Framework for Designing Production Systems 4.0

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Abstract. Today's dynamic market conditions pose great challenges for producing companies. One promising answer to navigate through the increasingly volatile environment is "agility". Although agile principles were first applied in product development, producing companies can only harvest on it if it is pursued throughout the product life cycle. However, the implications of agile principles on production cause a conflict of aims between higher flexibility on the one hand, and other production aims, e.g. high utilization, on the other. While Industrie 4.0 offers the potential to solve this conflict of aims, the challenge for producing companies lies within the identification and implementation of favourable Industrie 4.0 solutions. Due to the radical character of these solutions, traditional production systems, which are based upon Kaizen principles and thus focus on incremental improvements, are hardly capable to support the required radical improvements. In this paper, a framework is developed for the redesign of production systems in the context of Industrie 4.0 which enables radical process improvements in the context of Industrie 4.0. It serves as guidance for producing companies in order to cover the major aspects that need to be considered. The framework was validated and detailed with eight international manufacturing corporations.

Keywords: Manufacturing system · Production · Agility

1 Introduction – Need for Agile Production Systems

Producing companies are in constant dynamic interaction with their environment [1]. As the environment becomes increasingly volatile, producing companies must find a way to deal with shorter product life cycles, permanent price pressure, higher demand for customized products, higher product complexity, fast changing competitive situations and new evolving technologies [2]. "Agility" is one answer for companies to navigate through this increasingly volatile environment [3]. Originating from the Latin term "agilitas", agility means mobility, nimbleness and quickness [4].

In 2001 the Agile Manifesto was formulated as a new guideline for agile software development as counter movement to conventional, non-flexible development approaches [5]. Prior to the Agile Manifesto, in 1986 Nonaka and Takeuchi introduced a new software development approach which was based on iterations instead of traditional sequential processes [6]. The Agile Manifesto elevates the iterative

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development idea to a new paradigm while explicitly emphasizing the importance of customer orientation and responsiveness.

With the increasing integration of software into physical products, agile development principles found their way into the physical world and enabled manufacturing companies to respond to the increasingly volatile environment [7]. However, the advantages of agile product development can only be capitalized if they are sustained throughout the product life cycle. This includes subsequent process steps, e.g. prototyping, validation, industrialization, production, etc. In consequence, production systems must enable agile principles and comply with the fast changing product requirements. Furthermore, they need to quickly respond to direct impacts of the company's volatile environment on production, such as technology, nature and society [1].

The presented research work aims at the development of a framework which enables the systematic design of agile production systems in order to fulfil the requirements for the described fast responses to the company's volatile environment.

2 The Conflict of Aims in Agile Production Systems

The demand for increasing agility does not replace the traditional target of production systems, which is to increase productivity. Conventional lean principles target the elimination of waste and therefore enable companies to focus on core value-adding processes. However a study conducted by the Laboratory of Machine Tools and Production Engineering (WZL) at RWTH Aachen indicates that an increasing penetration of lean principles is not necessarily correlated with higher productivity (cf. Fig. 1) [8]. The effect of conventional lean methods seems to be asymptotically limited. This puts conventional production systems under pressure to find new approaches for radical process improvements to achieve higher productivity.

Productivity is a one-dimensional target for which proven methods for waste identification and elimination are available at hand. Due to increasingly volatile market conditions, agility becomes a second complementary target for production systems. Its ultimate goal is to enable companies for fast, proactive and effective adaptation to changes, e.g. to fluctuating demand [9]. Traditionally manufacturing companies strived for flexibility as a mean for adaptation commonly by reserving free production capacities [10]. Today highly volatile market conditions call for significantly higher adaptation speed in the face of unforeseeable changes [11]. In this context, flexibility only represents a sub-dimension of agility [12]. In order to achieve true agility, manufacturing companies need to proactively identify the need for changes, e.g. via databased learning and pattern recognition. Only then proactive actions can be initiated and also instantly implemented due to the reserved capacities. In doing so, reserving free capacities remains a sub-solution for achieving agility in the practice of many manufacturing companies [9]. Therefore the two-dimensional target of higher productivity and agility often create a conflict of aims [13, 14]. Solving this conflict of aims, i.e. maintaining high utilization while striving for high agility, requires the capability to manage a high degree of complexity in the production environment.

