

Sustainability Aspects of a Digitalized Industry – A Comparative Study from China and Germany

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Industrial production is currently undergoing a fundamental transformation, leading towards a digitalized and interconnected industrial production, which is subsumed under the term Industrial Internet (of Things) or Industrie 4.0. This paper discusses the changes that digitalization is expected to bring about in the industrial sector by comparing a highly industrialized (Germany) with a major emerging industrial economy (China). We conducted two empirical surveys asking manufacturing companies from different sectors in Germany and China respectively, how they expect the digitalization of their processes will affect them. Both questionnaires addressed the future of work in production and the future of production itself. The main contribution of this paper is its empirical investigation of how the digitalization of industry is likely to affect sustainability aspects of manufacturing companies in two countries with very different industrial structures. Our findings suggest that this transformation will not only impact the ecological dimension (resource efficiency, renewable energy), but that the technical transformation is likely to be accompanied by social transformations. The findings of this paper will help decision-makers in the political sphere to anticipate and shape pathways towards a more sustainable future in the industrial sector.

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NOMENCLATURE

N = Total amount of given answers

1. Introduction

Industrial production is currently undergoing a process of fundamental transformation.^{1,2} This process is informed by the vision of a fusion of the physical world of industrial production with the digital world of information technology - in other words, the creation of a digitalized and interconnected industrial production. This vision has entered into public debate under different names in different regions: in Germany, where it first emerged, it is commonly referred to and promoted under the term “Industrie 4.0”, whereas in the US it is known as the Industrial Internet (of Things).

Industry has always played an important role in finding pathways to sustainable development, as evidenced by both the Brundtland Report in 1987, which dedicates a whole chapter to the trade-off between

environmental and economic benefits, and current discussions of the UN Sustainable Development Goals, in particular Goal 12 - “Ensure sustainable consumption and production patterns”. It is therefore essential to monitor the current transformations in industry also from a sustainability science perspective. The quality of changes induced by the industrial digitalization may vary between countries depending on their current industrial structure though - a country with a high degree of automation in its manufacturing sector might be affected differently than a country where manufacturing is mainly based on manual work.³ Policy makers should seek to anticipate the international heterogeneity of impacts potentially caused by the nationally varying consequences of digitizing the manufacturing sector.

This paper therefore approaches the potential impacts of industrial digitalization on sustainable development through a comparison of two countries with a largely different structure in their manufacturing sector, which have agreed to cooperate closely in this field: Germany, as a highly industrialized pioneer of “Industrie 4.0” with an already high degree of automation (292 robots per 10,000 employees), and China, one of the largest emerging industrial economies, where a lot of manufacturing processes are still executed manually (only 36 robots

per 10,000 employees).⁴

In Germany, industry accounts for 25.5% of gross value added.⁵ Almost a fifth (18.8%) of employees in Germany work in the industrial sector.⁶ The industrial sector is responsible for 27.6% of final energy consumption.⁷ As a result, industry is one of the largest emitter of greenhouse gases and is responsible for 19.5% of all emissions.⁸

The industrial sector is a major contributor to air pollution, as European statistics show. According to the European Environment Agency, the industrial sector is the second largest source of particulate matter (PM10) in Europe, and the third largest source of nitrogen oxides (NOx). Industrial facilities are also a major source of environmentally harmful heavy metals (46% of all lead emissions and 34% of mercury emissions, respectively). In Europe the cost of harms to the environment and human health caused by industrial air pollution in 2012 has been estimated at EUR 59-189 billion.⁹

In May 2015, the Chinese Central Government released the initiative of 'Made in China 2025' which aspires to revive China's manufacturing sector, and based on this plan involving "Smart Manufacturing" and "Industrie 4.0" instead of labour-intense production, China aims to become the leading industrial power by 2049. According to the statistical yearbook issued by the People's Republic of China, the Chinese industrial sector (excluding construction) currently accounts for 31.6% of Gross Value Added. And yet, industrial facilities were responsible for 69.8% of overall energy consumption in 2012. That year, 66% of all energy was derived from coal and 18.4% from oil.¹⁰ These figures offer some insight into the contribution of industrial sources to overall emissions. Air pollution is an enormous problem in China: in 2013 none of the thirty-one Chinese key cities surveyed met the annual air quality standards for particulate matter set by the EU (in some cases air pollution reached levels twice the European standard) - a fact that is reflective of the immense energy requirements of the Chinese industrial sector.

