedded systems throughout the entire value chain. By including Cyber-Physical-Systems, advanced communication between machines is tantamount to their dialogue with humans. The increasing utilization of information and communication technology allows digital engineering of products and production processes alike. Modular simulation and modeling techniques allow decentralized units to flexibly alter products and thereby enable rapid product innovation. The present article describes the developments of Industry 4.0 within the literature and reviews the associated research streams. Hereby, we analyze eight scientific journals with regards to the following research fields: Individualized production, end-to-end engineering in a virtual process chain and production networks. We employ cluster analysis to assign sub-topics into the respective research field. To assess the practical implications, we conducted face-to-face interviews with managers from the industry as well as from the consulting business using a structured interview guideline. The results reveal reasons for the adaption and refusal of Industry 4.0 practices from a managerial point of view. Our findings contribute to the upcoming research stream of Industry 4.0 and support decision-makers to assess their need for transformation towards Industry 4.0 practices.

Keywords**—**Industry 4.0., Mass Customization, Production networks, Virtual Process-Chain.

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I. Introduction

THE three industrial revolutions of the past were all triggered by technical innovations: the introduction of water- and steam-powered mechanical manufacturing at the end of the 18th century, the division of labor at the beginning of the 20th century and introduction of programmable logic controllers (PLC) for automation purposes in manufacturing in the 1970s [1]. According to experts from industry and research, the upcoming industrial revolution will be triggered by the Internet, which allows communication between humans as well as machines in Cyber-Physical-Systems (CPS) throughout large networks. For Germany, a successful transformation of the manufacturing industry is of very high importance as it contributes over 25% of the GDP and provides over 7 million jobs [2], [3]. As relocation of production towards low-wage countries particularly affects mass production of standardized mass-products, high-wage countries have to focus on resolving the tension between economies of scale and scope as well as a planning and value orientation. The Cluster of Excellence “Integrative Production Technology for High-Wage Countries” of RWTH University focuses on the resolution of the “Polylemma of Production” in the following research areas: Individualization, virtualization, hybridization and self-optimization [4]. All four research areas have a strong link to the topics associated with industry 4.0.

Alongside to technological innovation, the organization structure of industrial production has undergone several major shifts in the past to face changing markets. Industrial production started with the transformation from craft production to mass production with strict division of labor and standardization. On a seller market with production as the major bottleneck, the organization structure was focused on increasing outputs and productivity disregarding variations in customer needs. As market saturation increased, markets transformed into buyers markets and forced manufacturing companies towards product differentiation. In order to raise effectiveness at growing product varieties, lean production has become very popular as it allows eliminating waste along the value chain [5]. The growing demand of customized products in combination with decreasing product lifecycles asks for further transformation towards organization structures, which cope with increased complexity. Distributed Systems can handle high complexity and form the starting point for the so-called cybernetic management, which incorporates self-controlling systems [6]. The Internet has been identified as a powerful instrument to manage distributed systems and technologies like Radio Frequency Identification Devices (RFID) and can be used to track individual products throughout the process chain. In this article we have analyzed several research streams in the context of industry 4.0, which promise to have a considerable impact on the global industry landscape and the value added particular in Germany.

II. Theory

A. The Research Fields Associated with Industry 4.0

Industry 4.0 focuses on the establishment of intelligent products and production processes. In future manufacturing, factories have to cope with the need of rapid product development, flexible production as well as complex environments [7]. Within the factory of the future, also considered as a smart factory, CPS will enable the communication between humans, machines and products alike [8], [9]. As they are able to acquisition and process data, they can self-control certain tasks and interact with humans via interfaces Fig. 1. In the smart manufacturing environment, intelligent and customized products comprise the knowledge of their manufacturing process and consumer application and independently lead their way through the supply-chain [1]. The resolution of the automation pyramid towards self controlling systems leads to an extreme amount of data, which can be extracted, visualized and used for end-to-end engineering [10].

