Design Principles for Industrie 4.0 Scenarios: A Literature Review

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Design Principles for Industrie 4.0 Scenarios: A Literature Review

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Abstract: Although *Industrie 4.0* is currently a top priority for many companies, research centers, and universities, a generally accepted definition of the term does not exist. As a result, discussing the topic on an academic level is difficult, and so is implementing Industrie 4.0 scenarios. Based on a literature review, the paper provides a definition of Industrie 4.0 and identifies six design principles for its implementation: interoperability, virtualization, decentralization, real-time capability, service orientation, and modularity. Taking into account these principles, academics may be enabled to further investigate on the topic, while practitioners may find assistance in implementing appropriate scenarios.

1 Introduction

Industrie 4.0 is currently one of the most frequently discussed topics among practitioners and academics in the German-speaking area (Dais, 2014, p. 625; Drath & Horch, 2014, p. 56). Since the German federal government announced Industrie 4.0 as one of the key initiatives of its high-tech strategy in 2011 (Kagermann, Wahlster, & Helbig, 2013, p. 77), numerous academic publications, practical articles, and conferences have focused on that topic (Bauernhansl, Hompel, & Vogel-Heuser, 2014, p. V).

The fascination for Industrie 4.0 is twofold. First, for the first time an industrial revolution is predicted a-priori, not observed ex-post (Drath, 2014, p. 2). This provides various opportunities for companies and research institutes to actively shape the future. Second, the economic impact of this industrial revolution is supposed to be huge, as Industrie 4.0 promises substantially increased operational effectiveness as well as the development of entirely new business models, services, and products (Kagermann et al., 2013, p. 16; Kagermann, 2014, p. 603; Kempf, 2014, p. 5). A recent study estimates that these benefits will have contributed as much as 78 billion euros to the German GDP by the year 2025 (Bauer, Schlund, Marrenbach, & Ganschar, 2014, p. 5).

With Industrie 4.0 becoming a top priority for many research centers, universities, and companies within the past three years, the manifold contributions from academics and practitioners have made the meaning of the term more blurry than concrete (Bauernhansl et al., 2014, p. V). Even the key promoters of the idea, the "Industrie 4.0 Working Group" and the "Plattform Industrie 4.0", only describe the vision, the basic technologies the idea aims at, and selected scenarios (compare Kagermann et al., 2013, p. 5; Plattform Industrie 4.0, 2014), but do not provide a clear definition. As a result, a generally accepted definition of Industrie 4.0 has not been published so far (Bauer et al., 2014, p. 18).

According to (Jasperneite, 2012, p. 27), scientific research is always impeded if clear definitions are lacking, as any theoretical study requires a sound conceptual and terminological foundation. Companies also face difficulties when trying to develop ideas or take action, but are not sure what exactly for. “Even though Industrie 4.0 is one of the most frequently discussed topics these days, I could not explain to my son what it really means”, a production site manager with automotive manufacturer Audi puts it. This quote underlines the findings of a recent study revealing that “most companies in Germany do not have a clear understanding of what Industrie 4.0 is and what it will look like” (eco, 2014)[1].

As the term itself is also unclear, companies are struggling when it comes to identifying and implementing Industrie 4.0 scenarios. Design principles explicitly address this issue by providing a “systemization of knowledge” (Gregor, 2009, p. 7) and describing the constituents of a phenomenon. Therefore, design principles support practitioners in developing appropriate solutions. From an academic perspective, design principles are the foundation of design theory (Gregor, 2002, p. 11). Regarding Industrie 4.0, however, the authors of this paper could not find any explicitly stated Industrie 4.0 design principles during their literature research.

The paper aims at closing this gap in research. Based on a literature review, the authors provide a definition of Industrie 4.0 and identify six design principles, which companies should take into account when implementing Industrie 4.0 solutions.