The management of complexity in the production environment is the second major advantage of lean principles beside higher productivity. By eliminating waste and

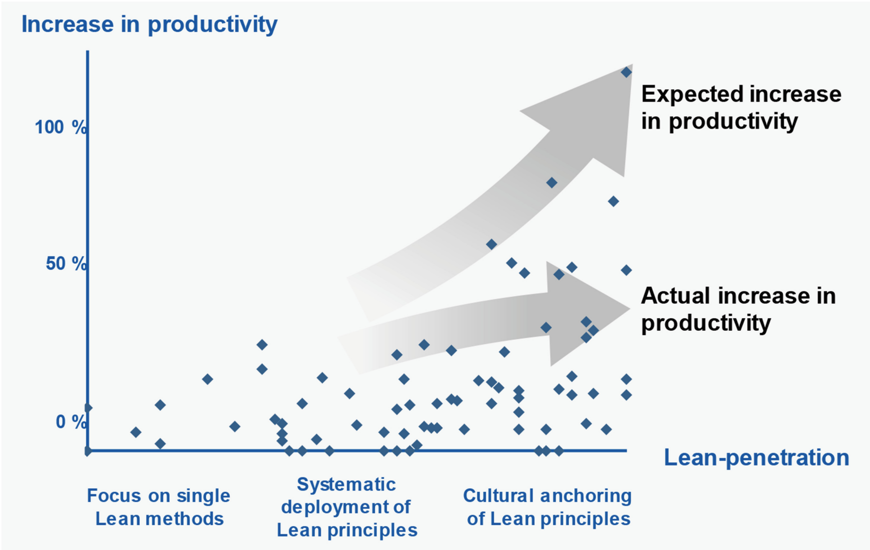

Fig. 1. Correlation between lean-penetration in production systems and increase in productivity [8].

focussing on core value-adding activities, they help to decrease process complexity to a degree that can be processed more easily [15, 16]. However, the above described conflict of aims results in a dramatic increase of complexity in the production environment. In many discussions with industry partners, it was strongly questioned whether this complexity can be reduced to a human-manageable degree by applying lean principles only.

3 The Role of Industrie 4.0 and Process Innovations in Designing Agile Production Systems

In a joint study between the WZL, the German Academy of Science and Engineering (acatech), the German Research Center for Artificial Intelligence (DFKI), the Hein Nixdorf Institut (HNI) of the Paderborn University and the Department of Computer Integrated Design (DiK) of the Technical University of Darmstadt, Industrie 4.0 was described as a real-time networking of products, processes and infrastructure through the integration of Cyber-Physical Systems (CPS) via the internet [17]. In the face of the described challenge, Industrie 4.0 offers the potential to support human workforce by processing the remaining complexity that humans cannot [16]. In analogy to modern navigation systems, the system complexity is not eliminated but processed autonomously in the background. The result is a drastically reduced complexity of information that is being presented to the user for optimal decision support. What is more, not only can Industrie 4.0 help to manage the complexity resulting from the conflict of aims, it can also support the two dimensions individually [18]. On the one hand, Industrie 4.0 can radically increase a firm's productivity by offering advanced automation solutions, new process methods and the identification of cross-domain optimization potentials which are hidden to the human intelligence. On the other hand, it can increase a firm's agility by enabling radical new process methods and by providing decision support via data analytics and artificial intelligence.

Due to these manifold advantages, Industrie 4.0 needs to be systematically integrated into a company's production system as a holistic concept. At the same time, it is important to regard Industrie 4.0 not as a substitution, but a supplement to lean principles in order to enable further productivity improvements and higher agility. Only with stable processes as a result of applied lean principles, Industrie 4.0 can unfold its full potential.

