Sustainable Production and Consumption 31 (2022) 287–300

Contents lists available at ScienceDirect

Sustainable Production and Consumption

journal homepage: www.elsevier.com/locate/spc

Impact of Industry 4.0 on corporate environmental sustainability: Comparing practitioners' perceptions from China, Brazil and Germany

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ARTICLE INFO

Article history:
Received 2 November 2021
Revised 16 February 2022
Accepted 23 February 2022
Available online 25 February 2022

Editor: Dr. Charbel Jabbour

Keywords:
Industry 4.0
Corporate sustainability
Digitalisation
Resource efficiency
Environmental management

ABSTRACT

Industrial production needs to be fundamentally transformed if the UN Sustainable Development Goals shall be met. Digital technologies can potentially drive such a sustainable transformation, but two main objectives of environmental sustainability must be considered for achieving this target: decarbonisation and dematerialisation. We empirically investigate the potentials for these two objectives by employing a survey-based approach, investigating companies' developments in China, Brazil, and Germany, in a variety of industrial sectors, and in companies of different sizes. These cases provide insight on a multi-country perspective into developments in digitalisation in countries with different pre-conditions for digital transformation, which is a novelty to this research field. We show that even though most industrial practitioners expect an improvement of the environmental sustainability of their respective company due to the application of Industry 4.0 technologies, factual improvements in resource efficiency and energy consumption are not expected to develop in a similarly optimistic fashion. These findings challenge the assumed effects of Industry 4.0 discussed in the vast majority of prior literature which expresses high hopes for positive impacts on resource efficiency and energy consumption . This can be interpreted as an indication that Industry 4.0 will not automatically lead to environmental improvements instead this transformation towards a more sustainable economy needs to be accompanied by supporting measures. On the positive side we find that the higher the current Industry 4.0 level of companies, the greater their ability to match their supply with the actual demand and their likelihood for participating in Demand Response schemes. This is an important prerequisite for the stabilisation and efficient use of future renewable energy systems. Our study provides insigths to policy makers and practitioners but also fellow researchers regarding current trends in the implementation of Industry 4.0 and in how far they support the transformation towards more sustainability. We conclude that the implementation of the Industry 4.0 concept should always be critically evaluated against the background of the SDGs and must be supplemented by a combination of regulation and incentives through governing bodies, which includes setting binding targets for saving energy and material and reducing non-recyclable waste.

1. Introduction

In the literature on Industry 4.0, attention has recently increased on how digitalisation will impact the environmental sustainability of industrial production companies (Müller et al., 2018; Beier et al., 2021; Rajput and Singh, 2020; Sousa Jabbour et al., 2018) and some scholars have suggested frameworks to integrate these two concepts (Yadav et al., 2020; Jamwal et al., 2021; Sousa Jabbour et al., 2018). Considering the fact that the industrial sector is one of the largest energy consumers (IEA, 2020) and emitters of greenhouse gases (Climate Watch, 2021) worldwide - whilst consequently also playing a large role in the environmental degradation of our planet – it is clear that a profound transformation of the industrial sector will likely have a significant impact

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https://doi.org/10.1016/j.spc.2022.02.017

on environmental sustainability, too. However, little empirical evidence substantiates the assumption that digitalisation will make industrial production more sustainable. Thus, whereas a number of studies predict that Industry 4.0 will enhance energy and material efficiency whilst also accelerating the integration of renewable energy forms in industrial manufacturing (Stock and Seliger, 2016; Ghobakhloo and Fathi, 2021) – there is a growing body of literature that urges caution and underlines the fact that sustainability benefits are no foregone conclusion, but rather need to be actively integrated with the digitalisation strategies of the respective companies (Renn et al., 2021; Beier et al., 2020b). Finally, scholars such as Stock and Seliger (2016) emphasise that the adoption of digital technologies – if not steered in the right direction – may even make production more resource-intensive, as opposed to more environmentally sustainable and climate-friendly

The main contribution of this paper is to generate empirical data to reflect on the few and ambiguous assumptions about the effects of Industry 4.0 on environmental sustainability currently existing in the scientific literature. Our results are based on a survey carried out amongst employees in industrial production companies in China, Germany, and Brazil. To our knowledge taking such a multi-country perspective is new to the scientific literature on the environmental effects of Industry 4.0. Specifically, we will analyse employees'perceptions of the current environmental advantages and drawbacks induced by the Industry 4.0 implementation. We will also assess the extent to which increased digitalisation is linked to corporate environmental management systems (EMS) on a broader level.

China, Brazil, and Germany have been chosen as suitable case studies based on their socio-economic relevance for their respective continents and their different preconditions for digitalisation as well as the integral role that digitalisation is presumed to play in industrial transformation in all three countries. With regards to the latter, digitalisation is regarded a relevant driver for economic development and therefore supported by policies and investment in all three countries. In Germany, this is manifested in the countries High Tech Strategy, whereas China has put forward its "Made in China 2025" strategy, and Brazil highlights its goals concerning Industry 4.0 in the Brazilian "Digital Transformation Strategy" (State Council of China, 2015; Ministry of Science, Technology, Innovation and Communications, 2018; Federal Ministry of Education and Research, 2018). Concerning differences in the development stages of Industry 4.0 between countries, the Network Readiness Index (NRI) assesses the application and impact of information and communication technology (ICT) and their digital transformation potential for different economies (Portulans Institute, 2020). According to this index Germany holds the 9th· China the 40th and Brazil the 59th position in their overall ranking (covering 134 economies in total). Even though the NRI cannot be read as an explicit Industry 4.0 maturity index, its overall ranking is indicative of a digital gap between Germany on the one hand and China and Brazil on the other hand. Lastly, our country selection is also motivated by the pressing issues of industrial environmental sustainability, stressing the importance for further investigation of the drivers and potential remedies for unsustainable practices. For instance, according to Eurostat the industrial sector accounts for 28% of total energy consumption (2020) and 22% of GHG emissions (2019) in Germany respectively. Similarly, the rising industrial energy consumption that has accompanied China's economic development continues to be an important issue, emphasizing the need to improve energy efficiency (Lin and Tan, 2017). Likewise, energy efficiency especially of energy-intensive industries in Brazil has been shown to be low (Ciacco et al., 2017). In conclusion, all selected countries display interesting preconditions to explore the relationship between Industry 4.0 and environmental sustainability given the stated issues and respective goals.