The paper is structured as follows: Chapter 2 gives a short overview of how the idea of Industrie 4.0 came into being, what its vision and basic goals are, and what similar concepts can be found in the Anglo-Saxon world. Chapter 3 outlines the research process and the research method used. Chapter 4 illustrates four components which are closely related to the idea of Industrie 4.0, and provides a definition of Industrie 4.0 on the basis of these four components. Based on that definition, Chapter 5 introduces six design principles for identifying and implementing Industrie 4.0 scenarios. Finally, Chapter 6 outlines the contribution of the paper to both the scientific body of knowledge and the practical world, mentions limitations of the research conducted, and proposes paths for further investigation of the topic.

2 Background

The term “Industrie 4.0” is used for the next industrial revolution - which is about to take place right now. This industrial revolution has been preceded by three oth-

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[1] Original source: „Fachleute sind der festen Überzeugung, dass die meisten Unternehmen in Deutschland keine klare Vorstellung davon haben, was Industrie 4.0 eigentlich ist und wie sie aussehen wird.“

er industrial revolutions in the history of mankind. The first industrial revolution was the introduction of mechanical production facilities starting in the second half of the 18^{th} century and being intensified throughout the entire 19^{th} century. From the 1870s on, electrification and the division of labor (i.e. Taylorism) led to the second industrial revolution. The third industrial revolution, also called "the digital revolution", set in around the 1970s, when advanced electronics and information technology developed further the automation of production processes.

The term "Industrie 4.0" became publicly known in 2011, when an initiative named "Industrie 4.0" - an association of representatives from business, politics, and academia - promoted the idea as an approach to strengthening the competitiveness of the German manufacturing industry (Kagermann, Lukas, & Wahlster, 2011). The German federal government supported the idea by announcing that Industrie 4.0 will be an integral part of its "High-Tech Strategy 2020 for Germany" initiative, aiming at technological innovation leadership. The subsequently formed "Industrie 4.0 Working Group" then developed first recommendations for implementation, which were published in April 2013 (Kagermann et al., 2013, p. 77). In this publication, Kagermann et al. (2013) describe their vision of Industrie 4.0 as follows:

"In the future, businesses will establish global networks that incorporate their machinery, warehousing systems and production facilities in the shape of Cyber-Physical Systems (CPS). In the manufacturing environment, these Cyber-Physical Systems comprise smart machines, storage systems and production facilities capable of autonomously exchanging information, triggering actions and controlling each other independently. This facilitates fundamental improvements to the industrial processes involved in manufacturing, engineering, material usage and supply chain and life cycle management. The Smart Factories that are already beginning to appear employ a completely new approach to production. Smart products are uniquely identifiable, may be located at all times and know their own history, current status and alternative routes to achieving their target state. The embedded manufacturing systems are vertically networked with business processes within factories and enterprises and horizontally connected to dispersed value networks that can be managed in real time – from the moment an order is placed right through to outbound logistics. In addition, they both enable and require end-to-end engineering across the entire value chain." (p. 5)

Based on that vision, the "Plattform Industrie 4.0" developed further recommendations on how to implement the vision (Kagermann et al., 2013, p. 77). It understands Industrie 4.0 as “a new level of value chain organization and management across the lifecycle of products” (Plattform Industrie 4.0, 2014).[2]

As the term “Industrie 4.0” is not well-known outside the German-speaking area (Lasi, Fettke, Kemper, Feld, & Hoffmann, 2014, p. 261), it is worth to look at comparable ideas from a global perspective. General Electric promotes a similar idea under the name *Industrial Internet* (Bungart, 2014; Evans & Annunziata, 2012). It is defined as “the integration of complex physical machinery and devices with networked sensors and software, used to predict, control and plan for better business and societal outcomes” (Industrial Internet Consortium, 2013). The US government supports research and development activities in the area of the Industrial Internet with a 2 billion dollar fund for *Advanced Manufacturing* (President’s Council of Advisors on Science and Technology, 2014, p. 46). Further similar ideas can be found under the terms *Integrated Industry* (Bürger & Tragl, 2014, p. 560) and *Smart Industry* or *Smart Manufacturing* (Dais, 2014, p. 628; Davis, Edgar, Porter, Bernaden, & Sarli, 2012, p. 145; Wiesmüller, 2014, p. 1).