Since these are relevant quantities it should be investigated if and how digitalization could help industrial manufacturers to bolster the environmental and social dimension of sustainability. This is the main research question addressed in this paper. To this end, we conducted two empirical surveys asking manufacturing companies from different sectors in Germany and China respectively, how they expect the digitalization and interconnectedness of processes to affect them. Both questionnaires contained two main thematic blocks: the future of work in production and the future of production itself. More details regarding the operationalization of the questionnaires are provided in section 3. This empirical investigation is the main contribution of our paper.

The paper starts with a state of the art analysis giving a brief overview of existing research findings addressing the industry-relevant sustainability aspects mentioned above and how these might be impacted by the forecasted digitalization. Following this section we describe the methods used to design and conduct the survey, present and compare its results, and discuss its most pertinent findings. The paper concludes with a summary of our key findings and the outlook for future research.

2. State of the Art

The concept of Industrie 4.0 (the digitalized and interconnected

industry) is a relatively new one.¹¹ Due to this, research has largely focused on sustainability issues in manufacturing that are independent of the digitalization and interconnectedness being the salient features of Industrie 4.0. However, some research findings already address a variety of sustainability aspects that will potentially be affected by the comprehensive digitalization of industrial manufacturing processes. In recent years research of this type has primarily focused on changes in industrial work life and technological developments supporting the Industrial Internet. Considerably less research has been dedicated to investigating potentials for resource efficiency or a hypothetical symbiosis of a digitalized industry with renewable energy.

Prognoses on the future of work in a highly digitalized industrial sector vary widely. A number of large business consultancies have published data that draws a very positive picture with respect to the number of jobs likely to be created within industrialized countries and suggest, for example, that 390,000 new jobs might be created in Germany.¹² Findings from research institutions, on the other hand, point in the opposite direction. Bowles has analysed computerisation risk levels depending on the job characteristics and finds that countries in northern Europe, including Germany, France and UK, are at a high risk of losing large numbers of jobs to computerisation,¹³ while Wolter et al. forecast the loss of 100,000 jobs despite growing value creation.¹⁴

Many authors point out that such fundamental technological innovations will require a broad societal discourse about the organization of future work¹⁵ and the role human beings are supposed to play in the factory of the future.^{16,17}

Optimizing resource efficiency in producing companies in the classical technological context is not new to research. According to Duflo et al. resource efficiency approaches can be addressed on various levels,¹⁸ ranging from technological improvements on the tool machine level¹⁹ through to the restructuring of manufacturing sequences,²⁰ factory layouts and entire value creation networks in the case of globally operating enterprises.¹⁸ A broad review of these resource efficiency technologies and strategies is presented by Rohn et al.²¹

A more general consideration is presented by Meyer et al. with a simulation of the decoupling of economic growth from resource consumption which takes potential rebound effects into account.²² A more "consumption-friendly" approach that opens up opportunities for digitalized industry is published by Ding et al., who introduce an algorithmic description for a resource service scheduling problem in the context of industrial product service systems, helping to reduce overall resource consumption.²³

If one considers that energy consumed in Stand-by Mode accounts for 30% of the total energy consumed by machine tools²⁴ the relevance of energy consumption in production becomes obvious. Fysikopoulos et al. have taken up this challenge and developed a generalized approach to manufacturing energy efficiency based on a machine-level study.²⁵ A more IT-related concept is the energy simulation of manufacturing systems, where a flexible energy flow-oriented manufacturing system was simulated.²⁶ Schmidt et al. present a methodology for the reliable prediction of energy consumption of arbitrary manufacturing processes based on measurements and existing knowledge.²⁷ A more general approach also aiming at energy efficiency in manufacturing is the methodology for planning and operating energy-efficient production systems.²⁸

Digitalized industrial processes can be steered with the help of Cyber Physical Energy Systems (CPES), allowing for their temporal flexibility.²⁹ Using this flexibility of industrial processes can help enable and strengthen the so called Demand Side Management (DSM). Bornschlegl et al. present an approach to increasing energy efficiency through the use of cyber-physical systems (thereby supporting DSM): reducing the base load especially during unproductive periods in the production flow and selectively switching off temporarily unnecessary components to increase overall efficiency.²⁹ Shrouf and Miragliotta discuss more generally how established Internet of Things (IoT) technologies can be used to improve energy management in single-item production,³⁰ while Brizzi et al. present a case study on the remote monitoring of robot energy consumption, demonstrating the capability of intelligent applications for managing manufacturing processes.³¹

