Design Principles for Industrie 4.0 Scenarios

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Abstract

The increasing integration of the Internet of Everything into the industrial value chain has built the foundation for the next industrial revolution called Industrie 4.0. Although Industrie 4.0 is currently a top priority for many companies, research centers, and universities, a generally accepted understanding 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 quantitative text analysis and a qualitative literature review, the paper identifies design principles of Industrie 4.0. Taking into account these principles, academics may be enabled to further investigate on the topic, while practitioners may find assistance in identifying appropriate scenarios. A case study illustrates how the identified design principles support practitioners in identifying Industrie 4.0 scenarios.

1. Introduction

The convergence of industrial production and information and communication technologies, called Industrie 4.0, is currently one of the most frequently discussed topics among practitioners and academics in the German-speaking area [1]. Since the German federal government announced Industrie 4.0 as one of the key initiatives of its high-tech strategy in 2011 [2], numerous academic publications, practical articles, and conferences have focused on that topic [3].

The fascination for Industrie 4.0 is twofold. First, for the first time an industrial revolution is predicted a-priori, not observed ex-post [1]. 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 [2] [4] [5].

With Industrie 4.0 becoming a top priority for many research centers, universities, and companies, the manifold contributions from academics and practitioners have made the meaning of the term more blurry than concrete [3]. Even the key promoters of the idea, the "Industrie 4.0 Working Group" [2] and the "Plattform Industrie 4.0" [6], only describe the vision, the basic technologies the idea aims at, and selected scenarios, but do not provide a clear definition. As a result, a generally accepted understanding of Industrie 4.0 has not been published so far [7]. This impedes scientific research as any theoretical study requires a sound conceptual and terminological foundation.

"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 explains his struggles with the core idea. As the term itself is unclear, companies are facing difficulties when it comes to identifying and implementing Industrie 4.0 scenarios. Design principles explicitly address this issue by providing a "systemization of knowledge" and describing the constituents of a phenomenon [8]. Therefore, design principles support practitioners in developing appropriate solutions. From an academic perspective, design principles are the foundation of design theory [9]. 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.

This paper aims at closing this gap in research. Based on a quantitative text analysis and a qualitative literature review, the authors identify four design principles, which companies should take into account when implementing Industrie 4.0 solutions.

The paper is structured as follows: Chapter 2 introduces the idea, vision, goals, and components of Industrie 4.0, explains how it relates to the Internet of Things (IoT), the Internet of People (IoP), and the Internet of Everything (IoE), and what similar concepts can be found in the Anglo-Saxon world. Chapter 3 outlines the applied research process and the research method. Chapter 4 introduces design principles for identifying and implementing Industrie 4.0 scenarios. In Chapter 5, a case study illustrates how these principles support the identification and implementation of 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, and proposes paths for further investigation of the topic.

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2. Industrie 4.0

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 other 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 18th century and being intensified throughout the entire 19th 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. [1]

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 – supported the idea as an approach to strengthening the competitiveness of the German manufacturing industry [10]. Promoters of this idea expect Industrie 4.0 to deliver "fundamental improvements to the industrial processes involved in manufacturing, engineering, material usage and supply chain and life cycle management" [2].

Enabled through the communication between people, machines, and resources, the fourth industrial revolution is characterized by a paradigm shift from centrally controlled to decentralized production processes. Smart products know their production history, their current and target state, and actively steer themselves through the production process by instructing machines to perform the required manufacturing tasks and ordering conveyors for transportation to the next production stage. [11]

The German federal government supports 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 of the German economy. Research initiatives in this area are currently founded with 200 million euros from governmental bodies [1]. The "Industrie 4.0 Working Group" developed first recommendations for implementation, which were published in April 2013 [2]. In this publication, the authors name three key components of Industrie 4.0: the IoT, Cyber-Physical Systems (CPS), and Smart Factories. These components are introduced subsequently.

2.1. Components

The "Industrie 4.0 Working Group" considers the integration of the Internet of Things (IoT) into the manufacturing process as a key enabler for the fourth industrial revolution [2]. 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" [12].

