



Review

Industry 4.0: How it is defined from a sociotechnical perspective and how much sustainability it includes – A literature review



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ABSTRACT

Industry 4.0 has had a strong influence on the debate on the digitalization of industrial processes, despite being criticized for lacking a proper definition. However, Industry 4.0 might offer a huge chance to align the goals of a sustainable development with the ongoing digital transformation in industrial development. The main contribution of this paper is therefore twofold. We provide a de-facto definition of the concept “Industry 4.0” from a sociotechnical perspective based on its most often cited key features, as well as a thorough review of how far the concept of sustainability is incorporated in it.

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Contents

1. Introduction	2
2. Material and methods	2
2.1. Planning and preparation of the review	2
2.2. Data collection	3
2.3. Data analysis	3
3. Results	3
3.1. Category human	4
3.1.1. Employees	4
3.1.2. Communication	5
3.1.3. Human-machine interaction	5
3.1.4. Collaboration	5
3.2. Category technology	5
3.2.1. Automation	5
3.2.2. Big data	6
3.3. Category organization	6
3.3.1. Decentralization	6
3.3.2. Flexibility	6

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3.4.	Category-overarching features	6
3.4.1.	Interconnectedness	6
3.4.2.	Customization	7
3.4.3.	Efficiency	7
3.4.4.	Internet of Things	8
3.4.5.	Cyber-Physical Systems (CPS)	8
3.4.6.	Integration	8
3.4.7.	Autonomy	9
3.4.8.	Service-orientation	9
3.4.9.	Data management	9
3.5.	Consolidated definition of the established term industry 4.0	9
3.6.	Sustainability aspects in established understanding of industry 4.0	10
4.	Discussion	11
5.	Conclusions	12
	Funding	12
	Declaration of competing interest	12
	Acknowledgements	12
	Supplementary data	12
	References	12

1. Introduction

The concept Industry 4.0, which suggests to apply principles and technologies from the Internet of Things (IoT) on the manufacturing industry, was launched in 2011 by a council of the German Government that consisted of scientists and industry representatives. Due to this origin, the concept was not only characterized as a technological development, but was also intended to have a strong political connotation with the aim of supporting Germany's "position as a leader in the manufacturing engineering industry" (Kagermann et al., 2013). The concept was widely disseminated and has received great international attention. Consequently, there has been a rise in publications picking up the concept both in the academic community, as well as the private sector. However, the concept behind the term Industry 4.0 – which mixes political ambitions and technological developments – is often criticized for lacking a proper definition (Heng, 2015; Lasi et al., 2014; Oesterreich and Teuteberg, 2016).

The first research goal of this paper addresses this gap and seeks to provide a sociotechnical definition of the concept Industry 4.0 as it has been de-facto established by reviewing its description in the most widely recognized publications on the concept from 2013 to 2018.

The United Nations Environment Programme regards the transformation of industrial production as a "new economic paradigm – one in which material wealth is not delivered perforce at the expense of growing environmental risks, ecological scarcities and social disparities" (United Nations Environment Programme, 2011). Industry 4.0 might offer a huge chance to align the goals of a sustainable development with the ongoing digital transformation in industrial development, which in turn also carries the potential to turn into a threat if sustainability targets are not taken into account while implementing Industry 4.0.

The second research goal of this paper is therefore to investigate to what extent sustainability aspects are included in the currently established understanding of the concept Industry 4.0. We suggest that the concept as it is predominantly characterized is referring to sustainability aspects only in a very limited way. Since the definition of the concept is influencing the debate and agendas as well as its implementation (e.g. through funding schemes), this would leave little room for fostering more sustainable practices in the context of a digital industrial transformation. In the conclusion

section we therefore provide ideas on how sustainability aspects could gain more influence in Industry 4.0 through research and political activities.

The main contribution of this paper is twofold. Eight years after its first launch, we now provide a de-facto definition of the concept "Industry 4.0" from a sociotechnical perspective based on its most often cited key features, as well as a thorough review of how far the concept of sustainability is incorporated in this definition.

2. Material and methods

This literature review focusses on the established perception of the concept Industry 4.0 and how sustainability aspects are incorporated in it. The targeted audience are primarily scholars and to a lower extent also practitioners and policy makers.

2.1. Planning and preparation of the review

In order to prepare the qualitative literature review a classification scheme was developed, which was applied to categorize and structure the identified text fragments in the data analysis. The classification scheme consists of the three blocks: a) *system levels*, b) *effects and consequences* and c) *categories*.

The block *system levels* is divided into five subcategories (Table 1). The system level *product* refers to statements describing properties and characteristics of the product that will be developed, manufactured, used or exploited in an Industry 4.0 future. It explicitly considers the product in the creation process, as well as the state in which it leaves the factory. The system level *process* refers to the product development process. Statements captured in this level describe properties and characteristics of the processes through which an Industry 4.0 product is manufactured. The system level *enterprise* addresses resources, workflows and organizational structures of an economically independent unit that are not part of the product development process such as purchasing, logistics, controlling, accounting, IT or sales. The system level *value chain* includes resources, process and organizational structures and their interaction between several companies that cooperate within the framework of Industry 4.0 processes. It involves suppliers beyond the company's own boundaries. Finally, the system level *customer* is relevant for statements that describe effects of Industry 4.0 on end customers.

Table 1
Block „System levels“ in classification scheme.

System levels				
Product	Process	Enterprise	Value chain	Customer

The block *effects & consequences* is divided into five sub-categories (Table 2) all referring to (expected) phenomena resulting from the implementation of Industry 4.0: distinguishing *non-sustainability* related consequences, three sustainability related consequences (*social, environmental, economic*) and *evidence*. Statements that address only one of the sustainability dimensions will be marked accordingly, even though the authors are aware that some theories suggest that sustainability requires effects on all three dimensions. The subcategory *evidence* applies to those statements that plausibly substantiate the mentioned sustainability effects of Industry 4.0 (e.g. through empirical experiments, scientific studies or references to those).

The most relevant analytical block *categories* is divided into *human, technology* and *organization* (Table 3). The category *human* refers to effects of as well as on humans that are directly or indirectly affected by Industry 4.0. The category *technology* refers to effects of or on technical systems or technical concepts that are relevant in the context of Industry 4.0. The category *organization* refers to effects on both process and the structural organization of an enterprise.

Using this categorization scheme, a pre-test was conducted by analyzing four different Industry 4.0 related publications. In this process, the applicability for drawing an integrated definition and investigating sustainability aspects could be confirmed.

2.2. Data collection

In order to gain a holistic understanding of the concept Industry 4.0 and its characteristics as they are commonly perceived, the top cohort of currently prevalent literature on the topic was systematically examined. The keyword “Industry 4.0” was used for the according search query, which was conducted in December 2018. Only items published in the last six years (2013–2018) were considered. To ensure the analysis covers the perception of the concept not only in research but also in industry and politics the database *Google Scholar* was selected instead of purely scientific databases. The result of this search query was a list of publications that was ranked according to the main indicator: number of their respective citations. We defined the top cohort as this group of ranked publications where the successive entity needs to have more than 50% of the number of citations of its preceding entity. In order to ensure a certain level of scientific soundness, an equivalent search was performed in the genuinely scientific database *Web of Science*. The results match to 60%, which was

Table 2
Block “Effects & consequences” in classification scheme.

Effects & consequences				
Sustainability related			Non-sustainability related	Evidence
Social	Environmental	Economical		

Table 3
Block “Categories” in classification scheme.

Categories		
Human	Technology	Organization

considered sufficient by the authors.

Articles in anthologies were included as well as white papers from theory and practice for incorporating both scientific and non-scientific perspectives. However, considering the content, publications that fail to comply with basic scientific rules, such as reference handling, have been excluded from the analysis. Monographies have also been excluded, as they do not suit the qualitative research design. Thus, 40 journal articles, six conference papers, two research reports and three white papers from practice institutions represent the basis of this analysis (see Table 4 and Appendix I for the detailed list of included publications).

2.3. Data analysis

After all publications were read, 665 text fragments describing the respective understanding of the concept Industry 4.0 were extracted, evaluated and assigned to all parameters of the classification scheme. The most relevant words per text fragment were literally copied and stored as keywords for the respective text fragment. In a next step these keywords were used to achieve a weighting of phenomena, by clustering keywords with similar or related meaning into classes of keywords that we are calling key features in the course of this paper. This process was a joint effort of seven people with knowledge of the concept Industry 4.0 but with different disciplinary backgrounds. As an example the keyword “connected” was assigned to the key feature “interconnectedness”, keyword “integrate” to key feature “integration”, keyword “flexible” to key feature “flexibility”, keyword “adaptive” to key feature “adaptability”. An overview displaying the mapping of keywords to key features is provided in Appendix II.

3. Results

The following section describes the most relevant key features of Industry 4.0. Concretely, we present these ten key features which were mentioned in most publications for each of the categories *human, technology* or *organization*. If other key features receive the same “score” as the key feature in 10th place, these key features are also described in detail. Key features appearing within the Top 10 of more than one category (marked in italic in Table 5), are described in a category-overarching subsection.

Table 5 provides an overview of the key features of Industry 4.0 per category ranked by number of publications (P) describing this respective feature whilst also providing the total number of text

Table 4
Descriptive data of the data set.