On the methodological level Chu et al. introduce a future paradigm called Manufacturing for Design which uses hybrid manufacturing and smart factory as underlying technologies.³² Zhao et al. analyse the sustainability impact of manufacturing by introducing a new information model for product lifecycle management that integrates an energy simulation framework.³³

Generally, it must be said, the novelty of the concept of Industrie 4.0 means that there is very little research addressing the impacts of digitalizing and interconnecting industrial processes on sustainability aspects such as resource efficiency potentials.

3. Survey

The main objective of the survey was to analyse some effects Industrie 4.0 will have on future processes of manufacturing companies and how these impact certain sustainability indicators. To make sure all participants share the same understanding of the term Industrie 4.0 every participant was provided with a brief explicatory text describing the main characteristics of Industrie 4.0 as suggested by Kagermann and Wahlster.¹¹ Questions were mainly addressing the two dimensions ecological or social sustainability and participants were asked to give their personal estimation how specific indicators of these dimensions were influenced by the changes induced by Industrie 4.0 on a predefined multi-step scales. For both dimensions a set of indicators were selected. The majority of them were selected based on their perceived relevance due to frequency of reference in literature on Industrie 4.0, while some indicators were added because the authors are convinced of their future relevance for a more sustainable production. The ecological dimension was represented by the indicators material and energy efficiency, own renewable energy capacities and environmental strategy / standards, while for the social dimension the indicators staffing requirements, required qualifications, workload and support through digital assistance systems were selected.

3.1 Survey Methods

One survey was conducted in China in three phases: first, the questionnaire (originally designed in English) was translated into Chinese by local partners. The resulting Chinese questionnaire was discussed with some potential interviewees, collecting their feedback and comments for revising the design of the questionnaire. This

finalized Chinese version was retranslated into German by an independent Chinese native in Germany to verify the translation. Secondly, the questionnaires were distributed via three channels: via email, through on-site visits including direct interviews, and by distributing the questionnaires with the support of local government agencies. Before interviewees completed their questionnaires, researchers in China explained the relevant terminology and the contents of the questionnaire as well as the basic requirements with respect to the survey (either in person, by telephone, or via email). Regarding the terminology the more general term "Digitalization and Interconnectedness" instead of "Industrie 4.0" or "Industrial Internet" was used for the Chinese survey to ensure that the main features of this trend were always identified in the questions. The third phase was to collect the questionnaires and to aggregate and document the responses. A total of 120 questionnaires were sent out, all of which were returned to the researchers. However, 11 of the questionnaires were returned incomplete, which is why we could only take 109 samples into further analysis. 102 questionnaires were collected from Liaoning Province, a typical industrial zone in China, and seven from Jiangsu Province and Gansu Province. 47 questionnaires were sent back via email, 22 were collected on site, and 40 were collected with the support of local governments.

The Chinese survey focused mainly on medium to large sized companies and exclusively on people working in one of two engineering domains: development (34%) and manufacturing (66%). Most participants work in the branches machine and plant engineering (24%), automotive (22%), information and communication technologies (17%), electronics (15%) or aerospace (12%). 16% of the participants work in companies with more than 5 000 employees; 6% in companies with fewer than 5 000 but more than 2 500 employees; 22% in companies with fewer than 2 500 but more than 1 000 employees; while the vast majority of participants (56%) works in companies with less than 1 000 employees. 73.4% of the participants were male and 26.6% female.

The German survey was conducted with the help of an online questionnaire created with the tool LimeSurvey. The questionnaire started with a text, explaining all the relevant terms used in the following questions. The invitation to participate in the survey was distributed by email and published in selected newsletters from German engineering organizations such as VDI or ProSTEP iViP. The survey addressed individuals employed both in the engineering sector and engineering science who had already dealt with the issues relating to Industrie 4.0 in their professional roles. In total, 102 people participated in the German survey. Most participants work in the branches automotive (20%), information and communication technologies (20%), machine and plant engineering (18%) or aerospace (10%). 42 of the participants work in companies with more than 5 000 employees; 16 people in companies with fewer than 5 000 but more than 250 employees; while the rest of the participants works in companies with fewer than 250 employees. Unlike their counterparts in China, participants in Germany were not obliged to answer all of the questions. On the contrary, they were encouraged to leave blank those questions which they did not feel competent to answer. This is why the total amount of given answers (N) varies across questions.