In addition to the IoT, the fusion of the physical and the virtual world is a further important component of Industrie 4.0 [4]. This fusion is made possible by CPS, which 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." [13] 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 [14].

By integrating the ideas of the IoT and CPS in their operations, "smart factories constitute a key feature of Industrie 4.0" [2]. "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. […] 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. […]" [15].

Based on the given definitions, the Smart Factories of the fourth industrial revolution fill the idea of the IoE with life: By connecting people, things (such as machines and products), and data, new ways of organizing and conducting industrial processes emerge.

2.2. Related concepts

As the term "Industrie 4.0" is not well-known outside the German-speaking area [5], it is worth to look at comparable ideas in the Anglo-Saxon world. General Electric promotes a similar idea under the name "Industrial Internet" [16]. 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” [17]. As the Industrial Internet has a broader focus on many industries and application areas [1] [17], Industrie 4.0 and its emphasis on manufacturing and logistics processes can be understood as a subset of the Industrial Internet, which is expanded by a product life-cycle perspective [2]. The US government supports research activities in the area of the Industrial Internet with a 2 billion dollar fund for “Advanced Manufacturing” [18]. Further similar ideas can be found under the terms “Integrated Industry” [19], “Smart Industry”, or “Smart Manufacturing” [20] [21] [22].

3. Research process and research method

The research aimed at identifying central aspects of Industrie 4.0 and deriving design principles, which are accepted by both researchers and practitioners. The overall research design consisted of four steps: first, the identification of relevant literature, second, a quantitative text analysis, third, a qualitative literature review, and, fourth, a nominal group workshop.

As the number of publications on Industrie 4.0 has increased significantly [3], the automated approach of a quantitative text analysis was applied to extract key words and phrases from a larger amount of documents [23] [24]. However, an automated content analysis does not fully substitute reading the analyzed documents [23]. Consequently, the authors combined the quantitative text analysis with a qualitative approach [25] to benefit from the more inductive and exploratory character of qualitative research methods as well [26].

3.1. Identification of relevant literature

The authors of the paper took advantage of five publication databases (Scopus, EBSCOhost Business Source Complete, ECONIS, ScienceDirect, OAlster) to cover contributions in the fields of engineering, production, logistics, and management from both academia and business. These databases were searched for the terms “Industrie 4.0” and “Industry 4.0”. 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 identified publications were analyzed for their relevance to the topic by two researchers independently of each other, in order to ensure reliability of the review process [27] [28]. The publications regarded as relevant by both researchers were complemented by a backward and forward search [29]. This procedure led to a total of 130 publications in English or German with a clear reference to Industrie 4.0. 49 of these publications were published in academic journals or conference proceedings (thereof, 37 in English and 12 in German). The remaining 81 documents were found in practical journals or books (thereof, 52 in English and 29 in German).

3.2. Quantitative text analysis

For conducting the quantitative text analysis, the recommendations of Grimmer & Steward [23] and Jurafsky & Martin [30] were followed. In a first step, one list of words (unigrams) from the identified scientific publications and one list from all practical publications were generated.

As a second step, punctuation and capitalization were discarded and the vocabulary on the list was simplified through stemming. By removing the endings of the words, the total amount of unique words and, consequently, complexity of the data was reduced [30]. For example, the words *autonomic, autonomous, autonomously,* and *autonomy* were grouped together as *autonom*.

In a third step, very common words which occur frequently but are meaningless (stop words) – like *of*, *in* or *the* – were eliminated from the two lists [31]. For the remaining words and word stems, a frequency analysis was conducted by counting their number of occurrences.

As a fourth step, very uncommon words and word stems with only one or two occurrences were discarded following the recommendations of Grimmer & Steward [23]. Finally, this procedure led to a list of 1091 word stems for academic literature and 1212 word stems for the practical publications on Industrie 4.0. An excerpt of the resulting lists is provided in Table 1.