3 Research Process and Research Method

For the overall research design, the authors of the paper followed the recommendations of vom Brocke et al. (2009). To cover relevant publications in the fields of engineering, production, and management from both academia and business, the authors took advantage of five publication databases (CiteSeerX, ACM, AISeL, EBSCOhost, Emerald Insight) and Google Scholar. The literature review aimed at identifying central aspects of Industrie 4.0 in order to be able to derive a definition of this term that is accepted by both researchers and practitioners (Cooper, 1988, p. 109). To conceptualize Industrie 4.0 and identify key terms, a preliminary literature review was conducted (vom Brocke et al., 2009, p. 10) by searching for the terms “Industrie 4.0” and “Industry 4.0” in Google Scholar. The two different notations were applied in order to cover both German and English publications, as the term is mostly written with “ie” in German and with a “y” in English publications. The titles, abstracts, and keywords of the first 100 results for each search term (i.e. 200 publications in total) were analyzed by two researchers independently of each other, in order to ensure reliability of the review process (Randolph, 2009, p. 6). Each of the two researchers then assigned keywords to each publication analyzed. For example, Kagermann et al.’s vision of Industrie 4.0 (2013, p. 5), which is quoted in the previous chapter of this paper, received the keywords

[2] Original source: “Der Begriff Industrie 4.0 steht für die vierte industrielle Revolution, einer neuen Stufe der Organisation und Steuerung der gesamten Wertschöpfungskette über den Lebenszyklus von Produkten.”

CPS, *Smart Factory* and *Smart Product*, as these terms are explicitly used in the text, and *Internet of Things*, as this term is implicitly mentioned in the phrase “vertically networked with business processes within factories and enterprises and horizontally connected to dispersed value networks”. The two researchers then aggregated the keywords assigned and discussed those cases in which discrepancies had occurred. The final list included 15 (German and English) keywords (see “Keywords 2” in Figure 1).

Keyword 1		**Keyword 2**
Industrie 4.0, Industry 4.0	and	Cyber-Physical Systems, Cyber-Physikalische Systeme, CPS, Internet of Things, Internet der Dinge, Internet of Services, Internet der Dienste, Smart Factory, intelligente Fabrik, Smart Product, intelligentes Produkt, Big Data, Cloud, M2M, Machine-to-Machine

Figure 1: Keywords

After that, a search combining the keywords and “Industrie 4.0” or “Industry 4.0” was conducted in the five databases (see Figure 1). As this search resulted in only a few hits, Google Scholar was included into the search process. Following the recommendations of Webster and Watson (2002, p. xvi), the results were complemented by a backward and forward search. Of these results, only the publications which had a clear reference to “Industrie 4.0” in their title, abstract, or keywords were considered as relevant. This procedure led to 51 publications which were analyzed completely by the two researchers and then tagged with the respective keywords. Again, the results were aggregated and discussed in order to eliminate discrepancies. The keywords were then ranked according to their frequency of occurrence. The four most relevant keywords are presented as the basic components of Industrie 4.0 in the following chapter. In accordance with vom Brocke et al.’s (2009) last step in the literature search process, the paper outlines further possible research activities based on the literature review’s results in Chapter 6.

Based on the four basic components identified, the authors provide a definition of “Industrie 4.0”. This definition adheres to Aristotle’s rules of *genus proximum* and *differentia specifica*. While the first rule requires a definition to name the term’s genus (i.e the superordinate concept or species the term belongs to), the latter demands a definition to specify the distinct features which distinguish the term from other terms within the concept or species (Aristotle, 350 BC; Westermann, 2001).

In a final step, the authors derive Industrie 4.0 design principles based on the introduced definitions of the Industrie 4.0 components and the given examples. In order to ensure the reliability of the process, two researcher derived Industrie 4.0 design principles independently. The design principles found where combined and grouped. In total, six groups where found. Each group is represented by a generic term. According to Gregor (2002), these principles guide practitioners and scientists on "how to do" (p. 11) Industrie 4.0.