Outlet	Number of publications
Journal article	40
Conference paper	6
Research report	2
Practitioner white paper	3

fragments (T) dealing with it.

Detailed descriptions of key features are based on pieces of information taken from the analyzed publications. All descriptions contain a descriptive part explaining what the term means, how it is understood in the context of Industry 4.0, which functionalities it is supposed to fulfill (if applicable) and to which system level it is primarily referring to. Analytically detailed descriptions explain preconditions for and consequences of the respective key feature and how relevant it is for the concept of Industry 4.0. All descriptions conclude with a paragraph in which the mentioned implications on sustainability are summarized.

3.1. Category human

157 text fragments were associated with the category human, most of them addressing the process (61%) and/or the enterprise (53%) system level. The most relevant key features for this category are displayed in Table 5 while those exclusively relevant for the category human are described in detail in the following subsection. Besides the key features that function as a container for key words of similar or related topics, it is also noteworthy to get an idea of which words were predominantly used in the text fragments associated to this category. Fig. 1 shows a tag cloud of its 50 most often used words (excluding stop words).

3.1.1. Employees

The key feature employees is used in different contexts which can be roughly summarized in two sub categories. These firstly concern implications of Industry 4.0 on employees regarding tools (Heng, 2015; Stock and Seliger, 2016) and organizational aspects (Stock and Seliger, 2016; Xu et al., 2018) of future work and secondly qualifications, job descriptions and competencies for employees in an Industry 4.0 context (Erol et al., 2016; Gabriel and Pessl, 2016; Stock and Seliger, 2016).

On a more general level text fragments deal with the role of humans in an Industry 4.0 environment. Usually, it is claimed that there is a decline in the significance of physical work compared

with mental work, for example: “people are more conductors and the coordinators of the factory. Hard muscular work and also a part of the mental work is done by machines” (Gabriel and Pessl, 2016). Other important factors are the decentralization of decision making and more autonomy for employees (Schumacher et al., 2016; Stock and Seliger, 2016). It is claimed that career paths will become more flexible as well as the work itself regarding “space, time and content” (Bauer et al., 2015).

Analyzing statements relating to qualifications and requirements of future work, ICT skills, openness, communication and cooperation are named explicitly as important skills (Gabriel and Pessl, 2016; Sanders et al., 2016; Xu et al., 2018). Working in Industry 4.0 will also “require workforces to continuously develop new knowledge and capabilities” (Bauer et al., 2015) to participate in engineering tasks (Stock and Seliger, 2016) and to create innovations and develop improvements (Erol et al., 2016). Text fragments dealing with employees in Industry 4.0 do primarily address the process or enterprise level.

The majority of the identified text fragments deals with the expected consequences for future work. These include mostly positive ones such as a better work-life balance through more flexible working conditions or better prospects for older workers (Gabriel and Pessl, 2016; Heng, 2015). Three publications also state potential negative consequences with regard to a decrease of jobs for underqualified workers (Heng, 2015; Sommer, 2015; Stock and Seliger, 2016) and “greater psychological stress (emotional and mental)” (Gabriel and Pessl, 2016). All mentioned consequences for

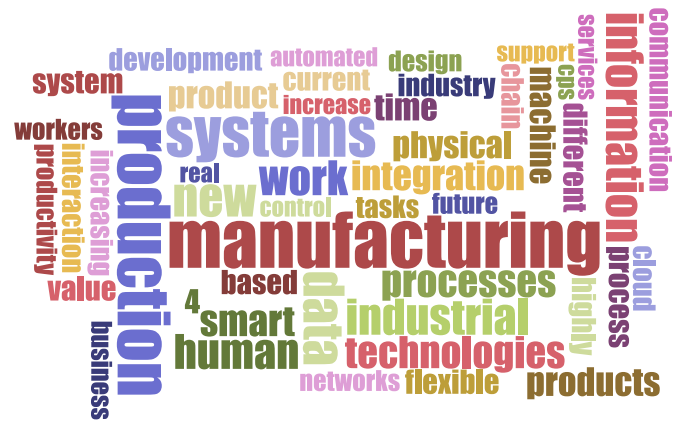


Fig. 1. Tag cloud of 50 most often used words within category human.

Table 5
Ranked key features of Industry 4.0 per category human, technology and organization.

Human			Technology			Organization		
Key feature	P	T	Key feature	P	T	Key feature	P	T
Interconnectedness	14	15	Cyber-Physical Systems	32	80	Interconnectedness	28	51
Customization	13	16	Interconnectedness	31	64	Autonomy	27	49
Employees	12	29	Autonomy	28	42	Integration	24	44
Communication	12	14	Internet of Things	27	69	Cyber-Physical Systems	24	49
Human-Machine Interaction	10	11	Integration	24	44	Service-orientation	22	38
Efficiency	9	11	Service-orientation	24	46	Efficiency	21	43
Internet of Things	9	12	Efficiency	24	44	Decentralization	21	27
Cyber-Physical Systems	9	14	Data management	21	38	Customization	19	32
Integration	8	10	Big Data	21	24	Flexibility	19	33
Autonomy	8	10	Customization	20	30	Data management	18	26
Collaboration	8	10	Automation	20	32	Internet of Things	18	36
Service-orientation	8	12	Cloud	18	41	Automation	17	26
Decentralization	7	7	Flexibility	17	23	Cloud	16	26
Virtualization	7	7	Communication	17	26	Real-time	16	28
Automation	7	10	Real-time	16	32	Communication	15	28

employees are important for grasping the *social* dimension of a sustainable development with regards to future working conditions.

3.1.2. Communication

Mainly two types of *communication* involving humans can be distinguished. In the first one communication is described in a technical sense in which humans are embedded in and surrounded by Industry 4.0 technologies that are expected to “enable and support the communication between humans, machines and products alike” (Monostori, 2014). The second type covers a more active type of human to human communication – e. g. supporting the “integration of customers” (Jazdi, 2014) which is described as one central consequence of Industry 4.0 (Li et al., 2017). One publication points out that it is not only the company establishing new types of customer communication, but also the customer who becomes more “demanding” in an Industry 4.0 scenario: “Under the Industry 4.0 concept, astounding growth in the advancement and adoption of information technology and social media networks has increasingly influenced consumers’ perception on product innovation, quality, variety and speed of delivery (Lee et al., 2014)”. To satisfy these demands “crowdsourcing can be used to incorporate end customers and suppliers in the product development” (Bauer et al., 2015).

Regarding the *social* dimension of sustainability, one publication suggests that exchanging ideas with customers could help to build more continuous and sustainable customer relations (Bauer et al., 2015). Indirect effects of *communication* such as the customization of products are expected to have consequences for the *environmental* dimension of sustainable development. Other references with regards to *communication* and sustainability are too unspecific to be evaluated.

3.1.3. Human-machine interaction

The key feature *Human-Machine Interaction* (HMI) assembles text fragments concerned with human-to-machine and machine-to-human communication, connections, collaboration and interfaces. According to the analyzed texts HMI is mostly seen as a prerequisite of Industry 4.0. The contexts in which the key feature is used are generally of a technical nature and HMI often appears as one in a list of many main features of Industry 4.0: “Industry 4.0 is [...] applying the principles of Cyber-Physical Systems (CPS), internet and future-oriented technologies and smart systems with enhanced human-machine interaction paradigms” (Sanders et al., 2016).

Examples for HMI given in the text fragments are “touch interfaces and augmented-reality systems” (Baur and Wee, 2015) as well as smart glasses, that “offer new possibilities to implement augmented reality” (Schuh et al., 2015) and “mobile devices such as tablets, which do not only make the presentation of information, but also data input more flexible” (Schuh et al., 2015). From the perspective of system levels HMI is most frequently associated with the *product*, *process* and *enterprise* level.

Two of the analyzed publications suggest consequences of HMI in the *social* dimension of sustainability. The first underlines the supportive character of new technical features for information and documentation: “documentation is easier in many cases, enabling efficient management of information in case of failures” (Schuh et al., 2015). The other points to the potential stressful effects of increasing HMI: “it leads to emotional stress, if communication and cooperation between employees is diminished by increasing interaction between humans and machines or if allocation of work no longer emanates from supervisor but from a technical system” (Gabriel and Pessl, 2016).

3.1.4. Collaboration

Manufacturing systems are expected to be collaborative systems of communicating physical agents, software agents and human agents (Xu et al., 2018). These manufacturing systems comprise of a service-oriented architecture “to provide collaborative, customizable, flexible, and reconfigurable services to end-users, thus enabling a highly integrated human machine manufacturing system” (Zhong et al., 2017). Horizontal integration through value networks is an enabler of *collaboration* between value chain partners across company borders such as customers, suppliers and other external partners (Liu and Xu, 2017; Oesterreich and Teuteberg, 2016). The use of Industry 4.0 technologies creates a suitable environment for enhanced collaboration and communication on all system levels, for instance, through the use of a centralized cloud-based collaboration environment in combination with Mobile Computing and Augmented Reality technologies (Oesterreich and Teuteberg, 2016).