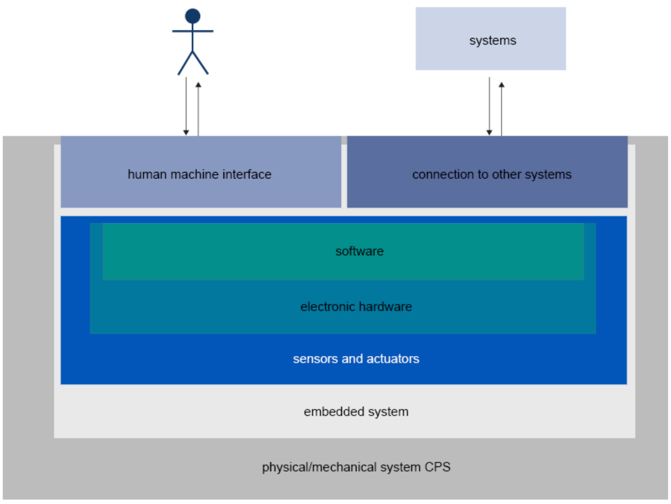


Fig. 1 Interaction between humans and machines via Cyber-Physical-Systems [11]

1. Individualized Production

The industrial production of high-tech products has to be leveraged between the satisfaction of heterogeneous customer needs through individualization and the realization of scale effects along the value chain. The dilemma between the economies of scale and scope can be addressed by the concept of Mass Customization (MC), which has been extensively discussed in theory [12], [13] and successful application [14], [15]. MC in the context of manufacturing is a production strategy that focuses on the production of personalized mass products, mostly through flexible processes, modularized product design and integration between supply chain members along the value chain [16]. At high volumes of standardized products, Germany cannot compensate the inferior cost structure due to high labor costs compared to low wage countries with a superior quality and productiveness alone. The increased importance of MC leads to fundamental changes in the product and production architecture.

Modularization is already an accepted mean to increase the variety of products, which are produced by tool-based technologies. For successful Modularization, the product architecture has to be decoupled into subsystems with very little interdependencies in order to achieve appropriate economies of scale. By flexibly adjusting the combination of standardized modules the speed of new product development drastically increases and time-to-market can be shortened significantly [17]. Although first introduced by modular products, the concept of modularity is applied to many different areas of the production system [18], [19] and the production planning and simulation [20], [21].

Within a smart factory, products can communicate with their environment and influence the arrangement of Reconfigurable Manufacturing Systems (RMS). Concrete structures and specifications of production processes are replaced by configuration rules, from which case-specific topologies can be derived automatically [1]. RMS enables manufacturing companies to adapt to changing production requirements in a cost-efficient way. Machine components can be added, removed or rearranged depending on their mechanical module interface [22].

Complexity of coordination can be reduced while increasing flexibility by dividing the production process into small value oriented units, which only share information regarding the consecutive process step [23], Fig. 3. However, distributed planning activities hold the risk of neglecting global optimization potentials as employees lose sight of the overall picture. To combine the advantages of planning and value oriented production, overarching modeling of the value chain can supply distributed units with indicators to align their actions with high-level goals.

As standardization is decreased, control needs to be redirected towards the shop-floor level for fast reaction and utilization of product-specific knowledge. To take advantage of synergy effects, data needs to be centralized and processes need to be globally modeled. This can mean, that suboptimal solutions in one unit are allowed to resolve a bottleneck in another. Nowadays decisions of process adaptions are predominately made by humans on the basis of experience. In the future, the decision process will be increasingly assisted by self-optimizing and knowledgeable manufacturing systems [24]. Distributed systems are capable of producing much smaller batch sizes and help particularly SMEs to dynamically follow market opportunities [10], [25].