3.2 Survey Results

The results of our survey suggest that the Industrial Internet (of Things) is viewed as an important emerging trend both in China and in Germany. When asked about the influence of digitalization and interconnectedness on their companies, the great majority of Chinese participants (91%) describe this influence as “Very big” or “Big”. This picture is differentiated by taking into account the estimated time horizon in which the transformation is expected to take place. As we explain in detail at the end of this section, our results show that Chinese companies expect substantial changes to result from digitalization over the longer rather than the shorter term. Nevertheless, according to our participants, 41.3% of companies have already adopted company-wide strategies with respect to the digitalization of production.

In Germany a much lower ratio of participants (66.7%, N = 69) characterize the influence on their companies as “Very big” or “Big”. On the other hand, German experts anticipate the implementation of digitalized production processes within the next decade and identify this as a topic for the mid-term agenda.³⁴

3.2.1 Future of Work

According to our findings, the digitalization of industry will lead to highly different staffing requirements across the domains under consideration. We asked participants how digitalization and interconnectedness will affect staffing requirements in their respective companies (and in different domains of production). In the case of development, Chinese participants painted a more or less balanced picture: 45.9% expect more or even many more workers to be employed in this domain, while 46.8% anticipate fewer or far fewer workers. The outlook for all of the other domains was far more pessimistic - 88% of participants anticipate that fewer or far fewer workers will be employed in manufacturing, assembly (79.8%), logistics (65.7%) and technical services (57.8%).

The results from the German survey show at least relative to the Chinese results on average a more optimistic picture (see Fig. 1). For the development domain (N = 65) 6.1% of the participants here expect many more jobs to be created, while 70.8% still expect more jobs. The domain with the second best future outlook according to the participants is services (N = 62): 11.3% expect many more and 62.9% more jobs; whereas only 3.2% of participants forecast fewer jobs. The remaining 22.6% do not expect to see changes in the numbers employed in the service domain as a result of Industrie 4.0. In the domains of manufacturing (N = 50) and assembly (N = 47) the majority of participants expect that Industrie 4.0 will lead to fewer or considerably fewer jobs: combined 56% and 53.2% respectively, while only 8% and 6.4% expect more jobs – none of the participants expect to see considerably more jobs being created in either of these domains. In logistics (N = 52) 28.9% expect more jobs, 46.2% no changes and 25% fewer jobs - none of the participants expect that Industrie 4.0 will result in the creation of considerably more or considerably fewer jobs.

But not only is the quantity of jobs anticipated to change. When we asked participants about the extent to which digitalization and interconnectedness will affect the qualifications that their company requires of its employees (in different phases of production), most Chinese participants anticipated changes in the quality of work. In all domains the vast majority of participants forecast that more

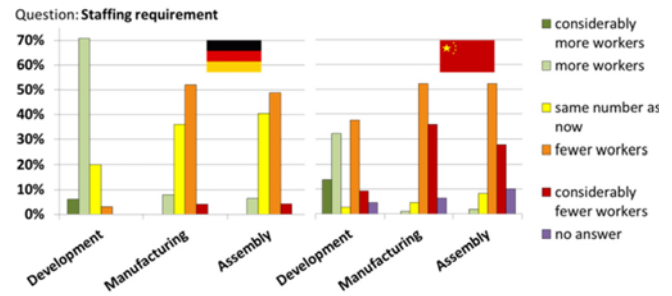


Fig. 1 Effects on staffing requirements due to digitalization per domain

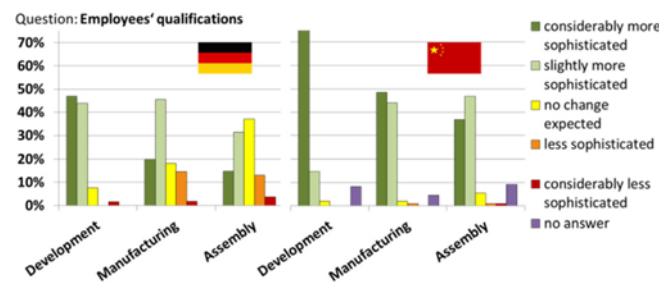


Fig. 2 Effects on required qualifications due to digitalization per domain

qualifications will be required (see Fig. 2). 75.2% expect that work in the development domain will become considerably more sophisticated, while another 14.7% still expect slightly more sophisticated qualification profiles. Not a single participant estimates that fewer or considerably fewer qualifications will be required of developers in future. The results for the manufacturing and assembly domains reveal similar expectations: a combined 92.7% and 83.5% respectively forecast that considerably or at least slightly more sophisticated qualifications will be required. 78.9% of participants expect to see the same outcome in technical services and 73.4% in the logistics domain.