Collaboration mainly addresses the *social* aspect of sustainability, either through sharing of services and resources, advances in HMI (Liao et al., 2016; Xu et al., 2018; Zhong et al., 2017) or direct collaboration with customers (Oesterreich and Teuteberg, 2016; Shrouf et al., 2014). *Environmental* and *economic* aspects of sustainability are discussed in the context of optimizing tightly integrated and interconnected value networks as these may allow for “the creation of dynamic, self-organized, cross organizational, real time [...] value networks” which then “can be optimized according to a range of criteria such as costs, availability and consumption of resources” (Liu and Xu, 2017).

3.2. Category technology

544 text fragments were associated with the category *technology*, most of them addressing the *process* (64%) and/or the *enterprise* (52%) level. The most relevant key features exclusively relevant for the category *technology* are described in detail in the following subsection. Fig. 2 shows a tag cloud of the 50 most often used words (excluding stop words) within the text fragments of this category.

3.2.1. Automation

Automation is mainly referring to the *process* level. The fundamental idea of Industry 4.0 lies in “boosting efficiency via sensible automation” (Heng, 2015). When specified, phrases refer to the automation of production, or also more specifically automated services (Lasi et al., 2014; Schlechtendahl et al., 2015), data

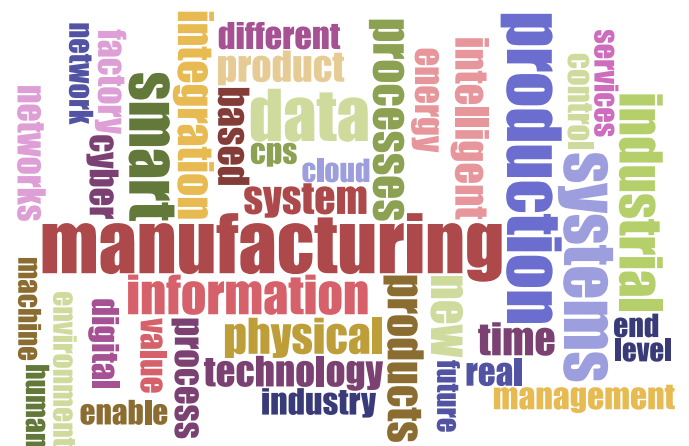


Fig. 2. Tag cloud of 50 most often used words within category technology.

exchange (Lu, 2017), communication (Shrouf et al., 2014), vehicles (Li et al., 2017), feedback to suppliers (Sanders et al., 2016) or employees (Schuh et al., 2015) or even “truly automated value chains” (Rüßmann et al., 2015). Several publications consider CPS (Li, 2018; Wollschlaeger et al., 2017) and IoT (Li, 2018; Wollschlaeger et al., 2017; Xu et al., 2018) as the technological drivers of increased automation.

None of the analyzed publications mentions environmental implications of increased automation. On the flipside, social implications are mentioned. Schuh et al. suggest the opportunity for “immediate automatic feedback for production workers” and “automatic pre-processing of collected production data” that “can be filtered, combined, aggregated and abstracted to facilitate cognitive acquisition and utilization by the employee” (Schuh et al., 2015). Li sees potential to relieve human operators through automation (Li, 2018), while Hofmann and Rüsç understand automation in Industry 4.0 as a means to enable logistics “without human interventions” (Hofmann and Rüsç, 2017).

3.2.2. Big data

Five publications consider Big Data a key technology or a foundation of Industry 4.0, almost exclusively referring to the system levels process and enterprise. Its main purpose is to help transform the huge amount of raw data (Almada-Lobo, 2016; Monostori, 2014) into useful information (Lee et al., 2014) in real-time (Vogel-Heuser and Hess, 2016) and thereby technically support automation (Jazdi, 2014). However, the vast majority of text fragments referring to Big Data either describe its role by combining it with or even just drop the term together with other technologies such as cloud (eleven publications) or CPS (six publications) – a pattern not noticed to that extent for any other key feature. A more detailed description of the actual function of Big Data in Industry 4.0 could not be found in any of the text fragments.

Only one text fragment dealing with Big Data is referring to sustainability in the broader sense, by stating it would contribute “to achieve high efficiency” (Wang et al., 2016).

3.3. Category organization

480 text fragments were associated with the category organization, most of them addressing the process (65%) and/or the enterprise (65%) system level. The most relevant key features exclusively relevant for this category are described in detail in the following subsection. Additionally, Fig. 3 shows a tag cloud of the 50 most often used words (excluding stop words) within the text fragments of the category organization.



Fig. 3. Tag cloud of 50 most often used words within category organization.

3.3.1. Decentralization

Decentralization in Industry 4.0 organizations refers to a shift away from centralized factory control systems to decentralized control (Shrouf et al., 2014) in form of self-organized entities (Lasi et al., 2014; Li, 2018). Thus, decentralization in organizations is not solely physical, but logical too (Almada-Lobo, 2016). Distributed entities will autonomously process information for taking decision using methods from the field of artificial intelligence (Stock and Seliger, 2016; Vogel-Heuser and Hess, 2016). In an organizational context decentralization is mainly referring to the enterprise and the process level. Prerequisites for the transformation to decentralized production processes (Sommer, 2015) are distributed systems with plug & play capabilities (Sanders et al., 2016), connected goods and materials (Almada-Lobo, 2016; Wollschlaeger et al., 2017), unique identifiers (Xu et al., 2018), a service-oriented architecture (Almada-Lobo, 2016; Gabriel and Pessl, 2016; Lu, 2017) and an increased adaptability (Sanders et al., 2016) of the involved systems. Autonomous production networks are seen as capable of controlling their operations efficiently in response to changes in the environment and follow strategic goals (Erol et al., 2016).

Text fragments dealing with decentralization do not refer to sustainability aspects with one exception which generally mentions “low-energy processes” to evolve next to the “distributed organization of production” (Wollschlaeger et al., 2017).

3.3.2. Flexibility

Flexibility is a key attribute of Industry 4.0 (Heng, 2015; Liao et al., 2016) mostly associated with the process and enterprise level. It refers to the capability to adapt to changing requirements by replacing or expanding individual modules (Vogel-Heuser and Hess, 2016) and is enabled by the application of Cyber-Physical Production Systems (CPPS) in value-creating networks (Shrouf et al., 2014). “Industry 4.0 allows a high flexibility both in the development, diagnostics and maintenance as well as in the operation of automated systems” (Jazdi, 2014), while potentially also improving the quality of services and products (Sommer, 2015). For that reason flexibility has become a relevant criterion for organizations when selecting suitable suppliers based on their factory needs (Shrouf et al., 2014). Preconditions for flexibility in organizations are interconnectedness (Heng, 2015), reconfigurable (Wang et al., 2016; Zhong et al., 2017) and modular systems (Vogel-Heuser and Hess, 2016; Weyer et al., 2015), as well as effective communication between producers and consumers (Li et al., 2017). This flexibility “enables business processes to be structured more dynamically” and to “react more flexibly to changes in demand or breakdowns in the value chain that occur at short notice” (Heng, 2015).

Shrouf et al. state that Industry 4.0 “will be highly flexible in production volume and customization, extensive integration between customers, companies, and suppliers, and above all sustainable” (Shrouf et al., 2014). Beyond that general relation, there are no concrete relations to aspects of sustainability.

3.4. Category-overarching features

The following subsections describe those key features that are relevant for more than one category (as marked in *italic* in Table 5).

3.4.1. Interconnectedness

One of the most often referenced key feature in all three categories is *interconnectedness* - a basic principle of Industry 4.0 (Schmidt et al., 2015). It is the basis for a “network of machines, workers, and systems” (Zhong et al., 2017) and enables the communication and information exchange between entities in an enterprise (Li et al., 2017; Liu and Xu, 2017), facilitating a

„networked and agile value chain” (Schumacher et al., 2016). A sociological metaphor for a production-related vision of Industry 4.0 is presented in (Lee et al., 2014): “machines are connected as a collaborative community”. The list of entities that could be connected is long and ranges from industries, supply chains, cooperating partners, production and logistics networks, services over machines, CPS, CPPS, products, devices, materials, servers and IT systems to employees and customers. Different classification schemes for these connections are suggested: “human-to-human, human-to-machine, and machine-to-machine” (Zhong et al., 2017), “people, objects and systems” (Hecklau et al., 2016), “manufacturing things, services, data and people” (Liu and Xu, 2017) or most generally “cyber space” and “physical world” (Lee et al., 2015). *Interconnectedness* also helps “to realize flexibility, adaptability, and efficiency and increase effective communication between producers and consumers” (Li et al., 2017). In the *human* category there is no clearly dominating system level associated to *interconnectedness*, while in the *technical* category it mainly refers to the *enterprise* and *process* level and in the *organizational* category the *process* as well as *customer* level prevail. CPS and IoT technologies such as wireless networks and RFID chips are named as the most common technological enablers.