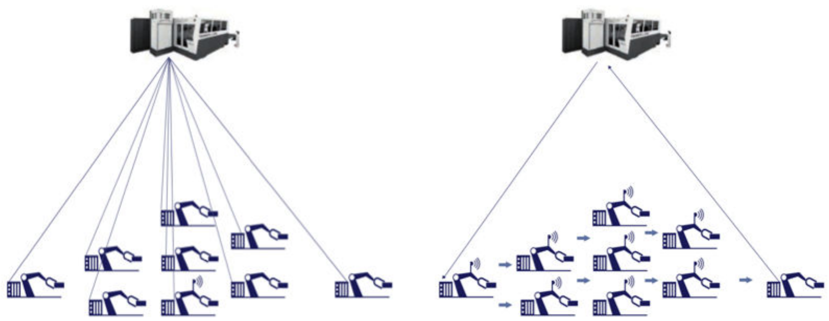


Fig. 2 Reduction of communication in distributed systems

For a further increase of product flexibility, rapid manufacturing (RM) techniques can be used, in which products are fabricated on the basis of 3D CAD models [26]. RM techniques, also known as solid free form fabrication, can be used to 'unlock' design options and have great potential to be used for small lot sizes [27]. Currently RM-technologies cannot compete with conventional manufacturing methods in terms of price and productivity and are only used for customized parts in very small batches for prototyping [28] and applications like biomedical parts [29].

2. Horizontal Integration in Collaborative Networks

As the depth of added-value within one factory and company generally decreases while the complexity of products and processes increase, Collaborative Manufacturing [30] and Collaborative Development Environments [31] gain importance especially for Small and Medium Enterprises (SME) with limited resources. Within a collaborative network, risks can be balanced and combined resources can expand the range of perceivable market opportunities [32], [33]. The organization in networks multiplies the available capacities without the need of further investments. Hence, companies in collaborative networks can adapt to volatile markets and shortened product lifecycles with high agility. In contrast to the many benefits, the decoupling and spatial separation of production processes whilst integrating comprehensive production data from multiple production-sites has drastically increased the need for coordination [34]. For increased productivity compared to traditional organizations, companies and their employees have to communicate with various departments across company boundaries very efficiently [35]. The availability of product-data throughout the entire network is a prerequisite for a global optimization of the production processes across factory and even company boundaries. To maintain a global competitive advantage, companies will have to focus on their core competencies while outsourcing other activities to collaborators in the network [36]. This potentially changes business models of manufacturing companies from offering superior products towards offering a superior manufacturing capability as manufacturing is moved from a necessity to a unique selling point [37]. In the scientific literature, networks of legally independent organizations that share competencies in order to exploit a business opportunity are referred to as virtual corporations [38]. According to Christopher, being able to leverage competencies of network partners in order to respond to market needs can lead to sustainable advantages [36]. Although these organizations have been proposed to increase flexibility and performance, they are not ubiquitous in the industry to this day [39]. Among other challenges, one obstacle to the establishment of close collaborations between companies is the absence of trust, as Managers are not used to share critical information with companies; they compete with on the market [40]. Findings have shown, that information sharing between SMEs can trigger innovation but can also lead to asymmetric learning caused by opportunistic behavior also referred to as learning races [41], [42]. Especially in global networks, different mentalities towards information and cost-sharing can result in high coordination costs, that have brought many collaborations to an end.

To exploit the flexibility potential of collaborations, the supply chain has to be designed to allow adaptation of routes and schedules. For high agility, the inventory levels and lead times within the value chain have to be decreased. To ensure, that customer needs can still be reliably satisfied, there needs to be a high level of synchronization between the organizations, wherefore information sharing is paramount. In the context of supply-chain management, agility goes hand in hand with the ability to track commodity flows but also data concerning delivery reliability and customer satisfaction [43]. Advancements of ICT's allow to monitor large amounts of product data in real-time. RFID can be used not only to track the status and position of goods but can hold entire work instructions to control and log the production process of a high resolution supply chain [44].

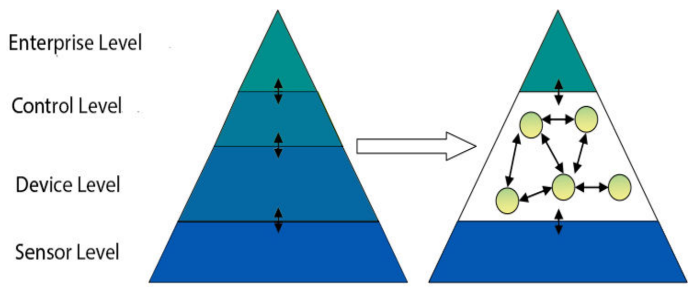


Fig. 3 Resolution of the classical automation pyramid with enhanced communication, compare [23]

