The Internet of Production: Interdisciplinary Visions and Concepts for the Production of Tomorrow

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Contents

1 Introduction 2
2 Research Domains in Production 3
3 Objectives of the Internet of Production 6
4 Fostering Interdisciplinary Research for the IoP 7
5 Conclusion 10
References 10

Abstract

Changes in society require changes in our industrial production. In order to remain competitive in the future, the masses of data available in production must be used urgently. This is still a challenge because data are often not accessible or understandable. Therefore, we developed the Internet of Production (IoP) concept which aims to collect, unify, and exploit different data sources and improve production. To this end, the various research domains of production technology, the need for a common infrastructure, and the concept of the Digital Shadow are presented. The vision can only be achieved through interdisciplinary cooperation

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between different disciplines. Therefore, the joint approach is explained and common research topics are presented. Interdisciplinary cooperation is the key for further steps to achieve the common vision.

1 Introduction

Production technology plays a central role in our economy. In order to avoid overcapacities and overproduction, to keep production in high-wage countries attractive, and to meet the needs of customers for more individuality of products (mass customization), a stringent digitalization of all production assets connected with production and the continuous involvement of the employee is necessary (Brecher et al. 2017). Even though this development has been observed for a long time under the term Industry 4.0, few digital solutions have been used in industry so far, and, in particular, end-to-end networking from the shop floor to the office and data exchange across company boundaries is still not feasible. Although large amounts of data are available in production technology, they are often inaccessible, uninterpretable, or incomplete. This can have technical and organizational causes, as can be witnessed in many projects. Either technical hurdles, such as the selection of suitable protocols and databases to provide data, or organizational hurdles, such as ensuring the reusability of data, are addressed. However, the larger vision of universally available data enabling new business models takes a back seat. A lack of trained staff and dealing with new risks also pose major challenges for companies.

The internet and approaches such as the Internet of Things (IoT) have revolutionized the availability of data and knowledge (Schuh et al. 2019). Therefore, advances under the terms such as *Industry 4.0*, the *Industrial Internet of Things* (IIoT), and *Made in China 2025* have been made to combine technological advances in Internet and Communication Technologies with the production technology (Jeschke et al. 2017; Mueller and Voigt 2018). However, these concepts cannot be transferred holistically to production technology. The number of parameters in production plays a decisive role here. So for knowledge to be generated from data in the production context, these data sources need to be extremely networked, contextualized, aggregated, and processed. An *Internet of Production* is necessary. The following vision was defined for this:

> The vision of the Internet of Production (IoP) is to enable a new level of cross-domain collaboration by providing semantically adequate and context-aware data from production, development and usage in real-time, on an adequate level of granularity.

The IoP pursues the idea of laying the foundation for a World Wide Lab in which production engineering models can be used across domains (Schuh et al. 2019; Kappel et al. 2022). The research project therefore connects material engineering with production technology and management on all life cycle phases through a digital infrastructure and business modeling. Each operation carried out is a potential experiment. New insights can be gained from the data provided. For this, an infrastructure must be created that connects data from different production domains, makes the data usable through modeling and aggregation, and provides algorithms for extracting knowledge. Therefore, we developed new data science approaches and artificial intelligence techniques ranging from reinforcement learning to process mining. At the center of the IoP is the human being who orchestrates the production technology (Brauner et al. 2020). This requires a new kind of collaboration between different disciplines: building on a strong link between production technology, materials science, and information technology, the production technology of tomorrow can be designed with the help of various sub-disciplines of the social sciences and management.

The necessary interfaces between the different research domains, a detailed presentation of the vision and the concepts (see Sects. 2 and 3), and the first success reports of the interdisciplinary research (see Sect. 4) are presented in the following sections.