2. Literature review

There are high expectations associated with Industry 4.0, especially amongst practitioners and political actors, regarding the potential of digital technologies to improve the environmental impact of corporate activities (Fritzsche et al., 2018; Kunkel and Matthess, 2020). The most prominent topics addressed in that context will be introduced in the following sections.

2.1. Industry 4.0 and environmental sustainability

Sousa Jabbour et al. (2018) attest Industry 4.0-associated technologies the "potential to unlock environmentally-sustainable manufacturing" Yadav et al. (2020). suggest a framework with the aim to increase sustainability in manufacturing organisations, while also analysing technological enablers for this purpose in the context of emerging economies. On a similar notion, Ghobakhloo (2020) has systematically assessed sustainability functions of Industry 4.0 and found that the economic ones such as production efficiency and business model innovation are more immediate outcomes of Industry 4.0 compared to their environmental counterparts. The sustainability implications of Industry 4.0 technologies have also been examined by Bai et al. (2020) who additionally introduce a sustainability measurement framework based on the SDGs and suggest a hybrid multi-situation decision method.

Other authors expect digitalisation in industrial production to improve its environmental sustainability, too, by e. g. an improved matching of supply with demand, enabling circular economy or supporting other resource-conserving methods (Siltori et al., 2021). The most prominent approach to saving materials is additive manufacturing, which is especially advantageous for parts of complex geometries and can also lead to lighter products, potentially enabling further savings in the usage phase (Ford and Despeisse, 2016; Dilberoglu et al., 2017; Rinaldi et al., 2020). A significant reduction in environmentally harmful emissions through the combination of lean manufacturing and green manufacturing approaches with Industry 4.0 technologies has been demonstrated by Amjad et al. (2021) in the context of the automotive industry. The literature also provides examples where digital technologies have helped improve energy efficiency in production. These examples include the systemic optimisation of the kinematic properties of large robot fleets (Riazi et al., 2017) or combining the production-side flexibility of Industry 4.0 with the high volatility of renewable energies by deliberately shifting production processes in such a way that their energy demand is greatest when renewable energy is available in large quantities (Ma et al., 2020; Faheem et al., 2018). This latter approach of energy management is often referred to as demand response management. On a more systemic level Pease et al. (2018) presented a toolset for industrial energy monitoring based on cyber-physical systems (CPS) and the Internet of Things (IoT) which allows for an "intelligent monitoring of process power cycles and tuning of three-phase energy usage in high-power industrial environments" as a technological innovation to improve resource efficiency and reduce CO_2 emissions. Similarly, Shrouf and Miragliotta (2015) developed a framework for IoT-based energy management in production, whereas Lopes de Sousa Jabbour et al. (2018) indicate potential use cases of real-time energy efficiency assessments in supply chains. In addition, simulation and modelling technologies can help to improve the environmental sustainability of companies, as observed by Machado et al. (2020). According to Ferrera et al. (2017) and Müller et al. (2018) simulations can support improvements in the factory to reduce energy consumption, and to optimise and add value to operations especially when they cover activities from the entire supply chain. The broad adoption of digital technologies across economies – and in industry in particular – also bears the potential to support the uptake of resource-friendly business practices that allow for increasing efficiency and closing resource cycles to build circular economies (Bag et al., 2021; Rajput and Singh, 2020; Jabbour et al., 2019). Despite claiming that this symbiotic topic is still in an early stage of scientific attention Piscitelli et al. (2020) conclude, that based on their review article there is big potential when using Industry 4.0 technologies for Circular Economy especially with regard to the topics remanufacturing, regenerating, life cycle management, and supply chain. Lopes de Sousa Jabbour et al. (2018) go one step further by conceptionally linking the technological concept Industry 4.0 with the Circular Economy approach. Against this backdrop, Rane and Thakker (2019) highlight the utilisation of enabling technologies of Industry 4.0, such as radio-frequency identification (RFID), to gain insights regarding the optimisation of logistics routes between supply chain partners or to enable remanufacturing of used products. A study looking at the role of micro small medium sized enterprises in India revealed that factors related to the supply chain and environmental issues are currently the main barriers to sustainability in Industry 4.0 (Jamwal et al., 2021).