On average, the participants in the German survey anticipated a less dramatic change with regard to the qualifications required to work in Industrie 4.0. Nevertheless, these participants forecast an abrupt change in the development domain (N = 66), where 47% expect qualification requirements to increase considerably and another 43.9% foresee a slight increase. For the assembly domain (N = 54) the German survey reveals that only 14.8% expect considerably more sophisticated and 31.5% slightly more sophisticated job requirements while more than every third participant expects no changes at all (37%). In the case of the service domain (N = 62), almost every second participant (48.4%) expects that job requirements will become only slightly more sophisticated, while every fourth (25.8%) expects that requirements will grow considerably. In the case of manufacturing (N = 55) and logistics (N = 52), 65.5% and 57.7% of participants respectively anticipate that requirements will become considerably or slightly more sophisticated. Finally, 14.6% expect that qualification requirements to become less sophisticated for manufacturing - for no other domain did so many participants articulate this estimation.

In addition to these questions on the number of jobs and the qualifications required to fill them, a number of questions in the survey focused on the nature of work in future. In the Chinese survey, we

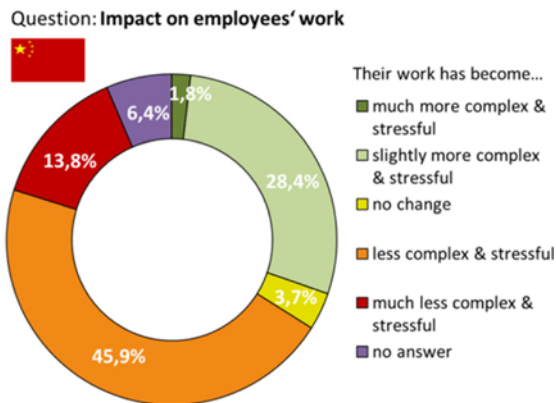


Fig. 3 Impacts on workload due to digitalization

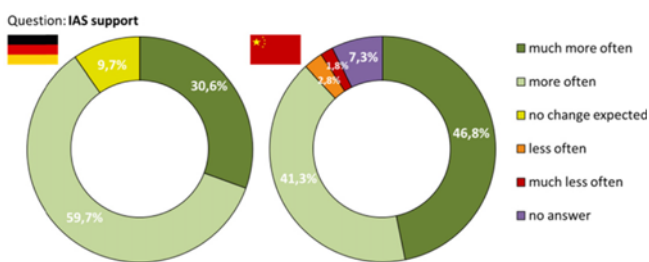


Fig. 4 Support by Intelligent Assistance Systems in the future

asked about the impacts of increasing digitalization on employee's workloads. Only two participants (1.8%) felt that workloads had become much more complex and stressful. 28.4% described workloads as slightly more complex and stressful, while 45.9% sense that workloads have become less and 13.8% even much less complex and stressful. 3.7% did not note any changes as a result of digitalization (see Fig. 3).

The German study included a similar question in which we asked the participants about their perception of the increasing digitalization of their working processes (N = 72). Here, 23.6% of participants perceived this development as very and 31.9% as slightly relieving, while 19.4% replied that it did not make any difference to their work. It is a worrying result that every fifth participant (20.8%) declared their daily work to be more demanding and 4.2% even very demanding due to digitalization.

A similar question, featured in both surveys, asked participants to consider how often workers would rely on the support of Intelligent Assistance Systems (IAS) (such as software accessed by tablet or head-mounted display) to undertake complex tasks in the future? In the Chinese survey 46.8% expect this to happen much more often and another 41.3% more often than now. A combined 4.6% foresee this to happen less or much less often, while no participant expected the current situation to remain unchanged. In the German survey (N = 72), not a single participant expects assistance systems to support employees less or much less often, 9.7% forecast no change, while a combined 90.3% expect this to happen more or even much more often (see Fig. 4).