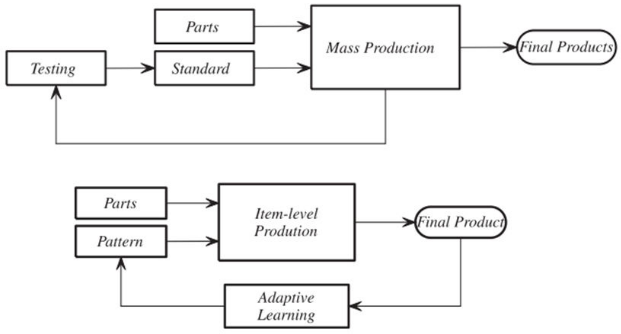


Fig. 4 Mass- vs. item-level production [48]

As prices of sensors have dropped significantly over the last years, there is an abundance of data that can be acquisitioned on the shop-floor level. This data can be made accessible throughout networks via the Internet and can thereby help to enhance communication between different hierarchy levels Fig. 3. As communication costs can be disregarded as a result of central data pools and automated information generation, different hierarchy-levels can access information at the desired level of detail [45].

3. End-to-End Digital Integration

Integrated engineering along the entire value chain using advanced methods of communication and virtualization promises significant optimization potential. Along this value chain it will be increasingly less important, which process is executed in which particular factory or company, as all participating entities can be supplied with access to real-time information and control is distributed to the shop-floor level. A central issue of Industry 4.0 is how business processes including engineering workflows and services can be integrated end-to-end using CPSs [1]. OEMs of the automotive industry already orchestrate large supply networks with various factories and companies in just-in-sequence supply chains [46] and integrate key-supplies into the product development. Automotive supply-chains are characterized by high complexity as automobiles are typically composed of more than 20,000 components and often involve over 80 companies in the development and production of a single model [47]. However, automobile manufacturers deal with relatively long product lifecycles and large batches of parts, so that they have little need for agile reorganizing of their supply-chain and flexible adaptations of manufacturing processes. Within the context of item-level production, information is used to constantly optimize the database and improve the basis of further development Fig. 4 [48]. Within collaborative networks, simulation and modeling the impact of process-steps on products need to be carried out across company borders. However, the collective setup of simulation chains requires an infrastructure, which enables the entities to integrate their data between heterogeneous simulations [49].

To ensure the exchange of information, uniform standards for data-transfer and utilization yet have to be applied throughout the industry [50]. The need for common grounds becomes apparent particularly in the context of simultaneous development of product families and their related supply-chains [51] and manufacturing capabilities [52]. Advanced visualization techniques of context-sensitive data via virtual reality (VR) can be used to illustrate information for effective collaboration. The local availability and understanding of global production data is paramount for a real-time intervention in case of a changing environment.

For many manufacturing companies, value added services provide an appropriate opportunity to differentiate themselves in addition to high product quality in order to ensure a strong competitive position. On top, long term service contracts can help to leverage risks of high demand volatility, as the actual product serves as a platform for further service sales over the time of utilization [53]. Embedded Systems of smart products and machines will enable entirely new remote maintenance concepts [54]. A wealth of data acquisitioned by smart products and machines during operation can be extracted and used for the development of new services and updates and will help to increase the perceived product quality.

B. Methodology of Cluster Analysis

In order to investigate the relevance of industry 4.0 and its associated research streams we have analyzed eight scientific journals in the fields of production research and business administration within the times pan of 2007 to 2012 with regards to the following research fields: Individualized production, production networks, and end-to-end engineering in a virtual process chain. We have employed cluster analysis to assign sub-topics into the respective research field on the basis of an extensive literature research Fig. 5. We have selected the Journals on the basis of their scientific focus, considering the impact on the research community evaluated of the Thompson Reuters Impact Factor and the Handelsblatt-Ranking Betriebswirtschaftslehre 2012. Taking into account that the term Industry 4.0 is mainly used in popular science and has not been established in the scientific literature to this point, we have included journals like productivity management and production engineering into our analysis, which are directed to executive leaders rather that the research community. Altogether we have analyzed 5911 articles of which 548 were found to be relevant with regards to one or more of the associated research fields. In addition to the literature review we have conducted face-to-face interviews with R&D managers from the manufacturing industry and consultants with experience in SCM to analyze potential challenges of implementation.