2.2. Industry 4.0 for corporate environmental management systems (EMS)

Environmental transparency has been shown to be positively associated with firm size, financial performance and country origin (Kouloukoui et al., 2019). Corporate environmental management aims to monitor and control the impact of their business activities on the natural environment (Gattiker and Carter, 2010) for example through a continuous improvement process (Beier et al., 2020a). Digital technologies are expected to support corporate environmental management, as they can improve the quality and availability of relevant data (e. g. real-time consumption data of machinery) on a product and process level. Big Data analytics and Artificial Intelligence are amongst the most promising digital approaches in that regard (Beier et al., 2020a). This is in line with the findings presented by Tiwari and Khan, who present an empirically formulated mapping between Industry 4.0 characteristics and their equivalents in the Global Reporting Initiative (GRI) framework (Narula et al., 2021; Tiwari and Khan, 2020). have researched this connection qualitatively and revealed a strong influence of Industry 4.0 technologies on the GRI standards (predominantly influencing economic, energy, and emissions aspects), concluding “that digitalization can act as a catalyst to improve sustainability factors and support the implementation of the GRI framework in organizations”.

The connection of Big Data analytics and environmental management was researched by Song et al. (2018) in an entrepreneurial context identifying potential for environmental performance measurement. A similar overlap between Big Data analytics and sustainability management was analysed by Etzion and Aragon-Correa (2016), who showed how operational and strategic corporate activities can be affected. Camargo Fiorini et al. (2019) have looked at potential contributions of information systems in general and Big Data approaches in specific for the evolutionary process of corporate environmental management with two case studies of Brazilian companies. Dubey et al. (2019) focus on the effects Big Data and predictive analytics have on the environmental performance of 205 manufacturing companies in India, finding that the combination of both approaches is a strong predictor of the social and environmental performance.

Even though there are number of approaches tackling this topic, it must be summarised that there is still a lack of scientific evidence and consideration with regard to the widespread application of Industry 4.0 technologies and their impact on the environmental sustainability of companies. Hence the central research aim of this study is to empirically analyse the expected impacts of Industry 4.0 on corporate environmental sustainability.

2.3. Hypotheses

Based on the previously presented content in the state of the art section our general assumption is, that with higher levels of Industry 4.0 implementation the environmental sustainability of companies is increasing and they are more likely to implement EMS. We operationalise this general assumption through the following hypotheses.

2.3.1. Industry 4.0 and environmental sustainability

- H1: The current level of Industry 4.0 implementation of a company is positively associated with the expectation to improve its environmental sustainability through the application of the Industry 4.0 concept.
- H2: The current level of Industry 4.0 implementation of a company is positively associated with the capability of the company to match its supply with the actual demand through Industry 4.0 technologies.
- H3: The current level of Industry 4.0 implementation of a company is positively associated with the expectation regarding energy consumption due to Industry 4.0 technologies.
- H4: The current level of Industry 4.0 implementation of a company is positively associated with its participation in Demand Response Schemes (willingness and capability to flexibly change production times).

2.3.2. Industry 4.0 for corporate environmental management systems (EMS)

- H5-a: The current level of Industry 4.0 implementation of a company is positively associated with the likelihood for operating an EMS.
- H5-b: The operation of an EMS is positively associated with the respective company size.

3. Methods

The main objective of this survey was to analyse to what extent Industry 4.0 will affect environmental sustainability of industrial production and what potential the increased use of digital technologies can provide for corporate EMS. We have decided to use a jointly developed questionnaire as the method of choice for data acquisition to ensure companies in all three countries are facing the same questions and answer options.

3.1. Questionnaire design

Based on a questionnaire used for a previous study by three authors amongst Chinese and German companies, the questionnaire was iteratively developed in multiple video conferencing sessions in English. The questionnaire started with a brief explicatory text describing the main characteristics of Industry 4.0 concept to ensure a shared understanding amongst participants. In order to allow for an easier understanding, we used the term ‘Digitalisation and Interconnectedness’ instead of the term ‘Industry 4.0′, which is mainly established in Europe. Apart from that it contained the basic structural elements: Personal characteristics, company characteristics, implementation of ‘Digitalisation and Interconnectedness’, ‘Digitalisation and Interconnectedness’ and corporate EMS.

The indicators were selected based on their perceived relevance in the scientific literature on Industry 4.0 or their relevance for a more sustainable production (see section 2). Variables were mainly measured through a 5-point Likert-type scale, multiple nominal (verbally described) options or, in few instances, allowed for a free

Table 1
Key parameters of the data acquisition process.

	Format	Duration	Sample size
Germany	Limesurvey (online survey)	12/2019 – 05/2020	**105**
Brazil	Limesurvey (online survey)	03/2020 – 06/2020	**117**
China	online survey and questionnaire	09/2019 – 06/2020	**445**

text response. Additionally, the first two variants of questions also provided the two answer options “Don't know” and “No Answer”. An overview of relevant questions addressed in this paper is provided in Appendix I.

The preliminary questionnaire was discussed with potential interviewees in China and Germany, collecting their feedback and comments for revising the design of the questionnaire. This finalised version was translated into German, Chinese and Brazilian Portuguese by professional translators and subsequently retranslated into German or English by native speakers who were not involved in the study, to verify the translation.

3.2. Data acquisition and analysis

The developed questionnaire was distributed in the official language of the respective country by separate teams in Germany, Brazil and China to acquire data. As a result, we have collected data in three different Chinese provinces: Zhejiang, Jiangsu, and Liaoning. The key parameters of the data acquisition process are provided in Table 1.

Most of the data analysis for the complete data set was carried out in Microsoft Excel, while only some additional statistical tests were performed with the statistics tool R. We used R Studio to perform Fisher's exact test on contingency tables of various indicator combinations derived from our research questions. Given the large tables (up to six possible replies per question), the p-value is estimated (i. e. not exact) based on $1e^7$ simulations.