2 Research Domains in Production

In order to take a holistic view of production technology, the three life cycle phases of development, production, and use must be considered:

Development (Fig. 1): Product development is always at the beginning of production. Increasingly, however, it is becoming more and more iterative, based on findings from production and use. Agile product development is therefore strongly intertwined with three processes and methods: market development, prototype engineering, and production. The goal is to radically reduce lead time while at the same time exceeding customer expectations. To establish new processes and methods, organizational structures must be investigated and data structures must be developed to overcome semantic conflicts and performance latencies. In addition, technologies for prototyping are needed, which in turn support the agile adaptation

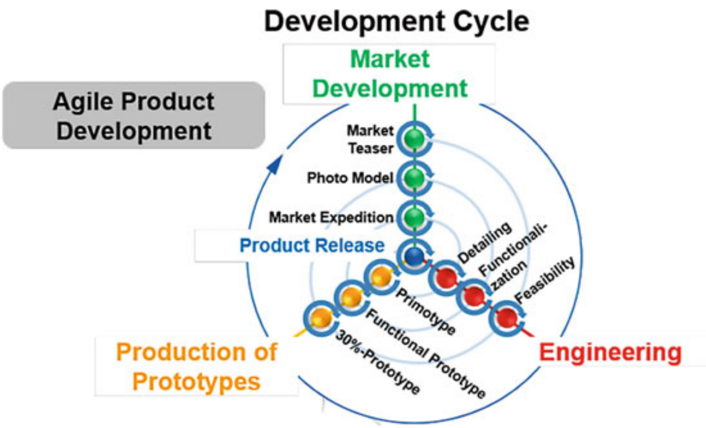

Fig. 1 Dimensions of the development cycle

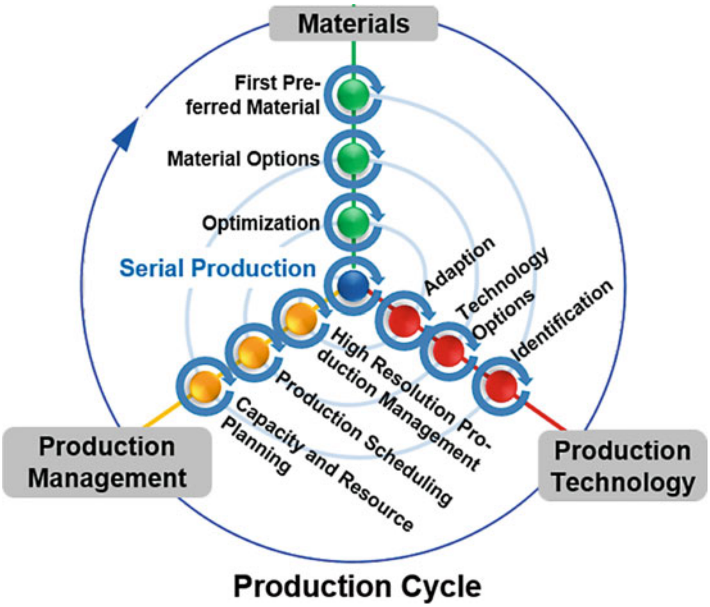

Fig. 2 Dimensions of the production cycle

of the product with the help of process data. A minimum viable product together with relevant data provided by the IoP enables continuous stakeholder involvement and cross-domain collaboration.

Production (Fig. 2): Within the production cycle, there are three essential sub-areas that only lead to high-quality products in harmony with each other: the consideration of materials, production technologies, and production management. The goal is to create an environment in which the production system can act adaptively despite uncertainties. For this purpose, data from all areas with their metadata must be made available across domains. The selection and use of materials forms the basis of the production process. Therefore, it is all the more important to incorporate findings from the production process and use into the selection of the material. For a longer service life, dynamic production scenarios and condition monitoring of components can be included. Adaptive production requires the reduction and composition of heterogeneous engineering models of production technologies to be able to analyze data from production in real time. This enables production management to make faster and better decisions to adapt highly specialized processes at all other levels of the company.