Table 1. The ten most frequent word stems in the identified publications on Industrie 4.0

Academic publications		Practical publications	
Word stem	Number of occurrences	Word (stem)	Number of occurrences
1. produc	1893	1. produc	2611
2. industr	1703	2. industry	2394
3. cyberphysi	1519	3. system	1196
4. system	1280	4. tech	1132
5. proc	1068	5. daten	963
6. tech	1065	6. automat	954
7. data	902	7. cyberphysi	934
8. control	850	8. info	828
9. info	819	9. maschin	606
10. time	711	10. prozess	575

In addition to unigrams, two- and three-word-phrases (bigrams and trigrams) [30] were extracted from the two publication groups as well. This ensured capturing phrases like s*mart factory* or c*yber physical systems*. Phrases with stop words were selectively removed from the bigram and trigram lists in a manual procedure. This approach ensured that meaningless phrases like *of things* or *internet of* were removed, but meaningful phrases like *internet of things* were kept in the lists. Table 2 presents the most frequent bigrams and trigrams.

Table 2. The ten most frequent bigrams and trigrams in the identified publications on Industrie 4.0

Academic publications		Practical publications	
Phrase	Number of occurrences	Phrase	Number of occurrences
1. industrie 4.0	484	1. industrie 4.0	1107
2. industry 4.0	277	2. industry 4.0	304
3. cyber physical systems	207	3. internet der dinge	96
4. production system	139	4. internet of things	96
5. industrial revolution	117	5. smart factory	89
6. internet of things	86	6. supply chain	85
7. manufactu-ring systems	83	7. cloud computing	69
8. visual computing	82	8. industrial revolution	62
9. production system	76	9. cyber physical systems	60
10. industrial automation	69	10. big data	58

3.3. Qualitative literature review

The identified words, word stems, and phrases were closer examined by two researchers through a qualitative context analysis. By looking at the sentences, in which the words occurred in the publications, the words' contextual meaning was grasped and could be considered in the following steps. For example, the context analysis led to the finding that the word stem *central* was used to describe the concept of central production control as opposed to decentralized decisions in the Smart Factories of Industrie 4.0. Based on these insights, the identified words and phrases were clustered into groups by the two researchers independently. The results were aggregated and discussed in order to eliminate discrepancies [27] [28].

Finally, nine clusters were identified, each representing a design element of Industrie 4.0. Table 3 illustrates the clusters resulting from the quantitative text analysis and the literature review.

Table 3. Identified Industrie 4.0 clusters and their three most frequent word stems

Cluster	Most frequent words stems in academic publications (number of occurrence)	Most frequent words stems in practical publications (number of occurrence)
I. Inter-connection	1. integr (522)	1. integr (479)
	2. communic (429)	2. kommuni (370)
	3. network (413)	3. platform (309)
	Total: 35 word stems with (2954 occurrences)	Total: 39 word stems with (3186 occurrences)
II. Collabo-ration	1. human (191)	1. mensch (438)
	2. collaborat (169)	2. mitarbeiter (270)
	3. train (128)	3. zusammen (134)
	Total: 19 (829)	Total: 20 (1437)
III. Standards	1. interface (278)	1. flexib (329)
	2. signal (246)	2. standard (307)
	3. dynami (203)	3. modul (184)
	Total: 21 (1697)	Total: 22 (2068)
IV. Security	1. secur (60)	1. sicher (478)
	2. sicher (38)	2. secur (160)
	3. safe (19)	3. safe (70)
	Total: 10 (152)	Total: 16 (895)
V. Data Analytics	1. data (902)	1. daten (963)
	2. control (850)	2. info (828)
	3. info (819)	3. data (332)
	Total: 65 (6220)	Total: 75 (5256)
VI. Information Provision	1. time (711)	1. verfüg (309)
	2. current (245)	2. qualit (204)
	3. delay (209)	3. schnell (168)
	Total: 31 (2632)	Total: 36 (2127)
VII. Decentralized Decisions	1. automat (482)	1. automat (954)
	2. intelligen (224)	2. intelligen (429)
	3. deci (192)	3. selb (259)
	Total: 27 (1631)	Total: 33 (2774)
VIII. Physical Assistance	1. support (303)	1. arbeit (221)
	2. help (68)	2. unterstütz (193)
	3. assist (50)	3. hilf (77)
	Total: 8 (508)	Total: 10 (684)
IX. Virtual Assistance	1. user (286)	1. mobil (253)
	2. enabl (209)	2. gerät (169)
	3. present (161)	3. user (83)
	Total: 23 (1142)	Total: 26 (1111)