4 Literature Review Results

The literature review identified four key components of Industrie 4.0: *Cyber-Physical Systems*, *Internet of Things*, *Internet of Services*, and *Smart Factory* (see Table 1). *Machine-to-machine (M2M) communication* and *Smart Products* are not considered as independent Industrie 4.0 components by the authors of the paper, as M2M is an enabler of the Internet of Things, and Smart Products are a sub-component of Cyber-Physical Systems (see Chapter 4.1.1 and 4.1.2 for further details). Likewise, and in line with Kagermann (2014, p. 605-606), the authors of the paper view *big data* and *cloud computing* as data services which utilize the data generated in Industrie 4.0 implementations, but not as independent Industrie 4.0 components.

In the following, the four basic Industrie 4.0 components will be described by providing the most often cited definition, explaining each component's link to Industrie 4.0, and giving an application example. Afterwards, the authors provide a new definition of Industrie 4.0, which is based on these components.

Table 1: Industrie 4.0 components *(as identified in the 51 publications under analysis)*

Search Term (Group)	Number of Publications in Which Search Term (Group) Occured
Cyber-Physical Systems, Cyber-Physikalische Systeme, CPS	46
Internet of Things, Internet der Dinge	36
Smart Factory, intelligente Fabrik	24
Internet of Services, Internet der Dienste	19
Smart Product, intelligentes Produkt	10
M2M, Machine-to-Machine	8
Big Data	7
Cloud	5

4.1 Industrie 4.0 Components

4.1.1 Cyber-Physical Systems (CPS)

An important component of Industrie 4.0 is the fusion of the physical and the virtual world (Kagermann, 2014, p. 603). This fusion is made possible by Cyber-

Physical Systems (CPS). CPS are "integrations of computation and physical processes. Embedded computers and networks monitor and control the physical processes, usually with feedback loops where physical processes affect computations and vice versa." (Lee, 2008, p. 363). The development of CPS is characterized by three phases. The first generation of CPS includes identification technologies like RFID tags, which allow unique identification. Storage and analytics have to be provided as a centralized service. The second generation of CPS are equipped with sensors and actuators with a limited range of functions. CPS of the third generation can store and analyze data, are equipped with multiple sensors and actuators, and are network compatible (Bauernhansl, 2014, pp. 16–17). One example of a CPS is the intelligent bin (*iBin*) by Würth. It contains a built-in infrared camera module for C-parts management, which determines the amount of C-parts within the iBin. If the quantity falls below the safety stock, the iBin automatically orders new parts via RFID. This allows consumption based C-parts management in real-time (Günthner, Klenk, & Tenerowicz-Wirth, 2014, p. 307).

4.1.2 Internet of Things

According to Kagermann, the integration of the Internet of Things (IoT) and the Internet of Services (IoS) in the manufacturing process has initiated the fourth industrial revolution (Kagermann et al., 2013, p. 5). The IoT allows "'things' and 'objects', such as RFID, sensors, actuators, mobile phones, which, through unique addressing schemas, (…) interact with each other and cooperate with their neighboring 'smart' components, to reach common goals" (Giusto, Lera, Morabito, & Atzori, 2010, p. V). Based on the definition of CPS given above, "things" and "objects" can be understood as CPS. Therefore, the IoT can be defined as a network in which CPS cooperate with each other through unique addressing schemas. Application examples of the IoT are Smart Factories (see explanation below), Smart Homes, and Smart Grids (Bauernhansl, 2014, pp. 16–17).