Many scientific studies were conducted to provide guidance in implementing Industrie 4.0 solutions in the manufacturing industry. However, new technical solutions alone do not necessarily lead to higher company performance, but need to be leveraged in order to achieve new manufacturing process innovations [19]. The Organisation for Economic Co-operation and Development (OECD) defines process innovations as the implementation of new or significantly improved production or delivery methods, including changes in techniques, equipment and/or software [20]. This differentiation between organizational (techniques) and technological (equipment and/or software) process innovations is widely acknowledged among researchers, as well as its enormous potential for helping any organization to achieve major competitive advantages [21–23].

Despite this acknowledgement, process innovations receive much less attention than product innovation in both science and industry [22]. Accordingly, no extensive studies were found on how to profoundly adapt production systems in order to systematically identify and implement process innovations. Such an approach is strongly required especially in the light of the radial character of Industrie 4.0 solutions. One of the few mentionable studies was conducted by Yamamoto who provides recommendations for introducing Kaikaku with the goal to create unique production systems [24]. In his definition, the Japanese word Kaikaku is a "large-scale improvement that involves fundamental rethinking and radical design of systems and processes related to production, with the primary purpose of achieving dramatic improvements in the performance of the production system which is frequently measured in terms of cost, quality, speed, and flexibility" [24]. The guideline consists of six operative levers within a three-step Kaikaku approach contributing to an unique production system. However, the recommendations are rather success factors that need to be considered than a framework for the redesign of conventional production systems.

With regard to the radical character of the concerned process innovations, it becomes obvious that their systematic identification and implementation are hardly possible in conventional lean production systems which focus on incremental improvements. Even lean techniques that focus on fast improvements, e.g. "Kaizen blitz" and "Kaizen events" which are usually conducted within days and in dedicated company areas, this contradiction between the radical and the incremental character is dissolved to some extent only [24–26]. In order to secure sustainable success of large-scale changes, the capability for radical process changes must be anchored within companies, resulting in a redesign of conventional production systems.

4 Research Aim

As shown above, Industrie 4.0 provides the potential not only to overcome the human limitation in processing the high complexity midst the conflict of aims between high agility and high utilization in manufacturing companies. It also supports these two target aims individually. The challenge for manufacturing companies lies within the systematic identification and fast implementation of radical process innovations in the context of Industrie 4.0. Because conventional production systems follow the Kaizen philosophy and therefore focus on incremental improvements, they are not suited for these tasks.

The presented research work aims at the development of a framework for designing production systems in the context of Industrie 4.0 – Production Systems 4.0 (hereafter referred to as ‘PS 4.0’). Such production systems enable the systematic identification and implementation of radical process innovations for the benefit of higher agility without compromising a high productivity.

5 Basic Conception of the Framework

As described above, Industrie 4.0 and lean principles are no substitutions but rather supplements for each other. Accordingly, the PS 4.0 needs to incorporate the basic elements of conventional production systems in order to maintain its benefits. At the same time, the PS 4.0 needs to compensate for the aforementioned deficiencies of conventional production systems, i.e. their limitations in further productivity improvement, complexity management and incorporation of radical changes. This results in the need for an *adaptation* of conventional production systems. In order to systematically exploit the radical potentials of Industrie 4.0, the PS 4.0 needs to provide the freedom for its full deployment. This implies a dedicated *extension* of conventional production systems (Fig. 2).

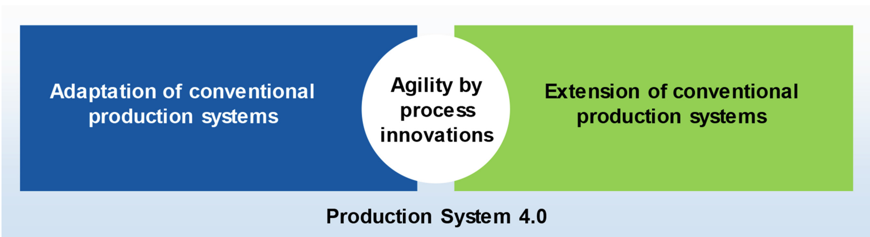

Fig. 2. Basic conception of the framework.

Based on these considerations, the research aim can be broken down into the following subordinate research questions:

(1) Which are the key elements of conventional production systems that need to be adapted?
(2) What are additional elements in the context of Industrie 4.0 that need to be considered?