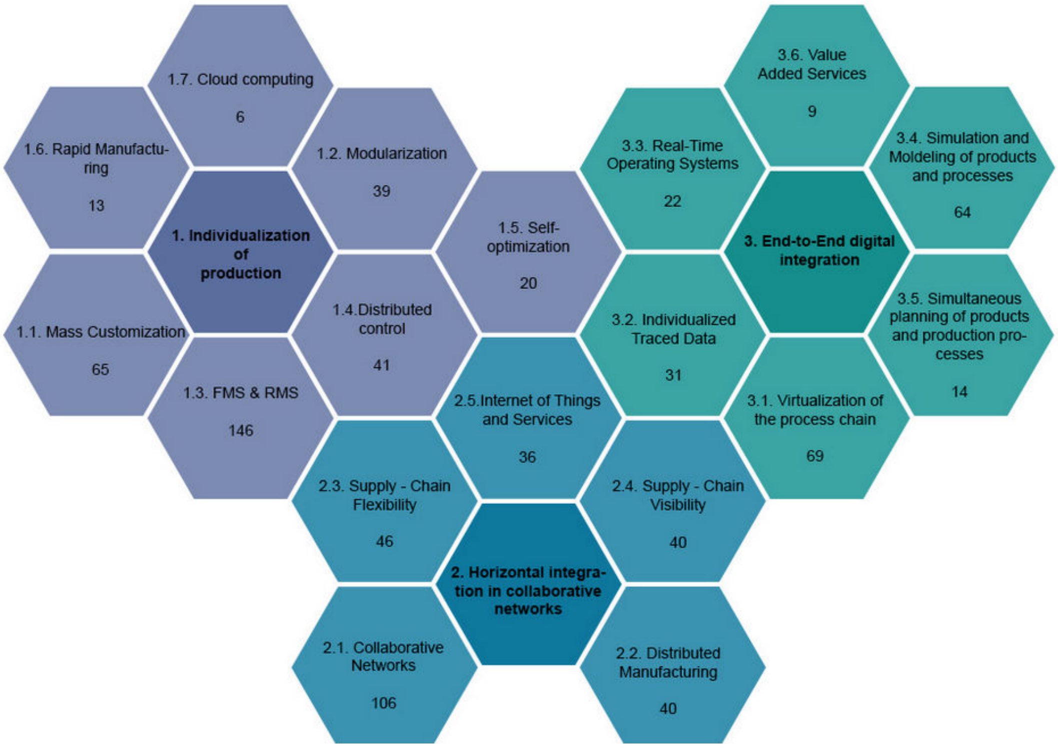


Fig. 5 Industry 4.0 related research streams; the numbers underneath the topics illustrate the assigned articles