3.4. Nominal group workshop

As the number of identified design elements was relatively high, and the elements are thematically overlapping, these elements do not qualify as design principles guiding practitioners and scientists on "how to do" Industrie 4.0 [9]. Therefore, the authors of this paper conducted a nominal group workshop with nine practitioners from various backgrounds (from logistics, engineering, production, information management, and supply chain management functions) and from different companies (three from two different chemical companies, two from an automotive manufacturer, two from automotive suppliers, one from an industrial machine manufacturer, and one from a consumer good producer).

The nominal group method was applied for this workshop because it is a very structured and efficient method for gaining consensual decisions in smaller groups [32] [33]. Following the recommendations of Van De Ven & Delbecq [33], the workshop participants received an information document introducing the basic idea of Industrie 4.0 – as in Chapters 1 and 2 of the paper – and presenting the results from quantitative text analysis and qualitative literature review. The participants were asked to group the nine elements on their own prior to the workshop. During the workshop, all participant present their solutions in the plenum. Afterwards, the expert group was asked by the researchers to agree on one solution. The workshop results were documented and sent to the participants for validation. This procedure resulted in four Industrie 4.0 design principles. These principles are depicted in Figure 1 and further detailed in the following chapter.

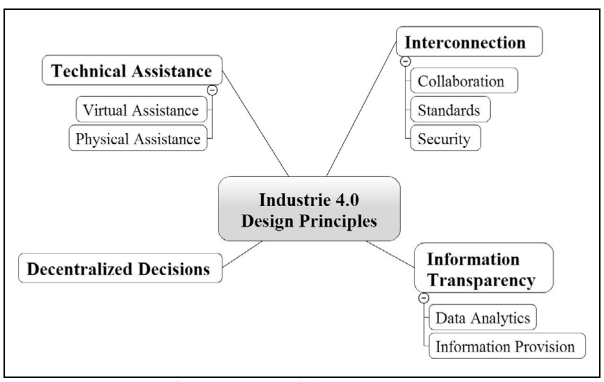

Figure 1. Industrie 4.0 design principles

4. Industrie 4.0 design principles

The quantitative text analysis and qualitative literature review identified four design principles guiding practitioners and scientists on "how to do" Industrie 4.0 [9]: interconnection, information transparency, decentralized decisions, and technical assistance. These principles are described in the following subchapters after a brief comparison of the word stems and, consequently, design principles used in the identified academic and practical publications on Industrie 4.0.

Overall, there are no contractionary results from the text analysis of the two different publication types as an analysis of each publication type on its own would have resulted in the same design principles. However, it strikes out that certain design elements are discussed more frequently in practical publications. In particular, human-machine collaboration, data and information security, and decentralized decisions are more often discussed in industry publications. The frequent discussion of the first two design elements highlights the biggest challenges for a successful implementation of Industrie 4.0 from a practitioner's perspective, while decentralized decision making as a key principle of Industrie 4.0 is understood as its most disruptive element and, therefore, explained on a very detailed and extensive level.

4.1. Interconnection

Machines, devices, sensors, and people are connected over the IoT [12] and IoP [34] and form the IoE [35]. Wireless communication technologies play a prominent role in the increasing interaction as they allow for ubiquitous internet access. Via the IoE, interconnected objects and people are able to share information, and this forms the basis of a joint collaboration for reaching common goals [12]. There are three types of collaboration within the IoE: human-human collaboration, human-machine collaboration, and machine-machine collaboration [36].

For connecting machines, devices, sensors, and people with each other, common communication standards are of great importance. Such standards enable the flexible combination of modular machines from different vendors [37]. This modularization enables the Smart Factories of Industrie 4.0 to flexibly adapt to fluctuating market demands or personalized (lotsize-1) orders.