6 Key Elements for the Adaptation of Conventional Production Systems

Although conventional production systems are mostly based on the well-known Toyota Production System that was developed in Japan, our understanding of production systems has been decisively influenced by the American authors Womack, Jones and Roos [27]. In their pioneering work "The machine that changed the world", they systematically analysed the Japanese automobile manufacturing industry and derived its success factors. Their work was widely responsible for the dissemination of Japanese production systems outside Japan which is mostly known as "lean production systems" [28]. Since then many companies around the globe have developed their own production systems or are trying to do so. In order to capture the maturity and capability of German manufacturing companies in developing production systems, the WZL conducted the study "Consortial Benchmarking – Production Systems" in the years 2010 and 2011. Together with ten industry partners, the widespread research among different industries aimed at the state of the art understanding of production systems as well as successful practices. The core result of the project was a jointly formulated, practice-oriented definition of a production system (cf. Figure 3). Especially with regard to their practical relevance, *Methods* and *Culture* were identified as the key elements of production systems [8].

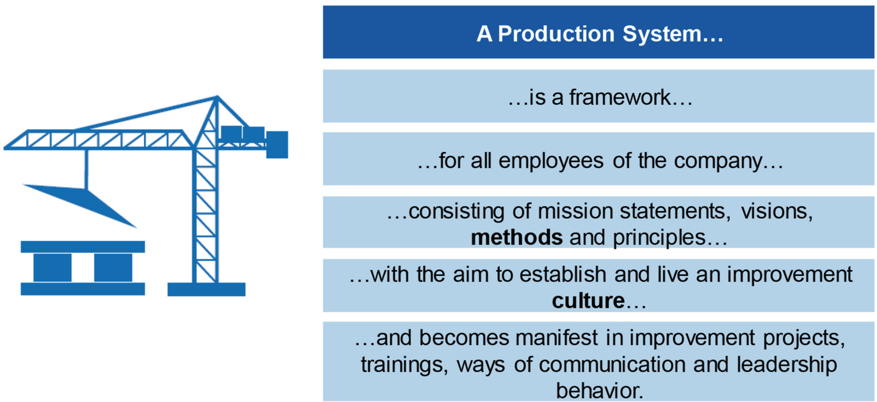

Fig. 3. Definition of a production system according to the WZL study "Consortial-Benchmarking Production Systems" from the years 2010–2011.

Methods Dimension. The dimension *Methods* offers a toolbox which contains a set of potential process innovations. At this point it is important to further detail the aforementioned differentiation between organizational and technological process innovations. Organizational process innovations target at working principles with the purpose of reducing cost, time, or to improve manufacturing KPIs. Prime examples are lean principles, e.g. Just in Time/Sequence (JIT/JIS), Kanban, Poka Yoke, which can lead to major process efficiencies [22]. Technological process innovations are primarily based on technical innovations which focus on physical principles and improve the physical process of product realization. For example, ultrasonic supported turning of stainless steel with diamond tools enables the manufacturing of surface roughness of less than 0.03 μm on one machine tool [29]. While the implementation of some technical innovations may lead to process innovations, others might not. Within the given example, a successful implementation of the ultrasonic supported turning can eliminate subsequent processes, e.g. fine turning and polishing, and therefore result in a process innovation. Another example is the use of Automated Guided Vehicles (AGVs) [30]. Although AGVs alone might be considered as a technical innovation, a systematic deployment might significantly change a company's intralogistics and result in a technological process innovation.

In conventional production systems, the method toolbox primarily contains lean methods [31]. In the context of the new formulated production aims productivity and agility, this toolbox needs to be adapted. While many lean methods may keep their validity, some may become obsolete while others may unfold new potentials due to Industrie 4.0. However, the authors of this paper suggest a wider interpretation of the term 'adaptation' of the toolbox in order to increase the catchment area for potential new process innovations. Apart from digitization of conventional lean methods, new methods might be found in adjacent departments (e.g. product development) and industries (e.g. electronic industries) in order to transfer and adapt to the manufacturing industry.