3.3. Data set

Some basic characteristics of our sample can be taken from the following tables.

3.3.1. Personal characteristics

Table 2 shows the personal characteristics of our sample. Regarding the respondents' age the difference between the youngest sample, Liaoning, and the oldest one, Germany, is 9 years according to the mean and 11 years when comparing the medians. With regards to the gender balance, Germany and Brazil have similarly male-dominated samples, while the Chinese samples are more balanced. When looking at the respondents' positions in the company, Germany's and Zhejiang's samples have a much higher proportion of managers included compared to Brazil, Liaoning, and Jiangsu.

3.3.2. Company characteristics

In terms of company size, Germany and the Chinese samples most prominently include companies which have less than 250 employees. However, although the proportion for Germany and Zhejiang is the same, Liaoning and Jiangsu are far more concentrated towards this company size. At the same time, whereas companies which have more than 5000 employees make up more than a third of the Brazilian and German samples, the values are far lower for the Chinese samples. Overall, we see considerable variation between the samples with regards to this indicator in Table 3.

The samples diverge regarding companies' sector. Although in four of the five samples one third of the companies are in plant construction, the other sectors differ in weight across the samples. For instance, whereas ICT makes up around a third of the sample for Liaoning and Jiangsu, the proportion is less than 10% for Germany, Brazil, and Zhejiang (see Table 4).

For all countries except Brazil, the largest group included in the sample are suppliers – with OEMs making up between a quarter and a third of each sample. The differences in the proportion of companies that are both supplier and OEM are also relatively small (see Table 5).

4. Results

In the results section, we present the findings for three topical clusters. In order to put the results from this survey into context, we start with an analysis addressing the current level of Industry 4.0 implementation of participating companies in the three different national economies. This is followed by the most extensive topical cluster, which is dealing with questions related to the impacts of Industry 4.0 technologies on the environmental sustainability of companies. The last cluster tackles questions around corporate environmental or sustainability management systems.

4.1. Current level of Industry 4.0 implementation

Question: To what extent has your company implemented the concept of ‘Digitalisation and Interconnectedness’ so far?

We have asked participants to what extent their respective company has implemented the concept Industry 4.0 so far. In the overall picture (see Fig. 1) it seems that companies of all three countries are currently at similar levels with German companies slightly trailing behind. We have calculated a weighted sum S_w per national economy, where we add up for all rating options i the value of a rating option r_i (reduced by one so that “not digitally interconnected” equals zero points while “fully digitally interconnected” equals 4 points) multiplied by the respective share of answers s_i:

$$S_w = \sum_{i=1}^{5} (r_i - 1) * s_i$$

For this weighted sum Brazil reaches the highest combined score with 1.85, while China reaches a value of 1.73 and Germany 1.62. It is noteworthy that only a very small share of participants did not know how to assess their company for that question.

There are, however, notable differences within the current Industry 4.0 level of companies between the three Chinese provinces that took part in this survey. If we apply the weighted sum, companies in Jiangsu province turn out to be much more digitally interconnected on average (1.97) than the ones in Zhejiang (1.69) and Liaoning province (1.57).

4.2. Industry 4.0 impacts on environmental sustainability

Question: How do you think that ‘Digitalisation and Interconnectedness’ will impact your company's environmental sustainability? (Options ranging from “1 - Significant deterioration” to “5 - Significant improvement”)

Overall, respondents from all countries have in common that they expect Industry 4.0 to lead to an improvement (answer category 4) of environmental sustainability most frequently, corresponding to shares of 38% ($n = 104$) in Germany, 45% ($n = 116$) in Brazil, and 44% ($n = 441$) in China (see Fig. 2). Moreover,

Table 2
Age, sex and position of company of respondent.

Country	Age		Sex			Position in Company		
	Mean	Median	Female	Male	Other	Management	Operational	Other
Germany	45	46	15%	85%	0%	71%	23%	6%
Brazil	37	34	16%	84%	0%	45%	30%	25%
China	39	37	42%	58%	0%	54%	36%	10%

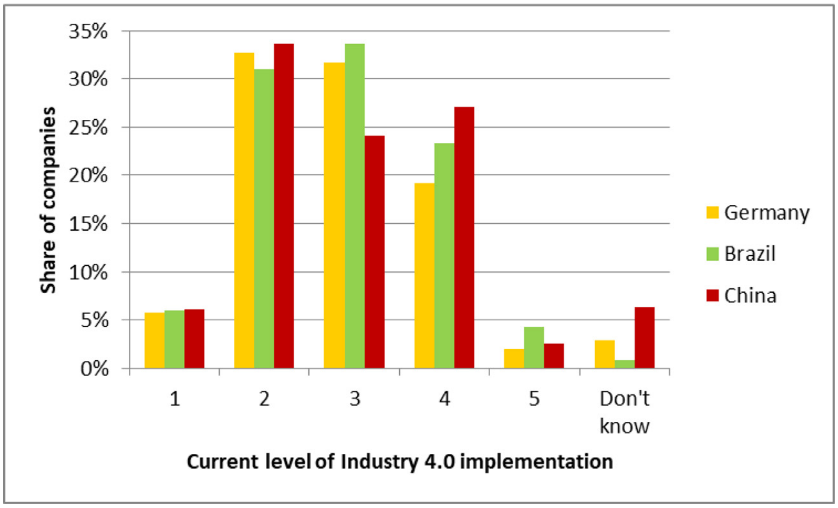

Fig. 1. Self-assessment of current Industry 4.0 implementation level (ranging from “1 - Not digitally interconnected” to “5 - Fully digitally interconnected”) per country.