Usage (Fig. 3): The usage phase of the products and equipment should bring new insights for the development and production of products. Networked data, products, and equipment generate added value. This means that products and equipment must also provide data during usage. Moreover, many manufacturers engage crowdsourcing of critical feedback and innovative ideas from premium

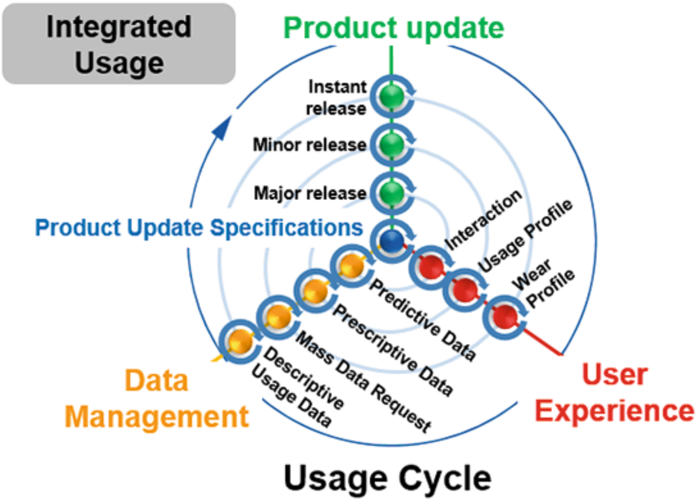

Fig. 3 Dimensions of the usage cycle

user communities. Through holistic data management with the help of descriptive, prescriptive, and predictive mass data, product update specifications can be created and thus the product can be regularly renewed. In addition, human interaction with the product, the equipment, and associated services can be improved. Interfaces to the technical systems need to be developed that contribute to the development of capabilities, the evolution of organizational structures, and the selection of an appropriate governance mode. Production systems become more transparent to people. This is achieved through an internal view, which deals with the cooperation of the human with the technical system, and an external view, which deals with possible platform and business models.

Following the discussion above, the IoP Cluster of Excellence has been organized in five Cluster Research Domains (CRDs): one for the development perspective (Fig. 1), one for usage (Fig. 3), and one for each of the three dimensions of the production cycle (Fig. 2). Each of the CRDs is further subdivided in work streams in which interdisciplinary teams address specific research challenges or use cases.

Moreover, all three domains have one thing in common: they need an open, shared infrastructure to unfold their potential. Therefore, a conceptual, physical, and functional infrastructure has to be developed that connects all major domains of networks of companies within a World Wide Lab in the future. The World Wide Lab should enhance a cross-company and international division of labor and cooperation for mutual learning from dependencies. Moreover, to ensure resilience, we need to carefully manage dependencies and limit the outflow of knowledge. The infrastructure must enable the execution of multi-agent models and data streams in distributed communication networks within and between layers while guaranteeing the required performance, reliability, security, and safety at all levels. In order to be able to use the extremely heterogeneous production data in a cross-domain manner, knowledge graphs (e.g., Noy et al. 2019) must be provided with data sources that provide the user with access and the data structure, as well as the context. In order to generate new, cross-domain knowledge from the data, reduced models must be combined with data-based algorithms and thus enable context-adaptive actions. In the future, it can be assumed that the domains will merge more and more. With the existing data and new cooperation between companies, new business models can be established that disruptively change production technology in its processes and organization. Furthermore, in the context of the circular economy (Riesener et al. 2019), the life cycle phases will no longer run sequentially with individual information returns. Rather, the life cycle phases will close in a circular fashion. Extensive knowledge about the history of individual components is therefore required in order to be able to feed them into an R-cycle. The basis for this can only be provided by the IoP, which includes all life cycle phases and provides an open, common infrastructure.