Given the highly volatile environment and the resulting need for agility, the toolbox itself needs to be continuously updated. Therefore, scouting techniques in order to identify new methods are required and need to be part of the methods toolbox itself.

Culture Dimension. A company's culture demonstrates a powerful influence on its change processes and substantially defines its success [32]. An organizational culture in which employees are open towards disruptive changes is therefore a crucial asset for manufacturing companies. Potential measures include change of organizational structures, relocation of specific employees and conduction of trainings. It is notable that the success of actively changing the corporate culture seems to be independent from the company size, but is mostly related to employees in leading positions [32]. Therefore, even though culture is regarded as a "soft" asset, changes always come with "hard" measures, e.g. replacement of employees in leading positions [33].

In the combination of the dimensions *Methods* and *Culture* and their adaptation towards PS 4.0, culture serves as the overarching condition. Only with the appropriate culture, methods can unfold their full potential (cf. Fig. 5) and lead to successful process innovation.

7 Key Elements for the Extension of Conventional Production Systems

With cyber-physical connection between machines, objects and humans, the industrial production can potentially be revolutionized in the same way our private life has been revolutionized by the Internet of Things (IoT). The transfer of the IoT principles to the production world offers immense potential to increase agility. However, the transfer comes with great challenges. One aspect of the challenges are the complex interrelations within the production environment. Another aspect is the low usability of required data. Although relevant data are mostly available, they are stored within proprietary silos along the product life cycle (ERP, PLM, CAD, etc.).

With the Internet of Production (IoP, cf. Fig. 4), the WZL has introduced an infrastructure to overcome these challenges and to enable data-based interdisciplinary collaboration within companies. The overall aim of the IoP is to offer real-time capable cross-domain decision support in all phases of the product lifecycle in order to increase a company's agility [34].

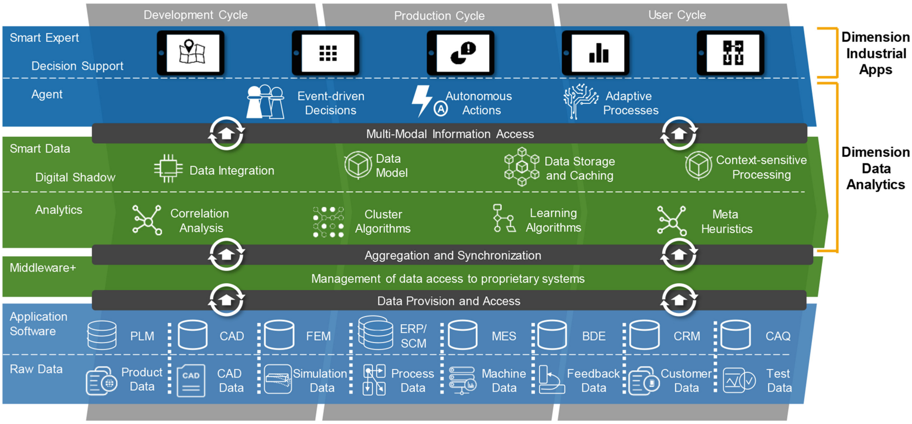

Fig. 4. Infrastructure of "Internet of Production" (IoP).

The IoP is horizontally structured into three areas: Development Cycle, Production Cycle and User Cycle. Within these cycles, various proprietary silos with raw data exist (lowest layer in Fig. 4). Usually these raw data can only be accessed and processed by experts with required system knowhow within their individual domain. These data need to be filtered and aggregated for any cross-domain analysis which usually results into immense manual effort. In order to facilitate an automated process, an intermediate layer between the technological layer (raw data) and the application layers (Smart Data and Smart Expert) is required [35]. Within the IoP, this task is being carried out by "Middleware+". It filters and aggregates the raw data by relevance and requirement to a degree at which the data be easily processed by commercially available computers.

Based on the IoP, *Data Analytics* and *Industrial Apps* were derived as additional elements for designing production systems in the context of Industrie 4.0.