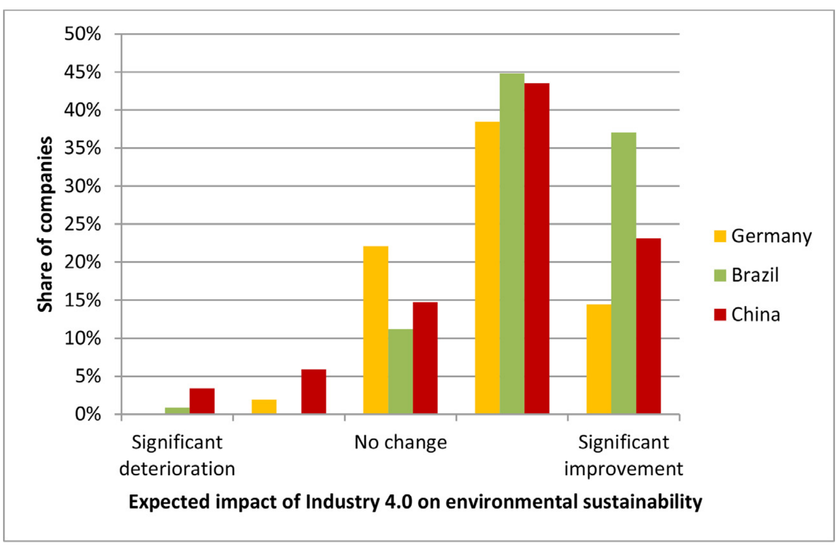

Fig. 2. Expected impact of Industry 4.0 on environmental sustainability on a scale from "1 - Significant deterioration" to "5 - Significant improvement".

Table 3
Company size.

Company size	Germany	Brazil	China
<250	37%	20%	52%
250–1000	18%	19%	22%
1000–2500	8%	13%	7%
2500–5000	2%	12%	10%
>5000	35%	35%	10%

Table 4
Sector.

	Germany	Brazil	China
Automotive	18%	29%	15%
Plant construction	41%	13%	33%
ICT	8%	5%	22%
Electronics	8%	4%	12%
Other	26%	49%	18%

less than 10% of respondents in each country expect a deterioration or significant deterioration of environmental sustainability as a consequence of Industry 4.0. In Brazil, a much larger share (37%) expects significant improvements of environmental sustainability due to Industry 4.0, compared to 23% in China and 14% in Germany.

Differentiating the findings between different company sizes, larger companies (> 5000 employees) exhibit noticeable differ-

Table 5
Supplier/OEM.

	Germany	Brazil	China
Supplier	40%	33%	43%
OEM	30%	36%	31%
Both	16%	17%	20%
Other	13%	14%	6%

ences between countries. German and Brazilian respondents representing larger companies have in common that above average shares expect improvements or significant improvements of environmental sustainability through Industry 4.0. In Germany, 67% ($n = 36$; average: 53%) of larger firms expected a positive impact on environmental sustainability, compared to 89% ($n = 36$; average: 82%) in Brazil. However, only 61% ($n = 46$) of larger Chinese companies expected a positive impact on environmental sustainability, as opposed to an average of 67% of overall Chinese respondents.

Looking at different sectors, differences between countries can be found in plant construction and engineering. In Brazil, all respondents ($n = 16$) expect improvements or significant improvements of environmental sustainability due to Industry 4.0. In comparison, only 49% ($n = 43$) of German companies, and 73% ($n = 144$) of Chinese companies respond in that manner. Respondents from the automotive sector portray a slightly different picture. In Germany, it is worth noting that an above average share expects significant improvements of environmental sustainability (26%, $n = 19$). Thus, the share of German respondents expecting improvements or significant improvements of environmental sustainability in the automotive sector combines for 58%, more than in the German plant construction and engineering sector. Different results were found in the Brazilian and Chinese automotive sector, where 80% ($n = 30$) and 58% ($n = 64$) expected improvements or significant improvements of environmental sustainability, a smaller share than in the respective country's plant construction and engineering sector.

Linking our findings from the current levels of Industry 4.0 implementation of companies to expected impacts on environmental sustainability, we find that respondents in all countries who report that their company is currently not digitally interconnected represent a below average share amongst those expecting improvements or significant improvements of environmental sustainability due to Industry 4.0. In Germany, only 33% ($n = 6$) expect (significant) improvements of environmental sustainability in this group, compared to 57% in Brazil ($n = 7$) and 48% ($n = 27$) in China. There is a tendency that companies reporting higher levels of Industry 4.0 implementation have higher expectations in terms of positive impacts on environmental sustainability, but this trend is non-linear (see Fig. 3). We performed Fisher's exact test to check for association between expected impact of Industry 4.0 on environmental sustainability and the respective current Industry 4.0 level of companies. A significant association was found in Brazil ($p = 0.0011$), and China ($p = 0.00001$), but not in Germany ($p = 0.0565$). Looking at Chinese subsamples, a significant association was found in Liaoning ($p = 0.0003$), and in Zhejiang ($p = 0.0302$), but not in Jiangsu ($p = 0.6754$).