Thames and Schaefer suggest software-defined networking as a “very cost-effective” option to achieve *interconnectedness* as an aspect for *economic* sustainability (Thames and Schaefer, 2016). Considering the *social* aspects of sustainability, Industry 4.0 fosters the connection between people within an enterprise (Hecklau et al., 2016) and with cooperating partners (Sanders et al., 2016). Although a number of publications suggest to also connect humans (e.g. staff and customers) as part of bigger networks only one publication emphasizes the need for “adequate systems to support workers” as a consequence of such interconnected and rapidly changing environments (Paelke, 2014). In (Hofmann and Rüsche, 2017), the future role of human workers in the value chain is fundamentally questioned by forecasting that “digital connectivity enables an automated and self-optimized production of goods and services including the delivering without human interventions”. Another text fragment addresses the potential of *interconnectedness* and integration “to plan for better business and societal outcomes” (Lu, 2017) but does not explain in detail what those societal outcomes could entail. No effects on *environmental* aspects could be found.

3.4.2. Customization

The *customization* of production, products and services is considered a fundamental paradigm shift (Gabriel and Pessl, 2016) of Industry 4.0. Industry 4.0 enables factories to better define customers’ behaviors and needs (Shrouf et al., 2014) and is supposed to realize “the manufacturing of individual products in a batch size of one while maintaining the economic conditions of mass production” (Lasi et al., 2014). This is referred to as mass customization, which allows individual preferences to be included in the design and enables last-minute changes (Heng, 2015; Shrouf et al., 2014). The IoT and Internet of Services (IoS) as well as advanced simulation-software for virtual prototyping are seen to be enabler of *customization* (Brettel et al., 2014; Sanders et al., 2016) under the conditions of highly flexible (large series) and modular production (Monostori, 2014; Weyer et al., 2015).

Customization is associated with a broad range of expectations, e.g. “to increase users participations, so that each user can experience the fun of creating products” (Zhou et al., 2015) or to enable “the customer not only to know the production information of the product but also to receive the advice of utilization depending on their own behaviours” (Qin et al., 2016). *Customization* is also influencing the production and product development process but

also services provided by other departments of the enterprise as well as the whole value chain (Liu and Xu, 2017). This is well reflected in our analysis where *customization* almost equally often refers to the *product*, *process* and *enterprise* level.

The main purpose of *customization* is often found in the *economic* dimension (Gabriel and Pessl, 2016; Oesterreich and Teuteberg, 2016). *Customization* is understood as “cost-effective adaptation of production to individual requirements” (Heng, 2015) and “resulting in a reduction of internal operating costs” (Oesterreich and Teuteberg, 2016), as well as supporting production “with higher quality, lower costs, and high productivity” (Liu and Xu, 2017). Many authors take up the narrative that individualized batch size one products can be produced cost-effectively or even under the conditions of mass production. According to (Gabriel and Pessl, 2016) this can become “a key success factor” especially for SMEs. *Environmental* sustainability is touched in only two text fragments: indirectly in (Rüßmann et al., 2015) where the technological opportunities of additive manufacturing are emphasized to enable batch size one products that also allows for lightweight designs, which in turn can lead to reduced material and energy consumption. In (Schmidt et al., 2015), the hypothesis is raised that customized products “may reduce the number of product returns”. *Customization* was not associated to any *social* aspects.

3.4.3. Efficiency

Efficiency is described as an important consequence in the Industry 4.0 context made possible by its enabling technologies: “Therefore, on-demand use and efficient sharing of resources can be enabled by the application of IoT technologies in manufacturing” (Zhong et al., 2017). Increased *efficiency* primarily refers to the production process and other value creation processes (Sommer, 2015) “mainly through consequent digital integration and intelligentization of manufacturing processes” (Schumacher et al., 2016). This is reflected in our analysis, where text fragments mainly relate to the *process* and *enterprise* level. More specifically, it shall be achieved through “efficient allocation of products, materials, energy and water by taking into account the dynamic constraints of the CPS, e.g. of the smart logistics, the smart grid, the self-sufficient supply or the customer” (Stock and Seliger, 2016). The idea of Industry 4.0 is based on rapid and efficient data transmission within the value chain (Heng, 2015) through which a higher level of operational efficiency (Thames and Schaefer, 2016) and productivity, as well as a higher level of automation (Lu, 2017) can be achieved.

A commonly identified narrative claims that Industry 4.0 will ensure factories become smart and adaptable, leading to an improvement in their resource efficiency and the overall integration of supply and demand processes (Li et al., 2017; Varghese and Tundur, 2014; Zawadzki and Żywicki, 2016). *Efficiency* is often used on an abstract level like in “boosting efficiency via sensible automation” (Heng, 2015) without defining what kind of efficiency is enabled through which means. Efficiency gains are accredited to the application of IoT technology or CPS (Xu et al., 2018; Zhong et al., 2017), the usage of mobile devices (Schuh et al., 2015) or to more efficient management practices (Schuh et al., 2015; Zhou et al., 2015). Lasi et al. regard sustainability and especially resource-efficiency as an increasingly important factor for the design of industrial manufacturing processes, taking them as “fundamental framework conditions for succeeding products” (Lasi et al., 2014). Efficiency-associated expectations for sustainable development are high, as can be illustrated by the following example: “Industry 4.0 needs to [...] present solutions to issues that need to be dealt with (such as the resource and energy efficiency, urban production, demographic change)” (Liu and Xu, 2017). However, no *social* implications are explicitly mentioned. *Economic*

implications are not explicitly stated either but are subsumed under the vague terms of improved efficiency and optimization of production. The often mentioned term resource efficiency presumably points towards *environmental* implications, occasionally specified as energy efficiency but only once as material efficiency. One of these efficiency claims is supported with empirical evidence (Xu et al., 2018), where a company achieved a reduction in energy consumption by 10% through the application of IoT technology.

3.4.4. Internet of Things

Seven publications claim that technical innovations in the framework of Industry 4.0 are mainly based on the *Internet of Things* (IoT) and Services and its technologies. IoT enables interconnectedness since “the industry-relevant items, for example, material, sensors, machines, products, supply chain, and customers, are able to be connected” (Qin et al., 2016). From the technological perspective, the descriptions addressing IoT can be summarized as a mix of methods and emerging internet technologies that facilitate the creation of a digitalized work environment using wireless sensor networks (WSN) based on as RFID, Near Field Communication (NFC) or Industrial Wireless Networks (IWN) or Mobile Communication Networks (MCN) such as 5G. The application of the IoT concept in an industrial context is sometimes referred to as Industrial Internet of Things (IIoT) also used synonymously for Industry 4.0: “The IIoT is a new revolution resulting from the convergence of industrial systems with advanced computing, sensors, and ubiquitous communication systems” (Thames and Schaefer, 2016). The IoT upgrades manufacturing technology enabling it to “sense, interconnect, and interact with each other to automatically and adaptively carry out manufacturing logics” (Zhong et al., 2017). In the category *human* IoT is mainly seen as an enabler for building new ways of interaction between machines and humans (Sanders et al., 2016; Xu et al., 2018; Zhong et al., 2017) allowing for „a highly integrated human machine manufacturing system“ (Zhong et al., 2017), while the role of humans or consequences for humans are not part of the description. The majority of text fragments relate to the *enterprise* (58%) or the *process* (46%) level, surprisingly few of them to the *value chain* (11%) level.

One publication describes IoT from a more sociotechnical point of view suggesting that in order “to promote work-based learning”, there is a necessity “to tap the full potential of Cyber-Physical Systems and the Internet of Things within socio-technical industrial production systems” (Schuh et al., 2015). In this sense the perspective on technological development is extended including social aspects and ideas about the role of humans in such IoT-enabled networks. This is important when assessing sustainability consequences in the *social* dimension regarding Industry 4.0. From an *economic* perspective IoT helps companies to “improve customer relationships, track tools, deliver products faster, and reduce costs [and to] create new business opportunities“ (Trappey et al., 2017). On the *environmental* side does the transparency through IoT allow “for optimization across factory sites in the area of production, and then improve factory efficiency“ including its energy efficiency (Shrouf et al., 2014).

3.4.5. Cyber-Physical Systems (CPS)

Cyber-Physical Systems (CPS) are regarded by nine publications as a core technological enabler of Industry 4.0. With their help machines are able to communicate with each other and decentralized control systems will be able to optimize efficiency of production (Xu et al., 2018). They are systems of collaborating computational entities that intensively connect the surrounding physical world and its on-going processes with the virtual world of information technology (Lasi et al., 2014; Schmidt et al., 2015; Sommer, 2015; Wang et al., 2016). These systems provide and use

data-accessing and data-processing services available on the Internet (Xu et al., 2018). CPS are “leveraging a wide range of embedded sensors and actuators, beyond connectivity and computing power. CPS know their state, their capacity and their different configuration options“ (Almada-Lobo, 2016). They can self-control certain tasks and interact with humans via interfaces (Brettel et al., 2014) but require a permanent exchange of data via virtual networks in real-time (Stock and Seliger, 2016). The services which CPS entities can provide allow for an orchestration of business processes related to quality, logistics, engineering and operations (Almada-Lobo, 2016). CPS enable manufacturing ecosystems driven by smart systems that have autonomic self-properties, for example self-configuration, self-monitoring, self-healing (Thames and Schaefer, 2016), self-organization and decentralization (Stock and Seliger, 2016). Key enabling technological elements integrated in CPS are intelligently linked “applied sensor systems for collecting data as well as actuator systems for influencing physical processes” (Stock and Seliger, 2016). According to our analysis, CPS mainly refer to the *process* and *enterprise* level and to a lesser extent also to the *value chain* and *product* level.