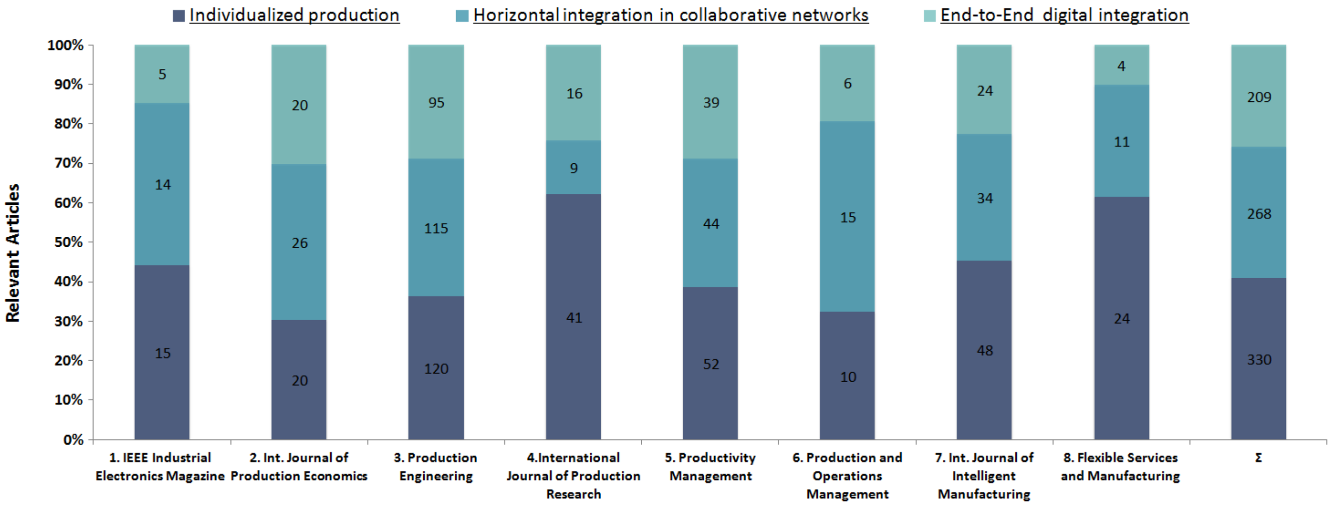
III. Results

A. Cluster Analysis

In the context of ‘individualization of production’ we assigned 330 articles to the sub-topics of 1.1. Mass Customization; 1.2. Modularization; 1.3. Flexible and Reconfigurable Manufacturing Systems; 1.4. Distributed control; 1.5. Self-optimization; 1.6. Rapid Manufacturing; 1.7. Cloud Computing. With 146 counts, the field of flexible FMS and RMS plays a dominant role, because the improvement and integration of those systems is paramount to an individual production on an industrial level but still impose profound challenges. The research field “horizontal integration in collaborative networks” consists of the sub-topics: 2.1. Collaborative Networks; 2.2. Distributed Manufacturing; 2.3. Supply-Chain Flexibility; 2.4. Supply-Chain Visibility; 2.5. Internet of Things and Services. Of the 268 relevant articles we assigned 106 articles to the scientific evaluation of collaborative networks in the contexts of the establishment and implementation of new organization forms. We assigned 209 articles to the sub-topics of ‘End-to-End digital integration’ in the context of engineering and production systems: 3.1. Virtualization of the process chain; 3.2. Individualized Traced Data; 3.3. Real-Time Operating Systems; 3.4. Simulation and Modeling of products and production processes; 3.5. Simultaneous planning of production and production processes; 3.6. Value Added Services. Within this research field, Virtualization and Simulation and Modeling with 69 and 64 counts, respectively, play an almost equally dominant role, as they are paramount for an information-based production.

B. Evaluation of Practical Relevance

According to an extensive survey conducted by the Laboratory for Machine Tools and Production Engineering in Aachen, over 90% of Managers from the German manufacturing industry have high interests in resolving the dilemma between scale and scope and until today, the establishment of product families is seen to be the primary mean to do incorporate flexibility into mass production [55]. One Head of Development of a medium manufacturing enterprise indicated within our interview process, that product design and development usually represents only 5-10%, but determines more that 80% of the costs of a product. Hence, the desired flexibility of a product family must be determined at a very early stage. However, as the benefit of flexibility is difficult to quantify, it is generally not included in a classical investment analysis of new machinery [56]. According to a survey of the Institute for Industrial Management in Aachen, the implementation of RMS is mainly hampered by the following deficits: lack of powerful IT-systems and their integration with each other, inadequate employee-knowledge of production processes and lack of change efforts within the company [25].



Number of exa-mined articles	333	2104	139	461	174	1672	576	452	**5911**
Relevant articles	22	90	33	40	18	231	82	32	**548**
Fraction	7%	4%	24%	9%	10%	14%	14%	7%	**9%**

Fig. 6 Cluster analysis with total number and fraction of relevant articles

The experts we interviewed agreed that decentralized autonomous systems have very high potential to cope with a highly complex environment and customized products. However, to have a significant impact on mass production, autonomous systems still need considerable research, which is supported by the technology program ‘Autonomics’ of the Federal Ministry of Economics and Technology in Germany. One of our interview partners predicts that successful development will lead to “emergent self-organization” of production cells. In the context of rapid manufacturing, the industry experts see great potential but also considerable obstacles to overcome in order to replace conventional production technologies. One expert from a small manufacturing company stated his concern about the warranty and certification of customized products produced by SFF-methods, as is it not economical to carry out extensive testing for individual products. For security-related products, manufacturers still lack experience in terms of product safety and component failure. As a complement to the popular belief, an experienced consultant with experience SCM stated, that although there is general trend towards customized products, there will always be a dominant mass production of standardized products designed to fit the wide majority.