Data Analytics Dimension. Within the IoP, the layer Smart Data is consecutively built on Middleware+. Its purpose is to identify hidden data correlations, complex optimization potentials and to enable real-time transparency of processes by combining various raw data silos across company domains. In order to unveil the desired information, the aggregated data provided by Middleware+ need to be processed with analytical algorithms according to the specific purpose. In this regard, the very first challenge for manufacturing companies is to identify and to collect relevant data in the required quality, i.e. completeness, precision, resolution, semantic, etc., as input for Middleware+. The second major challenge is to develop sophisticated analytical algorithms which will substantially decide on the usefulness of the Smart Data they generate. This results in the need for manufacturing companies to extend the employees qualification requirements by IT, mathematical and data analytics skills, e.g. programming and statistics. This trend already started during the third industrial revolution through the introduction of electronics and IT for further automation of production [36], but is becoming even more eminent in the current fourth industrial revolution.

The result of a holistic generation of Smart Data however, i.e. a real-time capable digital image of all relevant company processes, is called the Digital Shadow. Due to its real-time availability and instant accessibility, times of employees spent on searching and waiting can be reduced to a minimum and thus lead to significant higher productivity. Furthermore, both historic and real-time analyses can be conducted in order to identify optimisation potentials and to verify experience-based hypotheses. Given the holistic transparency of all relevant processes, process forecasts are also enabled for proactive reactions. For example, product change requests during the product development can have significant implications on later production and logistic processes. Typically these implications are discovered and escalated at later stages, e.g. in later quality gates, in prototyping or even production ramp-up phases. With a detailed understanding of the company's processes provided by the Digital Shadow, these implications can be discovered with minimum latencies and follow-up costs can be significantly reduced.

The layer Smart Experts is consecutively built on the layer Smart Data. It comprises two different sublayers. While applications of "Decision Support" are designed to support employees and therefore feature an user interface, "Agents" are designed to run autonomously as background applications. Agents can both analyse historic and memorize real-time data in order to learn from human decisions on the basis of Artificial Intelligence. By doing so, they can provide better decision options to the user or make autonomous decision in similar recurrent decision situations.

Due to its crucial purpose, Smart Data were identified as one additional element for the intended framework for designing PS 4.0. However, in order to implement Agents, companies need to extend employee skills by mathematics and data analytics which is similar to the development of Smart Data and distinctively different to the development of Decision Supports (as described in the next chapter). Because of this practical implication for manufacturing companies in designing and implementing PS4.0, Smart

Data and Agents are summarized in one dimension for the intended framework and named *Data Analytics* (cf. Fig. 4).

Industrial Apps Dimension. Due to the high complexity which still remains with Smart Data and Agents, applications with user-friendly interfaces are required in order to reduce the complexity to a minimum residual degree which can be processed by human intelligence, and thus provide user with manageable decision support (top layer of the IoP). Referring once again to the aforementioned example of navigation systems, the complexity of geographic maps and traffic information is processed in the background but drastically reduced in the presentation to the user. For the intended framework for designing PS4.0, the deviating term "*Industrial Apps*" was deliberately chosen instead of "Decision Support" in order to emphasize the analogy to the IoT. Due to their potential to revolutionize the industrial production in the same way our private life has been revolutionized by private apps, Industrial Apps were identified as another additional element for the intended framework. Different to the development of Smart Data, the required skills for developing Industrial Apps focus on design skills in order to maximize the user-friendliness of apps.

Similar to the cultural dimension, the Data Analytics dimension also serves as the overarching condition. Only with the appropriate *Data Analytics*, *Industrial Apps* can unfold its full potential (cf. Fig. 5).