4.1.3 Internet of Services

The Internet of Services (IoS) enables "service vendors to offer their services via the internet. […] The IoS consists of participants, an infrastructure for services, business models and the services themselves. Services are offered and combined into value-added services by various suppliers; they are communicated to users as well as consumers and are accessed by them via various channels." (Buxmann, Hess, & Ruggaber, 2009, p. 341). This development allows a new way of dynamic variation of the distribution of individual value chain activities (Plattform Industrie 4.0, 2013, p. 4). It is conceivable that this concept will be transferred from single factories to entire value added networks in the future. Factories may go one step further and offer special production technologies instead of just production types. These production technologies will be offered over the IoS and can be used to manufacture products or compensate production capacities (Scheer, 2013, p. 2). The idea of the IoS has been implemented in a project named *SMART FACE* under the “Autonomics for Industrie 4.0” program initiated by the Federal Ministry for Economic Affairs and Energy. It develops a new distributed production control for the automotive industry. The project is based on a service-oriented architecture. This allows the use of modular assembly stations that can be flexibly modified or expanded. The transportation between the assembly stations is ensured by automated guided vehicles. Both, assembly stations and automated guided vehicles offer their services through the IoS. The vehicle bodies know their customer specific configuration and can decide autonomously which working steps are needed. Therefore, they can individually compose the required processes through the IoS and autonomously navigate through the production (Fraunhofer IML, 2014).

4.1.4 Smart Factory

“Smart factories constitute a key feature of Industrie 4.0.” (Kagermann et al., 2013, p. 19). “The Smart Factory is defined as a factory that context-aware assists people and machines in execution of their tasks. This is achieved by systems working in background, so-called Calm-systems and context aware means that the system can take into consideration context information like the position and status of an object. These systems accomplish their tasks based on information coming from physical and virtual world. Information of the physical world is e.g. position or condition of a tool, in contrast to information of the virtual world like electronic documents, drawings and simulation models. […] Calm systems are referring in this context to the hardware of a Smart Factory. The main difference between calm and other types of systems is the ability to communicate and interact with its environment.” (Lucke, Constantinescu, & Westkämper, 2008, p. 115). Based on the definitions given for CPS and the IoT, the Smart Factory can be defined as a factory where CPS communicate over the IoT and assist people and machines in the execution of their tasks. An example of a Smart Factory is the WITTENSTEIN bastian’ production facility in Fellbach, Germany, which is organized according to the principles of lean production. For the implementation of a demand driven milk run, intelligent work piece carriers are used. They report when a work piece is ready to be picked up and allow to initiate the milk run only if there is a demand. This helps reduce the number of milk runs and relieve employees from unnecessary work (Schlick, Stephan, Loskyll, & Lappe, 2014, p. 66).

4.2 Definition of Industrie 4.0

Based on the findings from the literature review, we define Industrie 4.0 as follows: Industrie 4.0 is a collective term for technologies and concepts of value chain organization. Within the modular structured Smart Factories of Industrie 4.0, CPS monitor physical processes, create a virtual copy of the physical world and make decentralized decisions. Over the IoT, CPS communicate and cooperate with each other and humans in real time. Via the IoS, both internal and cross-organizational services are offered and utilized by participants of the value chain.

5 Industrie 4.0 Design Principles

The implications of the above presented results are now used to derive design principles for Industrie 4.0 scenarios. These design principles support companies in identifying possible Industrie 4.0 pilots, which then can be implemented. In total, six design principles can be derived from the Industrie 4.0 components (see Table 2).

Table 2: Design principles of each Industrie 4.0 component

	Cyber-Physical Systems	**Internet of Things**	**Internet of Services**	**Smart Factory**
Interoperability	X	X	X	X
Virtualization	X	-	-	X
Decentralization	X	-	-	X
Real-Time Capability	-	-	-	X
Service Orientation	-	-	X	-
Modularity	-	-	X	-

The design principles are explained in the following by using the example of the key finder plant of SmartFactory^{KL}. SmartFactory^{KL} is a vendor independent technology initiative settled at the German Research Center for Artificial Intelligence. The demonstration plant was built in the course of the RES-COM project. It processes parts for key finders and assembles them. The housing of the key finders is equipped with a RFID tag that provides all production relevant data (Schlick et al., 2014, pp. 74-75).

5.1 Interoperability

Interoperability is a very important enabler of Industrie 4.0. In Industrie 4.0 companies, CPS and humans are connected over the IoT and the IoS. Standards will be a key success factor for communication between CPS of various manufacturers. The German Commission for Electrical, Electronic & Information Technologies of DIN and VDE has recognized this need and published the “German Standardization Roadmap" in 2013. In the context of the SmartFactory^{KL} plant, interoperability means that all CPS within the plant (workpiece carriers, assembly station, and products) are able to communicate with each other "through open nets and semantic descriptions" (SmartFactory^{KL}, 2014).