As the number of participants in the IoE grows, monetary and political interests will lever the number of harmful attacks on Industrie 4.0 production facilities and, consequently, increase the need for cyber security [38].

4.2. Information transparency

Enabled by the increasing number of interconnected objects and people [5], the fusion of the physical and virtual world enables a new form of information transparency [11]. Through linking sensor data with digitalized plant models, a virtual copy of the physical world is created.

Context-aware information are indispensable for IoE participants to make appropriate decisions. Context-aware systems accomplish their tasks based on information coming from the virtual and physical world. Examples for information from the virtual world are electronic documents, drawings, and simulation models. Examples for physical world information are the position or conditions of a tool [15]. To analyze the physical world, raw sensor data must be aggregated to higher-value context information and interpreted. In order to create transparency, the data analytics' results need to be embedded in assistance systems that are accessible to all IoE participants [39]. For process-critical information, real-time information provision is of importance [14].

4.3. Decentralized decisions

Decentralized decisions are based on the interconnection of objects and people as well as transparency on information from inside and outside of a production facility. The combination of interconnected and decentralized decision-makers allows to utilize local with global information at the same time for better decision-making and increasing overall productivity [40]. The IoE participants perform their tasks as autonomous as possible. Only in case of exceptions, interferences, or conflicting goals, tasks are delegated to a higher level [41].

From a technical point of view, decentralized decisions are enabled by CPS. Their embedded computers, sensors, and actors allow for monitoring and controlling the physical world autonomously [13].

4.4. Technical assistance

In the Smart Factories of Industrie 4.0, the main role of humans shifts from an operator of machines towards a strategic decision-maker and a flexible problem solver. Due to the increasing complexity of production, where CPS form complex networks and make decentralized decisions, humans need to be supported by assistance systems. These systems need to aggregate and visualize information comprehensibly to ensure that humans can make informed decisions and solve urgent problems on short notice [39]. Currently, smartphones and tablets play a central role when it comes to connecting people with the IoT [42]. Wearables are predicted to become increasingly important in future as soon as current challenges such as their energy supply are overcome [43].

With further advances in robotics, the physical support of humans by robots is regarded as another aspect of technical assistance as robots are able to conduct a range of tasks that are unpleasant, too exhausting or unsafe for their human co-workers [44] [45]. For an effective, successful, and safe support of humans in physical tasks, it is necessary that robots interact smoothly and intuitively with their human counterparts [44] and that humans are properly trained for this kind of human-machine collaboration [46].

5. Case study

The following case study illustrates how to utilize the four derived design principles for identifying and evaluating Industrie 4.0 scenarios and, also, which additional methods are required.

In order to approach Industrie 4.0, a collaborative research project was initiated by a company from the chemical industry and the TU Dortmund University, Fraunhofer IML, and CDQ AG. It aimed at identifying Industrie 4.0 scenarios, which support the company's strategic objectives and are implementable as soon as possible to underline the company's reputation as an innovation leader in its industry. As depicted in Figure 2, the project roadmap was structured into five steps.

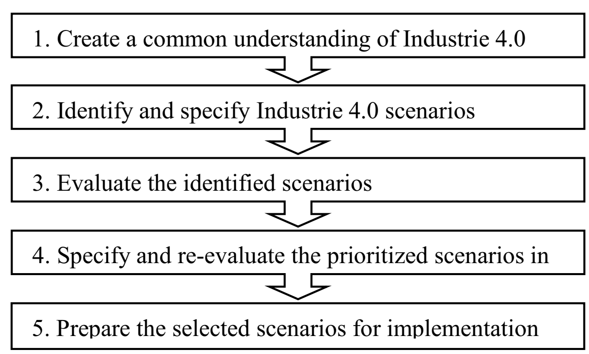

Figure 2. Project roadmap

5.1. Create a common understanding of Industrie 4.0

In the project's kickoff meeting, the Industrie 4.0 design principles were presented, illustrated with the help of exemplary scenarios – like the SmartFactory^{KL}, the Wittenstein's production facility in Fellbach, Germany [47] and Bosch's diesel injector manufacturing line in Homburg, Germany [48] –, and discussed with the project members. This created a common understanding among all involved parties. In all following project phases, the participants frequently referred to the design principles and exemplary scenarios introduced in this initial meeting when discussions arose whether a certain idea can be regarded as an Industrie 4.0 scenario.