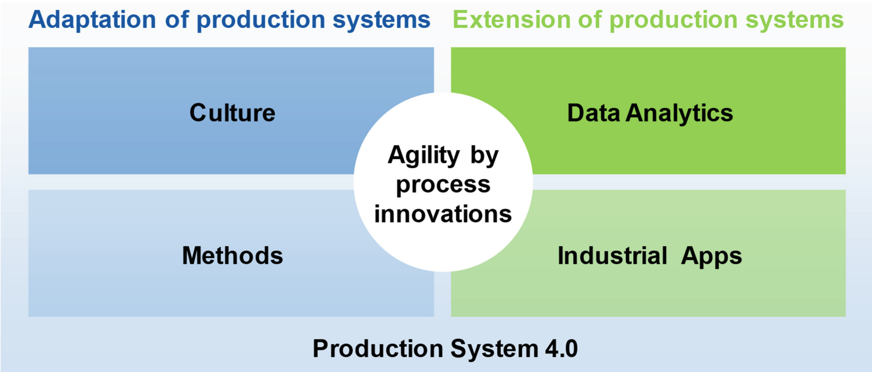

Fig. 5. Framework for designing Production Systems 4.0.

8 Detailing the Framework for Designing Production Systems 4.0

As described above, the dimensions *Culture* and *Methods* were identified as key elements of conventional production systems which need to be adapted for designing PS4.0. In addition, the dimensions *Data Analytics* and *Industrial Apps* were identified as key elements by which conventional production systems need to be extended for designing PS4.0. The developed framework is shown below.

The framework was presented to an industry consortium consisting of eight major international enterprises of the automotive, steel, home appliance, power tools, instrumentation and railway industries. In an extensive exchange with the enterprises' operations experts, the four dimensions of the framework were controversially discussed. Four fundamental conclusions were made which confirmed the developed framework:

– Today's corporate culture is often unsuitable to enable radical changes
– Industrie 4.0 enables new methods which are required for achieving higher agility and productivity
– The systematic collection and use of data is crucial, but the vast freedom of action and the high complexity pose a major challenge
– Intuitive support for workers and leaders with apps, similar to our private life, is possible and necessary

In order to further detail the developed framework, the major challenges of today's production systems as well as future requirements of PS4.0 were discussed. Based on the discussions, focus areas for each dimension were identified. The result of the joint discussion is represented in Fig. 6. This detailed framework enables producing companies to systematically consider the most relevant aspects when designing PS4.0.

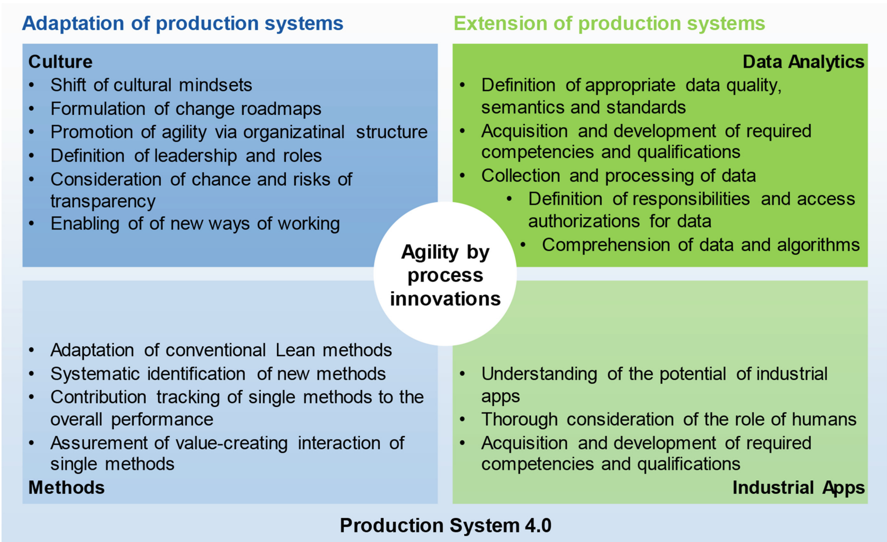

Fig. 6. Focus areas in each dimension of the developed framework.

In the *Culture* dimension, it became clear that many companies' culture is not suitable for radical changes and therefore needs to be adapted. However the introduction of a new corporate culture is a time consuming process. In any case, the implementation of changes needs to be carefully planned and executed (change roadmaps). It was postulated that the organizational structure as well as the definition of leadership and roles can have a positive influence on the company's agility. As the production environment becomes more and more digitalized, it was also found that the created transparency can lead to significant benefits, but also poses risks that need to be carefully taken into account. At the same time, new ways of working will be enabled, but the effects on workers, especially on different age groups, need to be considered.