5.2 Virtualization

Virtualization means that CPS are able to monitor physical processes. These sensor data are linked to virtual plant models and simulation models. Thus, a virtual copy of the physical world is created. In the SmartFactory^{KL} plant the virtual model includes the condition of all CPS. In case of failure a human can be notified. In addition, all necessary information, like next working steps or safety arrangements, are provided (Gorecky, Schmitt & Loskyll, 2014, p. 535). Hereby, humans are supported in handling the rising technical complexity (SmartFactory^{KL}, 2014).

5.3 Decentralization

The rising demand for individual products makes it increasingly difficult to control systems centrally. Embedded computers enable CPS to make decisions on their own. Only in cases of failure tasks are delegated to a higher level (ten Hompel, Otto, 2014, p. 6). Nevertheless, for quality assurance and traceability it is necessary to keep track of the whole system at any time. In the context of the SmartFactory^{KL} plant decentralization means that the RFID tags "tell" machines which working steps are necessary. Therefore, central planning and controlling is no longer needed (Schlick et al., 2014, p. 75).

5.4 Real-Time Capability

For organizational tasks it is necessary that data is collected and analyzed in real time. In the SmartFactory^{KL} the status of the plant is permanently tracked and analyzed. Thus, the plant can react to the failure of a machine and reroute products to another machine (Schlick et al., 2014, p. 75).

5.5 Service Orientation

The services of companies, CPS, and humans are available over the IoS and can be utilized by other participants. They can be offered both internally and across company borders. The SmartFactory^{KL} plant is based on a service oriented architecture. All CPS offer their functionalities as an encapsulated web service (SmartFactory^{KL}, 2014). As a result, the product specific process operation can be composed based on the customer specific requirements provided by the RFID tag (Schlick et al., 2014, p. 75).

5.6 Modularity

Modular systems are able to flexibly adapt to changing requirements by replacing or expanding individual modules. Therefore, modular systems can be easily adjusted in case of seasonal fluctuations or changed product characteristics. In the SmartFactory^{KL} plant, new modules can be added using the Plug&Play principle. Based on standardized software and hardware interfaces (Schlick et al., 2014, p. 75), new modules are identified automatically and can be utilized immediately via the IoS (SmartFactory^{KL}, 2014).

6 Conclusions

The paper contributes to the ongoing discussion centering around Industrie 4.0 within both the scientific and the practitioners' community.

By providing a definition of Industrie 4.0, the paper creates a common understanding of the term, which is needed for a reasonable scientific discussion on the topic. The design principles derived from four basic Industrie 4.0 components support academics in identifying, describing, and selecting Industrie 4.0 scenarios in the context of further investigations.

The paper's practical contributions are twofold: First, the definition given for Industrie 4.0 helps clarify the basic understanding of the term "Industrie 4.0" among practitioners. Second, the six design principles can be used for implementing Industrie 4.0 scenarios in companies. They help identify potential use cases and offer guidance during implementation.

Limitations of the paper result from its scope and the research method applied. As the focus is on German and English publications only, relevant contributions in other languages might be left unnoticed. Furthermore, it is possible that during the initial identification of search terms an important Industrie 4.0 related topic might have been overlooked, leading to an incomplete list of keywords and, consequently, to an imperfect definition of Industrie 4.0.

Researchers and practitioners are welcome to test the accuracy and usefulness of the definition given. Regarding the six design principles identified, further research should challenge their utility by identifying, describing, and selecting Industrie 4.0 scenarios from an academic or practical perspective. Since Drath and Horch (2013) underline that "Industrie 4.0 is a phenomenon that will come inevitably, whether we want it or not" (p. 58), both academics and practitioners are invited to further enhance the paper's contribution in order to make the idea of Industrie 4.0 an integral part of future manufacturing and production processes.

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