3 Objectives of the Internet of Production

To make cross-domain data access and cross-domain models user-friendly for a growing number of experiments throughout the World Wide Lab, we developed the concept of the Digital Shadow. In the growing literature on Digital Twins (Bauernhansl et al. 2018; Jones et al. 2020), Digital Shadows are often interpreted as the data supply link from the physical systems to their Digital Twins. However, this is only one of the aspects why Digital Shadows are important. As Fig. 4

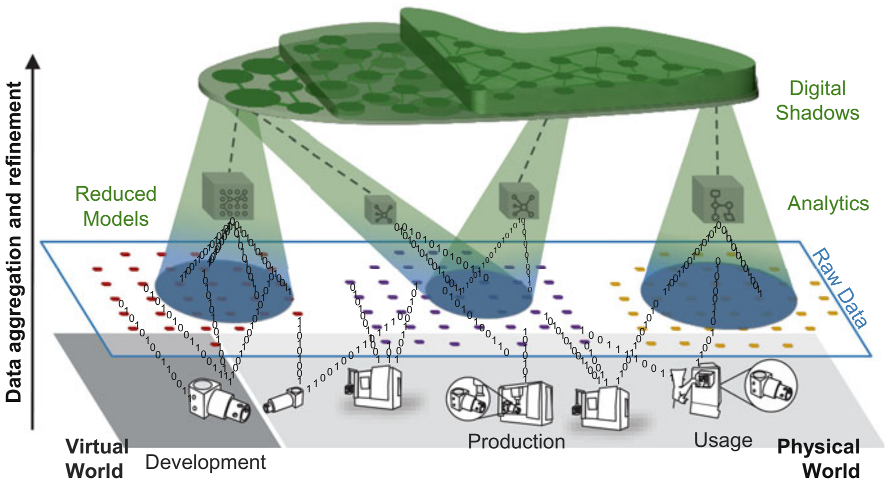

Fig. 4 Digital Shadows in the Internet of Production (Jarke et al. 2018)

illustrates, a World Wide Lab would host a huge variety of reusable Digital Shadows as condensed knowledge integrating reduced mathematical models with captured data from all phases and domain-specific perspectives, ranging from very small (materials science) to very large (worldwide management). The network of Digital Shadows thus constitutes the conceptual core of the IoP infrastructure.

Digital Shadows (Jarke et al. 2018) are based on recorded raw data streams – for example, heterogeneous production, development, or usage data. These data are transformed into knowledge with the help of production models. For this purpose, the data must be semantically processed, and an application-specific aggregation of the data of all domains relevant to the problem must be carried out in a task-specific granularity. To this end, the domain-specific knowledge, which is provided through mathematical or physical models or established standards, is extended with data-driven models with the aim of formalizing knowledge and acquiring new knowledge in order to provide recommendations in real time. The Digital Shadow enables different views to be taken and is continuously being developed. In this way, parallels between different use cases are to be found and knowledge transferred between domains.

In order to be able to implement the concept of the Digital Shadow, the infrastructure (Schuh et al. 2017) in production technology must be understood and expanded. The raw data in production engineering is heterogeneous, often unstructured, and application-specific. They are created in highly specialized software, machines, or sensors for which no uniform formats are defined. Therefore, an action layer is needed to handle these heterogeneous, highly voluminous, distributed data streams from production and to make them available in a seamlessly interoperable way. Based on this, a layer is needed to process the data (Smart Data). The data is described by means of comprehensive data models and processed and made available in a real-time and context-sensitive manner. By combining abstract and structured knowledge, the data is transformed into new insights using advanced analysis methods (e.g., process mining and other machine learning techniques). These new insights are made available to the experts as intuitive and interactive decision support (Smart Expert). Therefore, advanced engineering tools have to be developed in order to integrate new data-driven models.

It is not enough to describe the infrastructure theoretically: it must rather be implemented in direct application in the research and industrial environment. The Digital Shadow must not remain a concept. Hurdles must be jointly identified and removed through interdisciplinary cooperation. As Fig. 5 shows, interdisciplinarity is the key to the vision of the IoP.