Question: How does 'Digitalisation and Interconnectedness' affect your company's capacity to match supply with actual demand? (Options ranging from "1 - Significantly worsened" to "5 - Significantly improved")

The majority of participants states that the application of Industry 4.0 technologies has improved or significantly improved their company's capacity to match supply with actual demand. Brazilian companies seem to be especially positive in that regard (GER: 63%, $n = 104$; BRA: 90%, $n = 117$; CHI: 64%, $n = 441$). More than 62% notice a significant improvement compared to only 18% of German and 26% of Chinese companies respectively. All three countries have in common that "significantly improved" is mentioned more frequently in serial production than in single-item production.

The data indicate a moderate tendency for companies in all three countries, that improved matching of supply with demand due to Industry 4.0 implementation rises with higher levels of Industry 4.0 implementation. We performed Fisher's exact test to check for association between current level of Industry 4.0 implementation and the impact of Industry 4.0 technologies to match supply with demand. A significant association was found in Germany ($p = 0.0030$), and in China ($p = 0.0059$), but not in Brazil ($p = 0.1479$). Looking at Chinese sub-samples, a significant association was found in Liaoning ($p = 0.0117$), but not in Jiangsu ($p = 0.8449$) or in Zhejiang ($p = 0.8523$).

When interpreting these results, it must be mentioned that the number of companies in Germany and Brazil for both edge categories was relatively small (Not digitally interconnected: GER = 6; BRA = 7; Fully digitally interconnected: GER = 2; BRA = 5).

Question: In your company, what impact will 'Digitalisation and Interconnectedness' have on the overall material and energy use? (Options ranging from "1 - Much lower use" to "5 - Much higher use")

Expectations regarding a more efficient use of materials due to the application of Industry 4.0 technologies are varying between the three countries. In Germany, where almost half of all companies expect no change at all (46%, $n = 100$), only 25% expect a lower or much lower use of materials as a consequence. This value is much higher for Chinese companies (49%, $n = 441$). Expectations amongst Brazilian companies are the most polarized ones. While 32% ($n = 113$) foresee a lower or much lower use of materials, 31% are of the opposite opinion, foreseeing a higher or much higher use of materials. For German companies there is also a clear trend with regard to the size of the companies: the larger the company the higher the expectations for lowering material use through Industry 4.0 technologies. The same trend does also apply to Chinese companies, where large companies have high expectations for material efficiency due to the implementation of Industry 4.0. The company size does not seem to have an influence on that matter for Brazilian companies (see Table 6).

Differentiating those expectations by sector provides a rather mixed picture between the three countries. While the electronics sector is the most "pessimistic" of all sectors in Brazil (40% expect higher or much higher material consumption; $n = 10$) and China (30%; $n = 54$) it is at the same time the most "optimistic" sector in Germany (57% expect lower or much lower material consumption; $n = 7$). The most "pessimistic" German sector is the ICT sector (38%; $n = 8$), a sector that is fairly "optimistic" in Brazil (not a single vote for higher or much higher material consumption) and the second most "optimistic" of all sectors in China (52%; $n = 99$). However, the most "optimistic" sector in Brazil (40%; $n = 30$) and China (52%; $n = 64$) is the automotive sector. It is noteworthy though, that the combined "optimistic" assessments (options 1 + 2) are very similar in China across all sectors, ranging between 44% and 52%. Our data shows no big differences between OEMs and supplier companies in any of the three countries.

Expectations addressing a reduction of energy use due to the application of Industry 4.0 technologies vary between the three countries. In Germany more companies expect a lower or much lower use of energy (34%; $n = 102$) compared to 23% who expect a higher or much higher energy consumption. However, these two values hardly differ in Brazil (lower or much lower: 35%, higher or much higher: 36%; $n = 113$), while in China the "negative" expectations slightly prevail (lower or much lower: 37%, higher or much higher: 41%; $n = 441$) Table 7. shows that there is also no clear

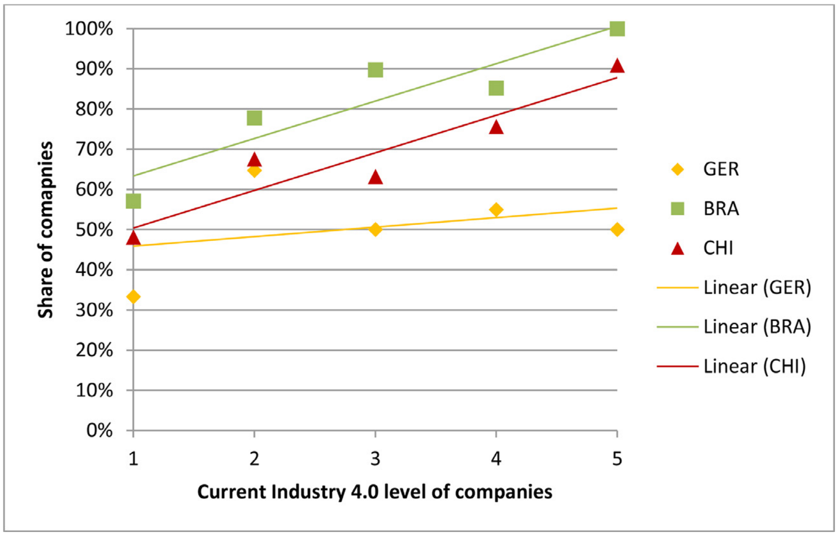

Fig. 3. Expectations for combined improvement or significant improvement of environmental sustainability due to Industry 4.0 per Industry 4.0 level of respective companies (ranging from "1 - Not digitally interconnected" to "5 - Fully digitally interconnected").

Table 6
Expectations on lower or much lower material use due to Industry 4.0 technologies per company size.