On the *economic* side of sustainability CPS-based manufacturing is supposed to open up new economic opportunities (Almada-Lobo, 2016; Bauer et al., 2015). On the *social* dimension CPS create “work environments with new opportunities to purposefully facilitate learning new tasks” (Schuh et al., 2015) and bring flexibility to the organization of work (Bauer et al., 2015; Xu et al., 2018). Additionally, CPS are supposed to allow for “communication between humans, machines and products” (Brettel et al., 2014) and may improve resource productivity and efficiency whilst enabling more flexible models of work organization (Thames and Schaefer, 2016; Xu et al., 2018). Their usage with intelligently networked objects in manufacturing enables a new quality of flexible working which constitutes tasks distributed in multiple dimensions of time, space and content (Bauer et al., 2015).

3.4.6. Integration

Industry 4.0 affects intra- as well as inter-organizational aspects (Xu et al., 2018) and is supposed to technically integrate CPS into production and logistics and to integrate the concept of the Internet of Things and Services into industrial processes (Heng, 2015). *Integration* is mainly referring to the *enterprise* and to a slightly lesser extent also to the *value chain* and the *process* level. Three types of *integration* are differentiated: horizontal integration, vertical integration and end-to-end integration (Qin et al., 2016). Their realization “requires change [s] in the enterprise architecture, ICT integration and processes“ (Xu et al., 2018).

Horizontal integration is understood as the linkage of “value creation modules throughout the value chain of a product life cycle and between value chains of adjoining product life cycles” (Stock and Seliger, 2016), while vertical integration describes the system integration at “different hierarchical levels (e.g. actuators and sensors on the shop floor, Manufacturing Execution Systems in production management and ERP-Systems on the corporate planning level)” (Gabriel and Pessl, 2016). Vertical integration enables the implementation of „a flexible and reconfigurable manufacturing system“ (Wang et al., 2016), which allows for a new level of organization and control over the whole value chain of the life-cycle of products (Li, 2018; Stock and Seliger, 2016). Furthermore, analytical and simulation-based approaches are integrated into the business processes of an enterprise (Monostori, 2014). End-to-end integration focuses on the integration of “digital industrial ecosystems” (Xu et al., 2018) and is supposed to work “across the supply chain from inbound logistics to production, marketing, outbound logistics and service” (Sanders et al., 2016). CPS and IoT technologies are considered major technological enablers for

integration purposes (Qin et al., 2016).

One main purpose of integration activities, which might also impact the aspects of sustainability, is to achieve end-to-end transparency, in order to eventually increase efficiency (Shrouf et al., 2014) and to enable efficient and quickly customizable products (Faller and Feldmüller, 2015). Another *environmental* improvement is the possibility to consider energy-related data management of production (Shrouf et al., 2014). One paper describes the vision of a comprehensive integration leading to a “highly integrated human machine manufacturing system”, which through the usage of AI could minimize the involvement of human beings in manufacturing (Zhong et al., 2017) as a *social* consequence.

3.4.7. Autonomy

For five publications the vision of the autonomously controlled factory includes the decomposition of the classic production hierarchy towards decentralized self-organization. Autonomous systems are capable of self-decision making, offering intelligent negotiation mechanisms (Wang et al., 2016). Small networked production networks are capable of efficiently controlling their operations and exchanging information in response to changes in the environment and strategic goals (Erol et al., 2016; Weyer et al., 2015). *Autonomy* is mostly discussed on the *product* and *process* level. In most cases with regards to the *human* category, *autonomy* refers to new forms of interaction between humans and machines based on the increased *autonomy* of the latter in Industry 4.0: as machines “are able to acquisition and process data, they can self-control certain tasks and interact with humans via interfaces” (Brettel et al., 2014). Only one statement from the *human* category takes a closer look at the role of humans in those self-organized networks: “The primary function of the worker will thus be to dictate a production strategy and supervise the implementation thereof by the self-organizing production processes” (Gorecky et al., 2014). A precondition for *autonomy* is a so-called “intelligence” of the respective entities or an underlying super system (Qin et al., 2016). The optimization of the value chain is assumed to be an outcome of higher autonomy in production (Kolberg and Zühlke, 2015). *Autonomy* and self-organization make the more complex structure in Industry 4.0 more manageable (Gorecky et al., 2014), for instance, self-organized logistics can react to unexpected changes (Shrouf et al., 2014).

From a sustainable development point of view, the role of the worker is of high relevance from a *social* perspective but is not really discussed in the text fragments or left to interpretation by the reader: “The digital connectivity enables an automated and self-optimized production of goods and services including the delivering without human interventions” (Hofmann and Rüscher, 2017). Another point of reference is the self-optimization of production networks “according to a range of criteria such as costs (Liu and Xu, 2017; Weyer et al., 2015), availability and consumption of resources” (Liu and Xu, 2017) which would benefit the *economic* dimension of sustainability and potentially but less explicitly also the *environmental* dimension.

3.4.8. Service-orientation

Industry 4.0 is expected to bring about a change from a predominantly product- to a greater *service-orientation* in the manufacturing industry (Heng, 2015; Lasi et al., 2014; Lu, 2017), where services are becoming an integral part of the production processes (Zhong et al., 2017). The Internet of Services is described as one very relevant feature of Industry 4.0 (Almada-Lobo, 2016). Text fragments dealing with *service-orientation* mainly refer to the *process*, *value chain* or *enterprise* level. They rarely relate to the *product* or *customer* level, even though the latter is an integral part

as service receiver. On the *product* level services are closely interlinked with customization as well as services to “predict product degradation” (Liu and Xu, 2017). On the *enterprise* level an increased value creation based on new services and resulting business models is expected (Hofmann and Rüscher, 2017; Lee et al., 2014; Lu, 2017). Emerging business models will be “data-driven services for production systems” (Rüßmann et al., 2015), “collaborative, customizable, flexible, and reconfigurable services to end-users” (Zhong et al., 2017) offered via the internet (Vogel-Heuser and Hess, 2016; Zhong et al., 2017). Examples for these services include on-demand manufacturing (Zhong et al., 2017) or more generally manufacturing-as-a-service (Xu et al., 2018). A Service-oriented-Architecture is understood to lead to organizational changes on the *process*, *enterprise*, *value chain* and *customer* level as it enables for example rapid orchestration and assembly of process services into larger, end-to-end processes (Xu et al., 2018; Zhong et al., 2017). Further enabling technologies for the emerging *service-orientation* are identification technologies, sensor networks (Xu et al., 2018), CPPS and CPS (Lee et al., 2014).

Few text fragments dealing with *service-orientation* address sustainability. Value creation based on new services and new business models could potentially benefit the *economic* dimension of sustainable development. The *service-orientation* is seen as providing “significant economic potential” (Lee et al., 2015). These manufacturing services may come with opportunities for more *environmental* sustainability, as they can potentially be shared or even circulated (Xu et al., 2018; Zhong et al., 2017).

3.4.9. Data management

In Industry 4.0 all processes related to data, information and knowledge will change (Zhou et al., 2015). Technologically Industry 4.0 “involves a new level of data integration and data processing” (Liu and Xu, 2017) for the manufacturing sector, which comes along with a “huge increase of variety, volume and velocity of data creation” (Schmidt et al., 2015). Therefore, data-intensity (Bauer et al., 2015) and data exploitation (Erol et al., 2016) are considered relevant attributes of Industry 4.0. With the help of “data science and analytical models” (Xu et al., 2018), “data mining and big data” (Qin et al., 2016) these high volumes of data from multiple integrated systems are analyzed to enable supported decisions by intelligent technologies (Qin et al., 2016). Due to the heterogeneous nature of raw data, data integration through standardization, data exchange formats and model-based interoperability are key challenges in Industry 4.0 (Vogel-Heuser and Hess, 2016) for enabling continuous data and information exchange between involved devices and parties (Shrouf et al., 2014). Consequently, IT security, data protection (Baur and Wee, 2015; Jazdi, 2014) and data validity (Li et al., 2017) are becoming increasingly important issues for the management of decentralized data.

On the *social* dimension (Paelke, 2014), raises the issue that workers must be supported in an environment characterized by high data volumes, while (Schuh et al., 2015) frames data-based automatic feedback and more easily interpretable data pre-processing and visualization as opportunities to support production workers in an Industry 4.0 environment. In (Zhou et al., 2015) privacy issues are seen as a potential social threat for employees. Surprisingly neither mention the role and integration of the customer in Industry 4.0 nor do the energy requirements to store and manage the enormous amounts of data play any role in the relevant text fragments dealing with the topic of *data management*.

3.5. Consolidated definition of the established term industry 4.0

According to the results from the presented analysis different characteristics can be summarized for the role of *humans*, future

manufacturing organizations and the envisioned technologies to implement Industry 4.0.

Humans in an Industry 4.0 setting are expected to do less physical but more mental work, increasingly communicate with partners across the value chain and react to customer preferences. They will be facing the challenge to collaborate with or manage more autonomous systems. Their tasks will be influenced by working in a more service-oriented organization. They will be interconnected with the manufacturing system through IoT technology and supported by HMI solutions. They will work in fully integrated environments that are optimized for maximum efficiency, while their tasks will be influenced by decentralized decision making.