5.2. Identify and specify Industrie 4.0 scenarios

In a next step, the project team compiled a collection of basic technologies of Industrie 4.0 which successfully enabled Industrie 4.0 scenarios at other companies. With the help of this compilation, the project members reviewed the company's production and logistics processes and analyzed their potential for improvements through Industrie 4.0 technologies. This approach led to 20 potential Industrie 4.0 scenarios ranging from autonomously flying drones as inventory assistants to intelligent containers that monitor their cargo. Each scenario was documented by describing its basic idea and the current challenges it addresses. Figure 3 illustrates this documentation.

Scenario: Assistance system for transport control
Scenario description: ▪ Autonomous distribution of transport orders via a multi-agent system ▪ Efficient use of resources through self-optimization ▪ Creation of transport orders via smartphone ▪ Autonomous guided vehicles and employees work site by site ▪ Modular system for easy extension
Current situation: ▪ Employees report transport requirements via phone ▪ Transports are centrally planned and manually assigned to a specific vehicle ▪ Only human-driven transportation vehicles

Figure 3. Scenario documentation

5.3. Evaluate the identified scenarios

In order to evaluate the potential scenarios, a decision model was developed according to the analytic hierarchy process (AHP) approach. This approach allows for assessing an alternative along qualitative target dimensions like "strategic fit" as well as quantitative dimensions such as return on investment [49]. The AHP breaks down a problem into items and sub-items and compares them pairwise to develop priorities [50]. The process consist of three major steps: 1. identification and selection of criteria, 2. determination of criteria weights, and 3. evaluation of the potential scenarios by using the weighted criteria [51].

The project's objectives describe the three main criteria categories: compliance with the basic idea of Industrie 4.0, contribution to the company's strategic objectives, and feasibility. For detailing out the main categories, all participant of the project specified the sub-criteria that are relevant to them. The proposed sub-criteria were discussed within the team leading to a list of fourteen items [52].

For the first category, the four design principles (interconnection, information transparency, decentralized decisions, technical assistance) were used as sub-criteria. The company's strategic goals were translated into five sub-criteria, which are not further detailed due to confidentiality reasons. Feasibility was broken down into another five sub-criteria according to the TELOS acronym. This acronym stands for technical, economic, legal, operational, and schedule feasibility and provides a first indication "for the project's likelihood for success, before committing large amounts of financial and human resources" [53]. In a next step, the identified sub-criteria's importance was determined using a pairwise comparison. Like suggested by Saaty [54], a scale from 1 to 9 was used to indicate how many times more important a criterion is over another criterion. 1 means "equal importance" and 9 "extreme importance". First, a pairwise comparison of the three main categories was conducted and, then, the criteria within a category were compared with each other. The project members conducted the pairwise comparison individually, discussed their results in the group, and jointly agreed on a final weighting. Afterwards, the weighting was normalized as described by Maede & Presley [49] resulting in a weighting score for each sub-criterion.

With the help of the developed decision model, the 20 potential Industrie 4.0 scenarios were evaluated. Again, a scale from 1 to 9 was used. 1 indicates "low compliance" and 9 "extreme compliance" of the scenarios with a sub-criterion. Again, the evaluation of the scenarios was conducted individually first, then, discussed and decided in the group. This procedure allowed for prioritizing the scenarios with the highest total score. As an example, Figure 4 depicts the evaluation of the scenario which received the highest score.