Lower or much lower material use	GER($n = 100$)	BRA($n = 113$)	CHI($n = 441$)
1 < employees <250	7.9%	34.8%	48.5%
250 < employees < 5000	29.6%	29.6%	42.8%
5000 < employees	40.0%	33.3%	71.7%

Table 7
Expectations for lower and much lower energy consumption due to Industry 4.0 technologies per company size.

Lower or much lower energy consumption	GER($n = 102$)	BRA($n = 113$)	CHI($n = 441$)
1 < employees <250	21.6%	33.3%	31.4%
250 < employees < 5000	46.4%	30.4%	38.6%
5000 < employees	37.8%	42.4%	56.5%

trend with regard to the size of companies in Germany and Brazil. Only Chinese companies tend to be more optimistic with regard to energy saving the bigger the size of the company.

Similar to the values for material savings, the expectations regarding energy savings are also very heterogeneous between the different national sectors. The sectors expecting highest energy savings due to the implementation of Industry 4.0 technologies are the electronics sector in Germany (63% foresee lower or much lower use; $n = 8$), and the automotive sector in Brazil (43%; $n = 28$) and China (39%; $n = 64$). The sectors with the lowest expectations regarding energy savings through Industry 4.0 are ICT (13%; $n = 8$) in Germany, plant construction (25%; $n = 16$) in Brazil and electronics (26%; n = 54) in China. Generally, these expectations do not differ much between Suppliers and OEMs in all three countries.

Interestingly, there also seems to be a tendency for Chinese and Brazilian companies that the higher their current level of Industry 4.0 implementation the lower are expectations for a combined lower or much lower energy consumption due to the application of Industry 4.0 technologies (see Fig. 4). No such trend could be identified for German companies, where the number of participants choosing Industry 4.0 implementation level 5 (fully digitally interconnected) was too small to be analysed here ($n = 2$; both selecting the “No answer” option).

In order to evaluate this potential association, we performed Fisher’s exact test between current level of Industry 4.0 implementation and expectations regarding energy consumption due to Industry 4.0 technologies. A significant association was found in Germany ($p = 0.0042$), and in China ($p = 0.0201$), but not in Brazil ($p = 0.1197$). Looking at Chinese sub-samples, a significant association was found in Zhejiang ($p = 0.0491$), but not in Liaoning ($p = 0.0519$) or in Jiangsu ($p = 0.922$).

Table 8
Willingness to participate in Demand Response schemes.

Willingness to change production times	Germany	Brazil	China
Yes	1.9%	31.9%	29.3%
Future: significantly	2.9%	13.8%	20.2%
Future: small extent	11.5%	8.6%	29.0%
No	42.3%	10.3%	6.8%
Don’t know	33.7%	25.0%	9.5%
N/A	7.7%	10.3%	5.2%
Number of participants	**104**	**116**	**441**

Question: Would your company change production times if, for example, that meant lower energy costs? (Four nominal options: Yes,we already do | We will in the future to a significant extent | We will in the future to a small extent | No)

According to our data more than 49% of Chinese ($n = 441$) and 46% of Brazilian ($n = 116$) companies do already shift their production schedules or intend to do so in a significant magnitude in the future, in order to reduce their energy costs. This holds true for only 5% of German companies ($n = 104$) – see also Table 8. However, it is worth noticing the large share of German and Brazilian companies here which could not answer this question.

If we add up all three categories which signalise a readiness to practice Demand Response management in the future or already

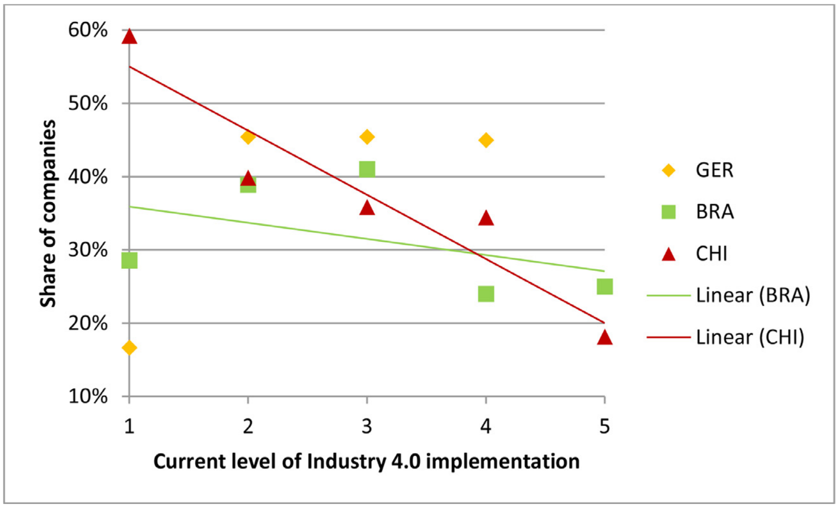

Fig. 4. Expectations for combined lower or much lower energy use due to Industry 4.0 per Industry 4.0 level of respective companies (ranging from "1 - Not digitally interconnected" to "5 - Fully digitally interconnected").

Table 9
Willingness to participate in Demand Response schemes per company size.

Participation in Demand Response scheme	GER	BRA	CHI
1 < employees <250	7.9%	50.0%	81.2%
250 < employees < 5000	17.2%	50.0%	78.3%
5000 < employees	24.3%	63.9%	65.2%

do so, the shares of Chinese companies are highest for all groups of company sizes. The biggest acceptance for such approaches can be detected for small and medium-sized companies in China. In Brazil and Germany the trend is reversed: here larger companies show bigger openness for such approaches (see Table 9).