On the technological side, highly efficient automated manufacturing systems will be interconnected building on the standards of the Industrial Internet of Things and a Service-oriented architecture, creating a so-called Industrial Internet of Things and Services. The informational intelligence of these manufacturing systems is based on CPS, IoT technology, Big Data approaches and an integrated but efficient management of relevant data. This combination is expected to allow manufacturing systems to become more autonomous and flexible, so that they can manufacture customized products with comparably little extra effort.

Organizations in Industry 4.0 need to make use of the above described technological opportunities to become decentralized and flexible, in order to being able to quickly adapt to frequently changing customer requirements. Preconditions for flexibility in organizations are interconnectedness, reconfigurable and modular systems, as well as effective communication between producers and consumers. Decentralized and more autonomous CPS are expected to permeate throughout organizations. Business processes of organizations need to be integrated and to allow for more service-orientation while still being very efficient.

3.6. Sustainability aspects in established understanding of industry 4.0

Our second research question investigates to what extent sustainability aspects have been reflected in the understanding of the concept Industry 4.0 as it is provided by the most cited publications on Industry 4.0. Amongst other criteria we focus on topics related to SDGs 8 (*decent work and economic growth*), 9 (*industry, innovation and infrastructure*) and 12 (*responsible consumption and production*).

Some text fragments highlight a positive influence on growth, productivity and work: "Industry 4.0 will allow us to achieve [...] accelerated growth in productivity" (Thames and Schaefer, 2016) is a typical example for the growth assumption while the work-related modification of job profiles and the workforce is assumed to change "the competitiveness of companies and regions" (Rüßmann et al., 2015). Although quite optimistic, both statements do not seem to be based on research results or calculations. None of the text fragments mention potential differences in countries of the Global South and North. Future working conditions are a part of the discussion about Industry 4.0 (see also category *human* and key feature *employee*). Some publications mention the threat of losing especially jobs with low skill profiles through automation (Sommer, 2015; Stock and Seliger, 2016), while others expect a positive influence on working conditions: Industry 4.0 "will free up more time for people to pursue their interests, which in turn enables more diverse and flexible career paths and will allow people to keep working and remain productive longer" (Xu et al., 2018). Additionally, new technological tools will be applied which have the potential of improving working conditions through "chronological and spatial flexibility" (Heng, 2015) while also "increasing the intrinsic motivation and fostering creativity by establishing

new CPS-based approaches of work organization and design" (Stock and Seliger, 2016). Efficiency is considered the most important topic with regard to the environmental dimension of sustainability. Industry 4.0 is expected "to present solutions to issues that need to be dealt with (such as the resource and energy efficiency, urban production, demographic change)" (Zhong et al., 2017). The technological development in the context of Industry 4.0 is believed to contribute to "a concept towards a holistic resource efficiency" (Stock and Seliger, 2016), "improve resource productivity and efficiency" (Xu et al., 2018) and give rise "to completely new innovations with added value and business models that support optimal resource utilization and smart control" (Jazdi, 2014).

Decentralization in the context of the category *human* is often part of a list of core principles without detailing what kind of decentralization is meant: "The principles of Industry 4.0 are interoperability, virtualization, decentralization, real-time capability, service orientation, and modularity" (Lu, 2017). It is also not clear who or what will be in charge of taking decisions in future production processes - machines or humans: "The decision itself will be taken by the workers or by the equipment using methods from the field of artificial intelligence" (Stock and Seliger, 2016). From a sustainability point of view the question of who will be responsible - human or machine - is a rather relevant one with potential consequences for the *social* but also the other dimensions. This question is touched upon but not answered in the analyzed text fragments.

Very few text fragments focus on inclusive and sustainable industrialization or production patterns. One publication found that Industry 4.0 "will bring benefits in four areas: productivity, revenue growth, employment, investment" (Rüßmann et al., 2015) – focusing exclusively on Germany though. Only (Gabriel and Pessl, 2016) addresses the special role of small and medium-sized enterprises in an Industry 4.0 future concluding it can be a "key success factor for (international) competitiveness", mainly due to the characteristics "lot size one, rapid response to customer, high quality and flexibility". The same publication also states "systems can be optimized continuously during production process in terms of resources and energy consumption or emission output" (Gabriel and Pessl, 2016) picking up the topic of CO₂ emissions and that "the most complex technical devices can be decomposed into its components at low cost and, subsequently, disposed or recycled" (Gabriel and Pessl, 2016) due to a future plus in product information.

The derived key features also show a great discrepancy with regard to how often they relate to the topic of sustainability - a parameter that is called "sustainability density" in Table 6. The two key features, where sustainability aspects seem to be an integral part (around three in four text fragments associated to this key feature deal with it) are *employees* (mainly *social* dimension) and *efficiency* (predominantly *economic*, half as often *environmental*). On the opposite side is the key feature *Big Data* where only one text fragment out of 24 is related to a sustainability issue. It is also apparent that the genuinely technical key features such as *Big Data*, *Internet of Things* and *Cyber-Physical Systems* dominate the lower third of the table.

From a sustainability point of view *economic* and *social* aspects are the dominating dimensions within the analyzed body of literature (see Table 7). Despite the large number of socially relevant text fragments referring to the *human* category, concrete implications for future work and job profiles are mainly imprecise and vague. The same finding applies to fragments referring to *efficiency*, where the majority of text fragments relates to *economic* issues promising either generally more *efficiency* or only concretizing the statement to more *efficiency* in production. For the categories *technology* and *organization* economic aspects are by far the most

Table 6
Sustainability density of key features.

Key feature	Nr. of text fragments (NTF)	NTF related to sustainability (NTF-Sus)	“sustainability density” (NTF-Sus/NTF)	NTF-Sus with (reference to) empirical evidence
Employees	37	29	78%	1
Efficiency	58	43	74%	2
Collaboration	16	6	38%	1
Automation	35	13	37%	0
Customization	40	14	35%	0
Human-Machine Interaction	11	3	27%	0
Flexibility	38	10	26%	0
Decentralization	28	6	21%	0
Service-orientation	54	9	17%	0
Data management	43	7	16%	0
Communication	37	6	16%	0
Integration	56	8	14%	0
Cyber-Physical Systems	80	11	14%	0
Internet of Things	69	8	12%	1
Autonomy	54	6	11%	0
Interconnectedness	70	6	9%	0
Big Data	24	1	4%	0

Table 7
Number of sustainability related text fragments per category and dimension.

	Overall text fragments	Text fragments with relation to ... dimension of sustainability			
		social	environmental	economic	any
Human	157	88	15	35	97
Technology	544	64	44	99	151
Organization	480	68	52	111	159
Overall	689	93	63	140	213

relevant sustainability topics. Many of these economic text fragments refer to the expectation that Industry 4.0 will provide for more (cost) efficiency in production (as described above) and open up opportunities for new business models and growth in general. *Environmental* aspects only play a minor role in all three categories; most significantly in the category *human*.

4. Discussion

This article defines the concept Industry 4.0 from a socio-technical perspective by providing an in-depth overview its key features. This is not only interesting from a descriptive point of view i.e. finding a definition of the ill-defined term Industry 4.0 (see the research gap stated in section 1), but also from an analytical point of view. How Industry 4.0 is perceived, defined and discussed is influencing the actual process of its development and implementation.

A first result is the vagueness of the term that still remains after our analysis. Although based on an extensive literature review the essential key features of Industry 4.0 were challenging to identify. Following this observation Industry 4.0 does not seem to be a sharply defined, homogeneous development rather a collective term of different developments. One reason for this might be the also politically rather than purely scientifically motivated origin of the concept. Adding to this complexity is the fact, that the majority of key features is associated with more than one category and system level (Appendix III provides an overview of all key features and how intensely each of them relates to the five *system levels* and *effects & consequences*). The huge overlap of key features between all categories underline that Industry 4.0 is a sociotechnical development that can and should not be reduced to technical aspects (see also (Davies et al., 2017)).

The second related result concerns the lack of conformity

regarding positive outcomes of Industry 4.0. The transformation of industrial production is one of the biggest challenges for a sustainable development. However, it is not clear to what extent Industry 4.0 will contribute to this development. Sustainability aspects such as “decent job creation” and resource efficiency are mentioned but not explained or derived from research. Besides the threat for “unqualified workers” none of the analyzed text fragments takes on a differentiated view on future working conditions by, for instance, discussing the chances of women, younger workers or people with disabilities to be equally employed in an Industry 4.0 future. Many text fragments claim improved resource efficiency as a consequence of Industry 4.0. It is not made clear though under which circumstances those efficiency gains are to be expected. A detailed contribution of Industry 4.0 to a decoupling of growth and resource consumption is also missing (see (Hickel and Kallis, 2019) for a more general critique on that matter). A single publication mentions improvements with regard to decomposing and recycling, without providing any scientific reference. The fact that in order to enable Industry 4.0, all entities participating in a digitized and interconnected production need to be equipped with ICT in the first place is also not considered (see also (Fritzsche et al., 2018)).