4 Fostering Interdisciplinary Research for the IoP

Interdisciplinary cooperation has grown over the years. Different scientists look at particular challenges in their domains (e.g., Niemietz et al. 2021) and gradually expand their solution space to other domains or disciplines (e.g., Kunze et al. 2021). It is a development from mutual empowerment, via linked research work,

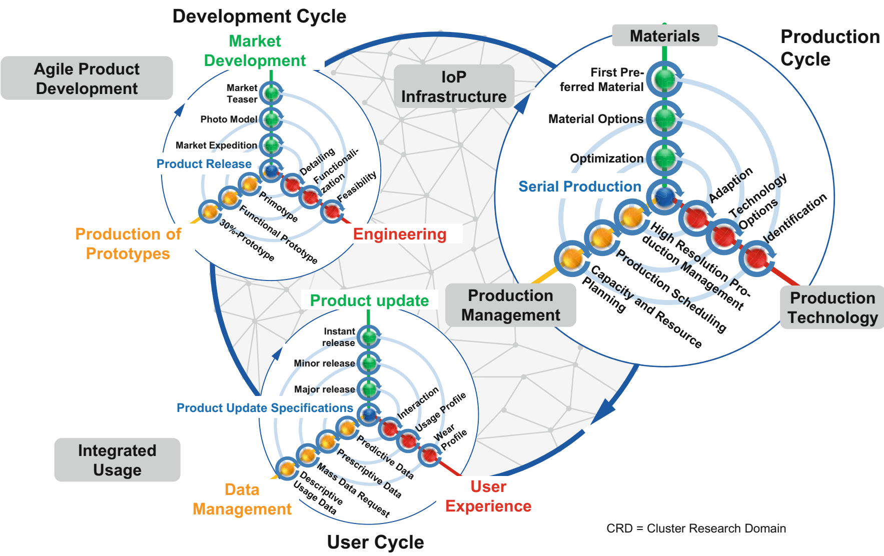

Fig. 5 Fostering the cycles onto the IoP infrastructure

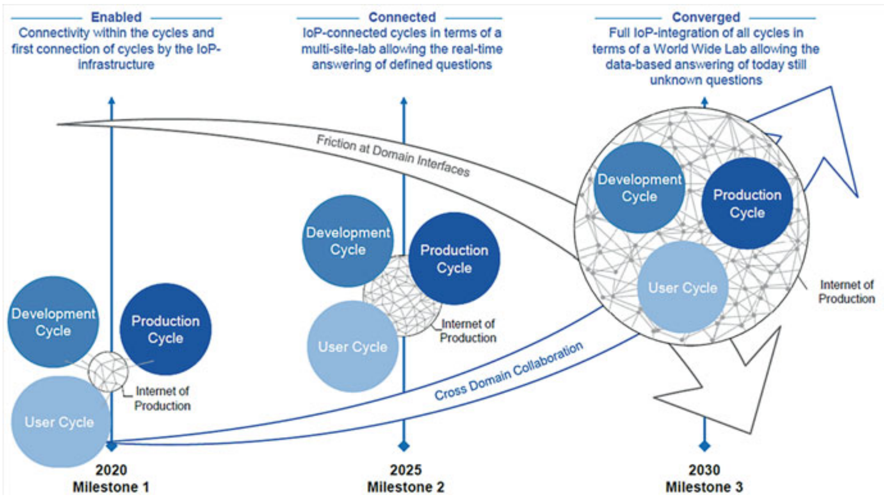

Fig. 6 Fostering interdisciplinary research: three stages of the Internet of Production

to converging issues of different domains. Figure 6 illustrates how the Cluster of Excellence IoP is organizing this challenging process in three major stages – across over 30 research institutes together with many external partners. In addition to getting external partners involved in specific use cases or by leveraging commercial platforms, intense debates in a comprehensive Delphi study (Piller et al. 2022) have instigated further research challenges and hypotheses to be further explored in the time range up to 2030.