In the future, new forms of cooperation will allow to flexibly allocate production capacity within a value chain. In order to do so, information needs to be accessible throughout collaborative networks, which poses a lot of potential for conflicts. According to an interviewed purchasing expert, companies usually refuse to disclose information about their production processes and cost structures to their partners to maintain a strong bargaining position. However, 45% of all German manufacturing enterprises adjust their capacity through outsourcing of jobs [25]. In order to overcome trust issues, dominant market forces like major OEMs from the automotive industry need to structure entire value chains and urge suppliers to share information. One of our interview partners pointed out, that institutionalized information sharing among partners often leads to costs. Unless one party sees a direct benefit, exchange of information often fails due to a lack of willingness to bear costs, which others benefit from. In order to exploit the potential of flexible allocation of capacities within collaborative networks, supply chains need to be designed for adaptation. According to one of our interview partners, Industry 4.0 “will only work, if machines can communicate via CPS and commodity flows are tracked by RFID or similar technologies” throughout large sections of the industry. Particularly RFID-tags impose technological challenges. An expert for sensor technology states, that reliable functionality of RFID transponders is impaired in the presence of water and large amounts of metal.

The level of process-virtualization strongly depends of the industry and company size as SMEs often cannot afford to independent units for simulation and modeling purposes. To overcome the barrier of integrating virtual processes with series production of products, training and research facilities like the Demonstrations fabrik Aachen GmbH and SmartFactory KL e.V. have been formed. One of our experts in SCM agrees to the hypothesis, that end-to-end virtual engineering is suitable to find the optimal operating point and to shorten the time-to-market of new product developments. Especially for the major OEMs of the automotive industry he sees enormous potential in global optimization because of their complex supply-chains and manual production steps. According to another expert, advanced simulation-software for virtual prototyping is the major keystone for Industry 4.0 as it allows “to bring down lot sizes from 1000 and more down to one". However, according to a survey of the VDE Association for Electrical, Electronic and Information Technologies e.V., the utilization of advanced simulation tools for virtual production especially in SMEs remains in the early stages [57]. A heterogeneous tool environment and insufficient standards cumber the further establishment and interoperability of systems in German factories. All our interview-partners agree, that simultaneous planning of products and production processes has great potential to improve product quality and decrease time-to market. Towards implementation there are split opinions: Some refer to successful projects as others emphasize the efforts required to coordinate many different parties from "different disciplines in feedback-loops". However, by integrating the development processes of OEMs and first-tier suppliers, both can benefit from superior products and long-term collaboration [25].

IV. Discussion

Currently, Industry 4.0 is a popular term to describe the imminent changes of the industry landscape, particularly in the production and manufacturing industry of the developed world. Yet the term is still used in different contexts and lacks an explicit definition. In this article, we assessed three different research topics affiliated with Industry 4.0 and employed a cluster analysis to assign sup-topics. We contribute to the emerging field of production research by illustrating the interlinks between very different research areas, usually examined individually. We illustrated this using the example of CPSs, for which collaborative networks are antecedents and a necessary consequence likewise as data can be and has to be acquisitioned and shared throughout the supply-chain for full exploitation. Especially for companies in the western automotive, machine and plant industry it will be important to offer customized products that are superior in quality and competitive in price. This can be achieved by intelligent automation and reorganization of labor within the production system. In the near future, labor work will change in content but will still remain irreplaceable, especially in view of customization resulting in an increasing need for coordination. Operators on the shop-floor need to be skilled in decision making as the separation of dispositive and executive work voids. Self-controlling systems communicate via the Internet and human, which alters the role of workers towards coordinators and problem-solvers in case of unforeseen events. To implement the changes of the impending industrial revolution, the German industry can rely on a well-founded technological basis supported by a wide network of excellent research facilities as well as established training centers.

Acknowledgment

The authors would like to thank the German Research Foundation "Deutsche Forschungsgesellschaft" (DFG) for the kind support of this research project, which is part of the Cluster of Excellence "Integrative Production Technology for High-Wage Countries" of RWTH Aachen University.

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