Hardly any of the text fragments that postulate effects of key features on sustainability aspects provide any kind of evidence or a reference to such evidence. In total only 17 out of 684 text fragments describing the concept Industry 4.0 provide such evidence (see right column of Table 6), which underlines the often more conceptual or subjective nature of the descriptions. In summary the analysis of sustainability aspects suggests that Industry 4.0 is associated with a number of desired outcomes, but hardly any of these mentioned positive sustainability aspects are a necessary result of digitalization. In other words only very few of the articles establish a scientific link between Industry 4.0 and sustainability aspects although often authors’ presentations are suggesting

otherwise. Sustainability aspects can therefore not be considered an integral part of the Industry 4.0 concept, but are rather treated as “add-on features”. As a consequence sustainability aspects are not researched comprehensively and possible potentials are not identified.

A contribution to a sustainable development of industry can only be expected when the transformation includes clear intentions from the very beginning. The leading question should not be how much positive influence Industry 4.0 will have on sustainable development but how sustainable digitalization of industry could look like. A sustainable industrialization as envisioned by the sustainable development goals will need a more transformative approach of integrating sustainability. The mere adding of potential positive aspects might be more of a hindrance in this regard than a support. Another major flaw with regard to a sustainable development is the lack of global consideration. Not a single text fragment within the scope of our analysis addressed potential social, environmental or economic implications of Industry 4.0 for the Global South. Hence Industry 4.0 sustains a rather traditional view on world economics and industrialization.

Industry 4.0 is often referred to as a disruption in industrial production. However, based on the analyzed publications it must be stated that the goals of Industry 4.0 follow traditional pathways. Modern digital technologies are incorporated into traditional production environments. CPS-enhanced machines are getting interconnected and equipped with so-called smart devices. This vision stands more for a digital update of the established patterns of industrial production rather than a disruptive concept with a transformative potential. This is especially harmful when it comes to integrating sustainability aspects in industrial processes. Industry 4.0 as it is described in the analyzed literature seems to sustain the path dependencies of the “traditional” instead of initiating a sustainable industrialization.

Further research on Industry 4.0 could also benefit from a more interdisciplinary perspective. Most descriptions are techno-centric, naming lots of modern technological approaches. What is missing in the analyzed body of literature are complex scenarios and in-depth analyses of what these developments might imply for employees or the environment. Especially when considering that humans still remain at the center of the dynamics between data and knowledge in Industry 4.0 (Kagermann et al., 2013; Dragičević et al., 2019) and constitute the decisive factor for operationalizing sustainable development with the aid of information and communication technologies (Seele and Lock, 2017).

5. Conclusions

This paper closes a research gap identified by many publications in the past, systematically deriving and describing the constituting key features of the concept Industry 4.0 through a qualitative literature review. In addition to identifying a scientifically sound definition of the commonly established understanding of the concept Industry 4.0, this paper also contributes an analysis of how far its key features reflect sustainability aspects.

The validity of the analysis is limited by a number of factors. The understanding of the term is solely based on literature on Industry 4.0, derived from only one database and one search string. The incorporation of the search results from other databases, a bigger number of publications or related concepts such as Industrial Internet of Things or Advanced Manufacturing may enrich the understanding of the concept and might lead to a better representation of sustainability. Furthermore, changing the perspective by an investigation of sustainability-focusing journals may shed more light on the incorporation of this concept in contemporary developments in sustainable manufacturing and how sustainability

is represented in current manufacturing approaches. Additionally, the concept of sustainability and its representation in Industry 4.0 can be considered in more depth regarding intersections between the three dimensions covering the *social*, *environmental* and *economic* aspects for more specific insights.

Industry 4.0 is not a single technology, but a sociotechnical concept in which technological, social and organizational aspects interact. Effects of individual aspects do not necessarily allow conclusions to be drawn about the overall impacts on the sustainability of the entire concept. Therefore, systemic studies that cover for example an entire value chain situated in broad system boundaries are necessary to be able to reliably estimate the actual sustainability implications of the concept Industry 4.0. More importantly, future research should consider the questions of how the concept of Industry 4.0 and its concrete implementation can contribute (1) to the realization of the United Nations sustainability development goals and (2) to sustainability aspects beyond efficiency and productivity. In summary, research in the context of Industry 4.0 has, thus far, failed to prove its benefits for a more sustainable production and, therefore, societal development. Our findings should encourage researchers working on Industry 4.0 to demonstrate specific *economic*, *environmental*, and *societal* benefits and generally provide evidence regarding the effects of the concept's implementation for sustainable development in different contexts. As reasoned in section 4, these questions should necessarily be studied from an interdisciplinary perspective.

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Appendix A. Supplementary data

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References

- Almada-Lobo, F., 2016. The industry 4.0 revolution and the future of manufacturing execution systems (MES). *JIM* 3, 16. https://doi.org/10.24840/2183-0606_003.004_0003.
- Bauer, W., Hämmerle, M., Schlund, S., Vocke, C., 2015. Transforming to a hyper-connected society and economy – towards an “industry 4.0”. *Procedia Manuf.* 3, 417–424. <https://doi.org/10.1016/j.promfg.2015.07.200>.
- Baur, C., Wee, D., 2015. Industry 4.0 Is More than Just a Flashy Catchphrase. *A Confluence of Trends and Technologies Promises to Reshape the Way Things Are Made*. McKinsey.
- Brettel, M., Friederichsen, N., Keller, M., Rosenberg, M., 2014. How virtualization, decentralization, and network-building change the manufacturing landscape: an industry 4.0 perspective. *International Journal of mechanical, aerospace, industrial and mechatronics engineering*. <https://doi.org/10.5281/ZENODO.2658202>.
- Davies, R., Coole, T., Smith, Alistair, 2017. Review of socio-technical considerations to ensure successful implementation of Industry 4.0. *Procedia Manuf.* 11, 1288–1295.