		Normalized weights	Assessment	Score
Industrie-4.0 compliance	Interconnection	0.082	8	0.656
	Information transparency	0.052	8	0.416
	Decentralized decisions	0.062	9	0.558
	Technical assistance	0.072	8	0.576
Contribution to strategic objective	Criterion 1	0.093	9	0.837
	Criterion 2	0.072	7	0.504
	Criterion 3	0.041	8	0.328
	Criterion 4	0.082	8	0.656
	Criterion 5	0.052	7	0.364
Feasibility	Technical feasibility	0.093	8	0.744
	Economic feasibility	0.072	8	0.576
	Legal feasibility	0.082	7	0.574
	Operational feasibility	0.072	7	0.504
	Schedule feasibility	0.072	8	0.576
				7.869

Figure 4. Scenario evaluation

5.4. Specify and re-evaluate the prioritized scenarios

The five scenarios with the highest score were detailed out. Based on interviews with company-internal and external experts, a detailed business case for each of the five scenarios was compiled, which included a risk estimation and cost-benefit analysis. As a result of this process, two scenarios were discarded.

5.5 Prepare the selected scenarios for implementation

In a final step, the three selected scenarios were prepared for their implementation by creating a specification book. This book included the following elements: detailed description of the current situation and the project's goals, interfaces to other systems, technical requirements, project schedule, and estimations for costs and benefits.

In order to illustrate the detailed descriptions from the specification book and to highlight the importance of the four Industrie 4.0 design principles, the scenario presented in Figure 3 is described in more detail in the following.

In the initial situation, human-driven transportation vehicles executed transportation orders in the company's production area. When goods were ready to be picked up, an employee reported this transport need via telephone to a central administration. The central administration disposed all transportation requests in a manual process and assigned the respective transportation orders to a specific vehicle.

The basic idea for improving this situation with the help of an Industrie 4.0 scenario is a multi-agent system with decentralized decisions. Multi-agent systems are computational systems in which autonomous agents cooperate to achieve common goals [55]. In this scenario, two kinds of transportation devices, human-driven and automated guided vehicles, receive information about new transportation orders and decide via a bidding system which vehicle is in charge of fulfilling the transportation order.

The most important requirement for this scenario is *interconnection*. While the automated guided vehicles can be interconnected via wireless communication technologies, human drivers need a user interface to communicate with the system. For this purpose, smartphones that withstand industrial requirements are eligible. The same devices can also be used to create transportation orders. The design of the system is modular and allows agents to be added on an ad hoc basis. After a login to the system, they can participate in the bidding process. This allows a flexible system where autonomous guided vehicles cover the base load, while the human-driven transportation vehicles are used to cover fluctuations.

As all vehicles and order issuers are interconnected and able to share their information, *information transparency* can be ensured across the entire transportation system. For example, the status of each transportation order and the position of each vehicle, human-driven or automated guided, can be determined in real-time. This allows for making strategic decisions on the necessity of additional transportation vehicles for the system.

As both types of vehicles are informed about their own status, capabilities, and order list, they are able to *decentrally decide* how capable they are of fulfilling open orders. Based on these information, the agents can make adequate offers for open orders. If their effort for fulfilling an order is high, they place a high-prized offer, and if their effort is low, they bid low. The vehicle with the lowest offer receives the nod.

Due to the bidding process, the multi-agent system is self-regulating and does not need to be controlled centrally. Hence, the planning effort is reduced and employees are *assisted* by autonomously distributed transportation orders. The human drivers of the transportation vehicles are provided with all needed information on their smartphone. This allows them to focus on their main work.

6. Conclusion

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

By providing design principles of Industrie 4.0, the paper creates a common understanding of the term, which is needed for a reasonable scientific discussion on the topic. Furthermore, these principles 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 design principles help to clarify the basic understanding of the term "Industrie 4.0" among practitioners. Second, these principles in combination with the case study help to identify potential use cases and offer guidance during implementation.

Limitations of the paper result from its scope and research method. As the focus is on German and English publications only, relevant contributions in other languages might be left unnoticed.

Researchers and practitioners are welcome to further test the accuracy and usefulness of the design principles. Since "Industrie 4.0 is a phenomenon that will come inevitably, whether we want it or not" [1], 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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