3.2.2 Future of Production

The next thematic block in the survey addressed the future of production. We asked participants to gauge the extent to which

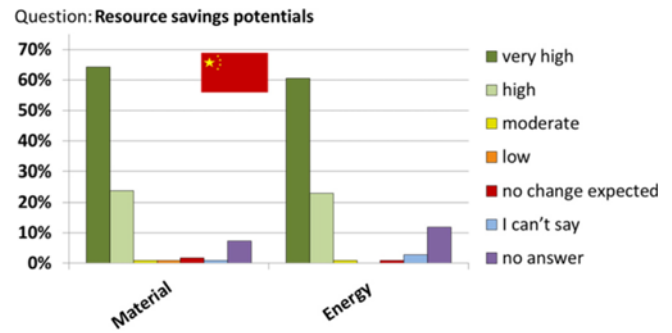


Fig. 5 Resource savings potential in China through digitalization

production facilities will be interconnected in the future - a) within their company and b) with external means of production. In both surveys not a single participant forecast a decrease in interconnectedness for either of these parameters. The German survey showed that 63.4% (N = 71) expect the means of production within companies to display a considerably greater degree of interconnectedness - a result that was closely tracked by their Chinese counterparts (61.5%). A slight increase was forecasted by 35.2% and 22% respectively. A greater degree of variation is evident with respect to the growth of connections to external entities. In the Chinese survey 68.8% of all participants expect to see a considerable increase in the degree of interconnectedness with external means of production, while only 39.4% of their German counterparts share this view. A slight increase was expected by 23.9% and 50.7% respectively. The Chinese results for this question should be interpreted against the background of the time horizons for transformation forecast by the participants. Three out of four participants (75.2%) do not expect any change within the coming year, while the majority (50.5%) expects only small changes to occur within the next three years. The majority of participants (51.4%) expect to see a moderate shift towards a more digitalized industry within ten years. So although the vast majority of Chinese participants anticipate an increasing degree of interconnectedness with external means of production in the future (combined 92.7%), this transformation still seems very distant.

3.2.3 Savings & Efficiency Potentials

The majority of Chinese companies have an environmental strategy (53.2%) and apply environmental standards (53.7%). The most commonly used standard is ISO14001 (75%). In Germany 57.1% of surveyed participants have implemented an environmental strategy (N = 70).

Companies in China and Germany anticipate that the digitalization of industrial production will influence environmental production factors such as resources and energy consumption. In China, material and energy efficiency are regarded as important factors for the future development of new production lines (see Fig. 5) - 80.7% of the participants stated that material efficiency will be more or much more important, and energy efficiency is an important or very important topic for 89.8% of companies with respect to the development of new production lines. 83.5% of Chinese participants expect to see high or very high savings in energy consumption as a result of digitalization. The potential for material savings is anticipated to be even larger, with 88.1% of Chinese participants forecasting very high or high savings potentials.

In Germany the majority of participants (91.6%, N = 71) see resource efficiency as an important or very important factor in strategic decision-making in the future. With regard to potential resource savings, we asked German participants if they expect to see changes in their overall electricity consumption. 20.3% of the participants do not anticipate any change, while 34.8% expect an increase and 23.2% a decline in electricity consumption (N = 69).

One strategy to save energy costs and reduce negative environmental impacts is the operation of company-owned renewable energy facilities. In Germany, 31.9% of all companies interviewed are considering producing their own renewable energy (N = 69). In China, only 3% of the companies interviewed plan to set up their own facilities for generating renewable energy in the next five years.