- Dragičević, N., Ullrich, A., Tsui, E., Gronau, N., 2019. A Conceptual Model of Knowledge Dynamics in the Industry 4.0 Smart Grid Scenario. *Knowledge Management Research & Practice*. <https://doi.org/10.1080/14778238.2019.1633893>.
- Erol, S., Jäger, A., Hold, P., Ott, K., Sihm, W., 2016. Tangible industry 4.0: a scenario-based approach to learning for the future of production. *Procedia CIRP* 54, 13–18. <https://doi.org/10.1016/j.procir.2016.03.162>.
- Faller, C., Feldmüller, D., 2015. Industry 4.0 learning factory for regional SMEs. *Procedia CIRP* 32, 88–91. <https://doi.org/10.1016/j.procir.2015.02.117>.
- Fritzsche, K., Niehoff, S., Beier, G., 2018. Industry 4.0 and climate change—exploring the science-policy gap. *Sustainability* 10, 4511. <https://doi.org/10.3390/su10124511>.
- Gabriel, M., Pessl, E., 2016. Industry 4.0 and sustainability impacts: critical discussion of sustainability aspects with a special focus on future of work and ecological consequences. *Ann. Fac. Eng. Hunedoara* 14, 131.
- Gorecky, D., Schmitt, M., Loskyll, M., Zühlke, D., 2014. Human-machine-interaction in the industry 4.0 era. In: 2014 12th IEEE International Conference on Industrial Informatics (INDIN). 2014 12th IEEE International Conference on Industrial Informatics (INDIN), Porto Alegre RS. IEEE, Brazil, pp. 289–294, 27.07.2014 - 30.07.2014.
- Hecklau, F., Galeitzke, M., Flachs, S., Kohl, H., 2016. Holistic approach for human resource management in industry 4.0. *Procedia CIRP* 54, 1–6. <https://doi.org/10.1016/j.procir.2016.05.102>.
- Heng, S., 2015. Industry 4.0: Upgrading of Germany's Industrial Capabilities on the Horizon. Deutsche Bank Research Report. Baden-Wuerttemberg Cooperative State University.
- Hickel, J., Kallis, G., 2019. Is green growth possible? *New Polit. Econ.* 4, 1–18. <https://doi.org/10.1080/13563467.2019.1598964>.
- Hofmann, E., Rüsche, M., 2017. Industry 4.0 and the current status as well as future prospects on logistics. *Comput. Ind.* 89, 23–34. <https://doi.org/10.1016/j.compind.2017.04.002>.
- Jazdi, N., 2014. Cyber physical systems in the context of Industry 4.0. In: 2014 IEEE International Conference on Automation, Quality and Testing, Robotics. 2014 IEEE International Conference on Automation, Quality and Testing, Robotics (AQTR). IEEE, Cluj-Napoca, Romania, pp. 1–4, 22.05.2014 - 24.05.2014.
- Kagermann, H., Wahlster, W., Helbig, J., 2013. Umsetzungsempfehlungen für das Zukunftsprojekt Industrie 4.0: abschlussbericht des Arbeitskreises Industrie 4.0. Forschungsunion Wirtschaft – wissenschaft; Deutsche Akademie der Technikwissenschaften. http://www.bmbf.de/pubRD/Umsetzungsempfehlungen_Industrie4_0.pdf. (Accessed 13 July 2015).
- Kolberg, D., Zühlke, D., 2015. Lean automation enabled by industry 4.0 technologies. *IFAC-PapersOnLine* 48, 1870–1875. <https://doi.org/10.1016/j.ifacol.2015.06.359>.
- Lasi, H., Fetteke, P., Kemper, H.-G., Feld, T., Hoffmann, M., 2014. Industry 4.0. *Bus Inf Syst Eng* 6, 239–242. <https://doi.org/10.1007/s12599-014-0334-4>.
- Lee, J., Bagheri, B., Kao, H.-A., 2015. A Cyber-Physical Systems architecture for Industry 4.0-based manufacturing systems. *Manuf. Letts.* 3, 18–23. <https://doi.org/10.1016/j.mfglet.2014.12.001>.
- Lee, J., Kao, H.-A., Yang, S., 2014. Service innovation and smart analytics for industry 4.0 and big data environment. *Procedia CIRP* 16, 3–8. <https://doi.org/10.1016/j.procir.2014.02.001>.
- Li, L., 2018. China's manufacturing locus in 2025: with a comparison of "Made-in-China 2025" and "Industry 4.0". *Technol. Forecast. Soc. Change* 135, 66–74. <https://doi.org/10.1016/j.techfore.2017.05.028>.
- Li, X., Li, Di, Wan, J., Vasilakos, A.V., Lai, C.-F., Wang, S., 2017. A review of industrial wireless networks in the context of Industry 4.0. *Wireless Network* 23, 23–41. <https://doi.org/10.1007/s11276-015-1133-7>.
- Liao, Y., Deschamps, F., Loures, E.d.F.R., Ramos, L.F.P., 2016. Past, present and future of Industry 4.0 - a systematic literature review and research agenda proposal. *Int. J. Prod. Res.* 55, 3609–3629. <https://doi.org/10.1080/00207543.2017.1308576>.
- Liu, Y., Xu, X., 2017. Industry 4.0 and cloud manufacturing: a comparative analysis. *J. Manuf. Sci. Eng.* 139, 34701. <https://doi.org/10.1115/1.4034667>.
- Lu, Y., 2017. Industry 4.0: a survey on technologies, applications and open research issues. *J. Ind. Info. Integrat.* 6, 1–10. <https://doi.org/10.1016/j.jii.2017.04.005>.
- Monostori, L., 2014. Cyber-physical production systems: roots, expectations and R&D challenges. *Procedia CIRP* 17, 9–13. <https://doi.org/10.1016/j.procir.2014.03.115>.
- Oesterreich, T.D., Teuteberg, F., 2016. Understanding the implications of digitisation and automation in the context of Industry 4.0: a triangulation approach and elements of a research agenda for the construction industry. *Comput. Ind.* 83, 121–139. <https://doi.org/10.1016/j.compind.2016.09.006>.
- Paelke, V., 2014. Augmented reality in the smart factory: supporting workers in an industry 4.0 environment. In: Proceedings of the 2014 IEEE Emerging Technology and Factory Automation (ETFA). 2014 IEEE Emerging Technology and Factory Automation (ETFA). IEEE, Barcelona, Spain, pp. 1–4, 16.09.2014 - 19.09.2014.
- Qin, J., Liu, Y., Grosvenor, R., 2016. A categorical framework of manufacturing for industry 4.0 and beyond. *Procedia CIRP* 52, 173–178. <https://doi.org/10.1016/j.procir.2016.08.005>.
- Rüßmann, M., Lorenz, M., Gerbert, P., Waldner, M., Justus, J., Engel, P., Harnisch, M., 2015. Industry 4.0: the Future of Productivity and Growth in Manufacturing Industries. Boston Consulting Group.
- Sanders, A., Elangswaran, C., Wulfsberg, J., 2016. Industry 4.0 implies lean manufacturing: research activities in industry 4.0 function as enablers for lean manufacturing. *JIEM* 9, 811. <https://doi.org/10.3926/jiem.1940>.
- Schlechtendahl, J., Keinert, M., Kretschmer, F., Lechler, A., Verl, A., 2015. Making existing production systems Industry 4.0-ready. *Prod. Eng. Res. Dev.* 9, 143–148. <https://doi.org/10.1007/s11740-014-0586-3>.
- Schmidt, R., Möhring, M., Härting, R.-C., Reichstein, C., Neumaier, P., Jozinović, P., 2015. Industry 4.0 - potentials for creating smart products: empirical research results. In: Abramowicz, W. (Ed.), *Business Information Systems. 18th International Conference, BIS 2015, Poznań, Poland, June 24-26, 2015, Proceedings*. Springer International Publishing, Cham, s.l., pp. 16–27.
- Schuh, G., Gartzert, T., Rodenhauer, T., Marks, A., 2015. Promoting work-based learning through INDUSTRY 4.0. *Procedia CIRP* 32, 82–87. <https://doi.org/10.1016/j.procir.2015.02.213>.
- Schumacher, A., Erol, S., Sihm, W., 2016. A maturity model for assessing industry 4.0 readiness and maturity of manufacturing enterprises. *Procedia CIRP* 52, 161–166. <https://doi.org/10.1016/j.procir.2016.07.040>.
- Seele, P., Lock, I., 2017. The game-changing potential of digitalization for sustainability: possibilities, perils, and pathways. *Sustain. Sci.* 12, 183–185. <https://doi.org/10.1007/s11625-017-0426-4>.
- Shrouf, F., Ordieres, J., Miragliotta, G., 2014. Smart factories in Industry 4.0: a review of the concept and of energy management approached in production based on the Internet of Things paradigm. In: Proc. Of the 2014 IEEE International Conference on Industrial Engineering and Engineering Management, Selangor Darul Ehsan. IEEE, Malaysia, pp. 697–701.
- Sommer, L., 2015. Industrial revolution - industry 4.0: are German manufacturing SMEs the first victims of this revolution? *JIEM* 8. <https://doi.org/10.3926/jiem.1470>.
- Stock, T., Seliger, G., 2016. Opportunities of sustainable manufacturing in industry 4.0. *Procedia CIRP* 40, 536–541. <https://doi.org/10.1016/j.procir.2016.01.129>.
- Thames, L., Schaefer, D., 2016. Software-defined cloud manufacturing for industry 4.0. *Procedia CIRP* 52, 12–17. <https://doi.org/10.1016/j.procir.2016.07.041>.
- Trappey, A.J., Trappey, C.V., Hareesh Govindarajan, U., Chuang, A.C., Sun, J.J., 2017. A review of essential standards and patent landscapes for the Internet of Things: a key enabler for Industry 4.0. *Adv. Eng. Inf.* 33, 208–229. <https://doi.org/10.1016/j.aei.2016.11.007>.
- United Nations Environment Programme, 2011. Towards a Green Economy: Pathways to Sustainable Development and Poverty Eradication, Nairobi Kenya, p. 630. (Accessed 16 November 2017).
- Varghese, A., Tandur, D., 2014. Wireless requirements and challenges in Industry 4.0. In: 2014 International Conference on Contemporary Computing and Informatics (IC3I). IEEE, Mysore, India, pp. 634–638, 2014 International Conference on Contemporary Computing and Informatics (IC3I), 27.11.2014 - 29.11.2014.
- Vogel-Heuser, B., Hess, D., 2016. Guest editorial industry 4.0—prerequisites and visions. *IEEE Trans. Autom. Sci. Eng.* 13, 411–413. <https://doi.org/10.1109/TASE.2016.2523639>.
- Wang, S., Wan, J., Zhang, D., Li, Di, Zhang, C., 2016. Towards smart factory for industry 4.0: a self-organized multi-agent system with big data based feedback and coordination. *Comput. Network.* 101, 158–168. <https://doi.org/10.1016/j.comnet.2015.12.017>.
- Weyer, S., Schmitt, M., Ohmer, M., Gorecky, D., 2015. Towards Industry 4.0 - standardization as the crucial challenge for highly modular, multi-vendor production systems. *IFAC-PapersOnLine* 48, 579–584. <https://doi.org/10.1016/j.ifacol.2015.06.143>.
- Wollschlaeger, M., Sauter, T., Jasperneite, J., 2017. The future of industrial communication: automation networks in the era of the internet of things and industry 4.0. *EEE Ind. Electron. Mag.* 11, 17–27. <https://doi.org/10.1109/MIE.2017.2649104>.
- Xu, L.D., Xu, E.L., Li, L., 2018. Industry 4.0: state of the art and future trends. *Int. J. Prod. Res.* 56, 2941–2962. <https://doi.org/10.1080/00207543.2018.1444806>.
- Zawadzki, P., Żywicki, K., 2016. Smart product design and production control for effective mass customization in the industry 4.0 concept. *Manag. Prod. Eng. Rev.* 7, 105–112. <https://doi.org/10.1515/MPER-2016-0030>.
- Zhong, R.Y., Xu, X., Klotz, E., Newman, S.T., 2017. Intelligent manufacturing in the context of industry 4.0: a review. *Engineering* 3, 616–630. <https://doi.org/10.1016/J.ENG.2017.05.015>.
- Zhou, K., Liu, T., Zhou, L., 2015. Industry 4.0: towards future industrial opportunities and challenges. In: Proc. Of the 12th International Conference on Fuzzy Systems and Knowledge Discovery. IEEE, Zhangjiajie, China, pp. 2147–2152.