In relation to the production domains, this means in many cases that the scientist identifies a problem and first collects data with the help of internal or external sensors. This data is usually processed and stored. Afterward, various data-driven algorithms (e.g., in combination with physical models, Brecher et al. 2022) are used to gain new insights. On this path, a first interdisciplinary exchange is already necessary, since the scientists have to think about the suitable infrastructure in addition to the actual production-technical problem, which is not trivial for each application (Pennekamp et al. 2019). The number of available technologies for networking production plants and algorithms is unmanageable and is constantly evolving, and the optimal use of suitable parameters poses a great challenge to scientists (e.g., Rom et al. 2022).

Technologies from the field of computer science are thus becoming enablers of production technology research. Organizing World Wide Labs requires contributions from different disciplines (Brauner et al. 2022), such as the deep intertwining of reduced physical models and their context adaptation by machine learning from data streams in Digital Shadows (Liebenberg and Jarke 2020); ensuring data quality and reusability of Digital Shadows by detailed provenance information (Becker et al. 2021); developing policies for sovereign data exchange across organizational boundaries (Jarke 2020), supported by industry-specific security and privacy technologies (Pennekamp et al. 2021); and the networking of individual Digital Shadows for the analysis of larger cooperation contexts, such as supply chain analysis, transfer learning across use cases (Baier et al. 2022), and process mining which provides techniques for process discovery, compliance checking, and predictive process analytics (Abouridouane et al. 2022; van der Aalst et al. 2021).

With the help of mutual enabling, a mutual understanding of the domains under consideration is created. The next step is to develop a common language (e.g., Mertens et al. 2022). With the help of this common language, common questions can now be developed. This is a central step for the development of a World Wide Lab. The concepts from computer science should not simply be applied to the production technology infrastructure. Commonalities and mediating data layers must be established that enable a real transfer between different domains.

To foster interdisciplinary research, the research program is extended with structural objectives. A Research School hosts different measures to give the researchers orientation inside the Cluster of Excellence. Internal and external conferences are organized to give the researchers the opportunities to have regular exchange regarding their research ideas and outcomes. In Research Summits, researchers take courses on interdisciplinary work and provide each other micro-trainings on enabling technologies. Leaders of the Cluster Research Domains and the work streams get special training on leading an interdisciplinary group. But also the promotion of young talents is important to sensitize students for the challenges and chances of interdisciplinary research. Therefore, Research-Oriented Teaching is performed by adding research topics into lectures, supervising interdisciplinary theses, and integrating student assistants into cluster-related tasks.

5 Conclusion

Production technology is a key part of our economy and needs to adapt to changing societal needs. Hence, more knowledge about processes and the interaction between humans and the processes have to be gained with available, but unstructured, data. Therefore, the vision of the Internet of Production was introduced, which demands cross-domain collaboration for gaining problem-specific knowledge from adequate and context-aware data. Concepts like the Digital Shadows and the World Wide Lab were introduced, which are based on an overarching infrastructure and bring together the main research domains in production: development, production, and usage. A strong collaboration between researchers from production technology, materials science, information technology, social sciences, and management is mandatory. The domain-driven research challenges lead to new interdisciplinary opportunities. First, success stories and the framework for working interdisciplinary by enabling the researchers through special training are presented.

The Cluster of Excellence Internet of Production reached the middle of the funding phase of 7 years. It can be seen that there is a good progress on reaching domain-specific knowledge through the usage of data-driven methods in the production environment. Although there are already a lot of collaborations between the different disciplines, the different domains have to come closer together. More transferable methods need to be found. With the great challenges ahead – decarbonization of the industry, circular economy, shortage of skilled workers, and aging society – important production and product knowledge must be enhanced and preserved. Therefore, the vision of the Internet of Production must be carried into industry.

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