3.3 Discussion and Interpretation of Results

The analysis of the survey data shows some interesting results with regards to the ecological and the social implications of the digitalization of industrial processes. Increasing the efficiency of material and energy usage is an important issue for Chinese manufacturers, who generally associate high expectations for more resource efficiency in industry with its digitalization. This might also be an indicator that today's manufacturing processes in Chinese companies still allow for improvements in efficiency. If the assumed potentials (foreseen by 83% for energy and 88% for material) can actually be realized by means of digitalization, the implementation of Industrie 4.0 could have a massive effect on the ecological dimension of sustainability in light of the enormous scale of China's industrial sector. This becomes especially relevant with regards to saving energy. The current energy mix in China, being mainly based on coal and oil, is not very sustainable. If the digitalization of industrial processes reduces overall energy consumption, positive impacts could arise indirectly in the areas of air quality and the reduction of greenhouse gas emissions, with positive implications for social aspects such as public health. Another technological trend potentially supporting these improvements is increasing the use of renewable energy (RE). This energetic transformation does not seem to be part of the mid-term planning of Chinese companies though. On the other hand, quite a large number of German companies already have plans to set up their own RE facilities (32%). If the implementation of Industrie 4.0 in Germany demonstrates the general compatibility of RE and the benefits to be gained from its utilization, the digitalization of industrial processes could also open doors for a broader acceptance of RE in emerging countries like China. Overall, there appears to be a widespread awareness of ecological issues within the Chinese industrial sector, as the majority of companies applies ecological standards (54%) - quite probably with the motivation to export goods into countries that demand environmental standards.

The findings relating to future of work in industry reveal a high potential for challenging outcomes in the social dimension. In both surveys the majority of participants expect enormous job losses as a result of digitalization in manufacturing and assembly - with Chinese participants forecasting the more dramatic outcome. The challenges ahead become apparent when one considers that the level of automatization in China is currently much lower than that in industrialized countries and a high percentage of employees in industry are concentrated in the manufacturing and assembly sectors, where pay

levels are increasing rapidly.¹⁰ As a result, there is considerable cost pressure to expand the role of digital technologies through the introduction of automated solutions and robotics. A number of recent developments suggest that this trend has begun to gain traction. Chinese companies are now buying enormous quantities of robots³⁵ and are expected to increase purchasing in this area so that by 2017 China will have installed more manufacturing robots than any other nation.³⁶ Many of these robots will replace manual workers. In addition to this, our findings show that the qualifications required of manual workers in a digitalized industry will increase substantially. The digitalization of industry is likely to result in a fundamental transformation of work in this sector, making huge efforts necessary to support and accompany the people employed under these conditions.

The findings of this study are limited to a certain extent by differences in the methods used to conduct the surveys in both countries and the relatively small number of participants, which does not allow for a representative, comprehensive picture of the respective national outlooks. Nonetheless, the results of these surveys provide a first impression of the potential impacts of the digitalization of industrial production on certain sustainability aspects.

4. Summary and Outlook

Industrial production is currently undergoing a fundamental transformation, leading towards a digitalized and interconnected industrial production. This paper discusses the changes this transformation is expected to bring about in the industrial sector by comparing two countries. The academic contribution and novelty of this paper is its empirical comparison of how the digitalization of industry is likely to affect sustainability aspects of manufacturing companies in two countries with very different industrial structures: Germany as an industrialized country and China as an industrializing one. The empirical results of two national surveys are presented, compared and discussed.

The results of the surveys indicate that the digitalization of industry provides a window of opportunity for the ecological dimension of sustainability - provided that the often-presumed improvements in resource efficiency can actually be realized - and a potential entry point for the increased employment of renewable energy sources. Future research in this field should address the development of new technological concepts focusing on opportunities created through the digitalization of industrial processes as well as the evaluation of already existing concepts for increasing resource efficiency in production (see The state of the art section) to see if they can be supported by a digitalization of industrial production. In addition to this, a thorough life cycle assessment should be conducted to quantitatively evaluate different approaches (differentiating effects depending on the size of companies), taking into account e.g. the IT hardware required to digitalize machinery and components as a prerequisite for Industrie 4.0 production processes.

The impacts of digitalization on the social dimension of sustainability are expected to be more substantial. Our findings support the more critical voices that foresee major job losses due to the increased automatization of production in both industrialized countries,

but even more dramatically in industrializing countries with a currently lower degree of automation in production. This bears the potential for enormous social challenges as competition for those jobs remaining intensifies. Future research should therefore address the complex global links between competition for jobs and the resulting social challenges. At the same time, the question of whether, in a time when economic growth is slowing around the world and value creation is increasingly the domain of machinery, the coupling of income and human labour still remains a necessity.

In conclusion, it can be said that the ongoing digitalization of industrial processes provides large opportunities for the ecological dimension of sustainability and the innovative strength of individual companies, while also posing a challenge for societies. Accordingly, this transformation should receive more attention from a sustainability point of view and be embedded in national and international sustainability policies to ensure the proper exploitation of opportunities and the identification of potential risks and respective countermeasures from the very beginning.

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