The highest ranked focus areas in the *Methods* dimension were the adaptation of conventional Lean methods as well as the systematic identification of new methods. While some Lean methods might unfold additional potentials through digitalization, others will remain unperturbed, and still some might become obsolete. This assessment of conventional Lean methods towards their future contribution is a crucial step when designing PS4.0. At the same time, new methods with significant potential for higher agility and productivity might emerge. Systematic approaches for the continuous identification of new methods are required. In order to guarantee sustainable success of new methods, their contribution to the company's performance needs to be evaluated before, during and after implementation. Furthermore, it was expected that a purposefully outlaid interaction of all methods will provide higher benefits than the sum of all individual methods and therefore needs to be deliberately designed.

The biggest challenge in the *Data Analytics* dimension were found the creation of its prerequisites, rather than the development of smart algorithms. Based on their experience, the involved industry partners found that an appropriate, uniform corporate definition of data quality, semantics and standards is a crucial key to the successful use of data. This is especially true for companies with multiple production sites. Companies without data analytics experience need to acquire and develop the required competencies and qualifications first. At the same time, the appropriate technological equipment and infrastructure need to be set up for data collection and processing. Challenges also arise in the handling of data. Clear responsibilities and access authorizations for data need to be defined for both effectiveness and security reasons. Eventually control over machines and data is crucial. This requires the understanding of the complexity of processes and algorithms, not only by few but a broad part of the human staff.

Although it was widely agreed that *Industrial Apps* can create significant benefits in the same way consumer apps created benefits for our private life, the implementation in practice was found very difficult. Among the focus areas of all four dimensions, the understanding of the potential of industrial apps ("What can apps actually do?") was found most challenging. Due to the fact that industrial apps are meant to interact with human workers, the role of humans needs to be carefully considered. This involves questions around the autonomy of human workers as well as the acceptance of industrial apps across generations. Furthermore, similar to the *Data Analytics* dimension, the acquisition and development of the required competencies and qualifications pose a great challenge for producing companies.

9 Outlook

The presented framework serves as a guideline for producing companies in designing future production systems in the context of Industrie 4.0. The framework is structured in four dimensions and eighteen focus areas along which companies can cover the major relevant elements of the intended production system. However companies can be even further supported with a set of proven solutions for the focus areas.

Together with the aforementioned eight enterprises, the WZL is conducting the “Consortial Benchmarking Production Systems 4.0”. The goal is to identify successful practices along the dimensions and focus areas in an extensive international study. Based on the identified successful practices, feasible and effective solutions will be derived in order to provide a wide potential solution space for designing Production Systems 4.0. Results will be publicly presented in the summer of year 2019.

10 Summary

The developed framework provides a guideline for designing production systems in the context of Industrie 4.0 (Production Systems 4.0) in order to increase both a company’s agility and productivity.

The first part of the framework was derived from conventional production systems and needs to be adapted in the context of Industrie 4.0. It includes the dimensions *Methods* and *Culture*. While the methods dimension focuses on the identification and implementation of new potential radical process innovations, the culture dimension serves as the overarching condition for a successful application of the methods. The second part of the framework presents the extension of conventional production systems and is derived from the presented infrastructure of the Internet of Production (IoP). It includes the dimensions *Data Analytics* for the cross-domain combination of raw data as well as the dimension *Industrial Apps* for intuitive decision support. Similar to the cultural dimension, the Data Analytics dimension also serves as the overarching condition for Industrial Apps.

The framework was presented to eight international corporations from various manufacturing industries and was found valid. Together with these companies, the framework was further detailed by identifying specific focus areas for each dimension. By using this framework, producing companies can systematically consider the most relevant aspects when designing PS4.0.

For a better support for companies in designing PS4.0, the authors of this paper intend to identify feasible and effective solutions for the dimensions and focus areas in order to provide a wide potential solution space for the framework. In order to do so, the WZL is conducting the “Consortial Benchmarking Production Systems 4.0” with a wide spread international study. Results will be presented in the summer of year 2019.

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