Not a single participating German company from the automotive, electronics or ICT sector currently changes its production times in order to save energy costs. This is quite different in Brazil and China, where more than 25% of companies in all sectors follow this approach already. Interestingly the values in China for the two options *"Yes, we already change production times depending on for instance energy costs"* and *"In the future: Yes, to a significant extent (>5% of the production volume)"* are very similar in all sectors. There are only marginal differences between OEMs and Suppliers and between single-item and serial producers in all three countries. When only looking at the two combined options for the willingness to follow this approach a) already now or b) in the future to a significant extent and relating them to the current Industry 4.0 level of companies one could assume a positive association for Brazilian companies – see trend line in Fig. 5.

In order to evaluate this hypothesis H4, we performed Fisher's exact test to check for association between willingness to change production times depending on external factors (including all answer options) and the current Industry 4.0 level. No association was found in Germany ($p = 0.4556$), Brazil ($p = 0.141$) or China ($p = 0.0543$). We also assessed association in the three Chinese sub-samples from Liaoning, Jiangsu, and Zhejiang. A significant association was found in the sample from Liaoning ($p = 0.0423$), but not in Jiangsu ($p = 0.7525$) or Zhejiang ($p = 0.521$).

4.3. Industry 4.0 potentials for environmental management systems

Question: 5.1 Does your company operate an environmental or sustainability management system (ISO 14,001, EMAS and/or guidelines like ISO 26,000, Global Reporting Initiative)? (Three nominal options: Yes | No |No, but we will in the future)

Broadening our scope regarding the impacts of Industry 4.0 on environmental sustainability, we asked participants to report about the operation of environmental or sustainability management systems (following e.g. ISO 14,001, EMAS or guidelines like ISO 26,000 or the Global Reporting Initiative) in their companies. The majority of participating companies does already have such an environmental or sustainability management systems (EMS) in place (GER: 51%; BRA: 56%; CHI: 61%) with a smaller share of companies planning to set those systems up in the future (GER: 4%; BRA: 10%; CHI: 15%).

There is also a noticeable difference in the degree of digital interconnectedness between companies operating an EMS and those who are not. amongst those who do, 28% in Germany ($n = 53$), 38% in Brazil ($n = 65$) and 35% in China ($n = 271$) report one of the two highest degrees of digital interconnectedness. In contrast, amongst respondents who report not to operate an EMS, these two highest levels of Industry 4.0 implementation are much lower in Germany (8%, $n = 26$), Brazil (10%, $n = 29$), and China (8%, $n = 36$). Overall, companies that do not have an EMS in place tend to be less digitally interconnected in all three countries. No clear pattern can be identified for the companies with such systems already in place. We checked this assumption by performing Fisher's exact test to assess the association between the Industry 4.0 level of companies and the operation of EMS. A significant association was found in Germany ($p = 0.000009$), Brazil ($p = 0.0152$), and China ($p = 0.000008$). Looking more closely at the Chinese subsamples, a significant association was found in Liaoning ($p = 0.0049$) and in Zhejiang ($p = 0.0016$), but not in Jiangsu ($p = 0.1515$).

With regards to company size, there are noticeable differences both within and between countries. In Germany and Brazil, respondents mention the operation of environmental management systems more frequently in larger companies, ranging from 21% in German SMEs ($n = 39$) and 17% in Brazilian SMEs ($n = 24$) to 84% in companies with more than 5000 employees in Germany ($n = 37$) and 83% in the same category in Brazil ($n = 36$). In Chinese responding companies, we find deviations especially in smaller companies. Noticeably, operation of environmental management systems is much higher in SMEs (59%, $n = 229$). It peaks at 65% in companies with a size of 250 – 5000 employees ($n = 29$), but drops to 61% in companies with a size of more than 5000 employees ($n = 46$) (see Table 10). Fisher's exact test shows a significant association between the operation of EMS and company size in Germany ($p = 0.0000003$), Brazil ($p = 0.00002$), and China ($p = 0.00002$). In the Chinese subsamples, a positive asso-

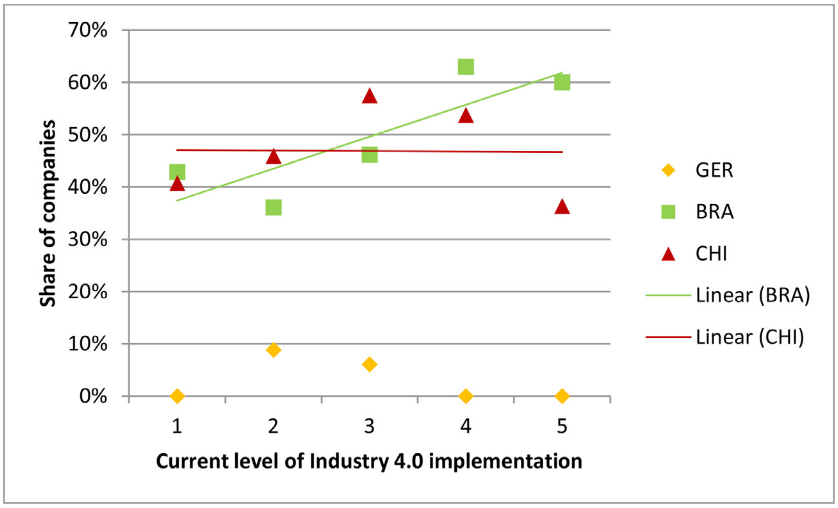

Fig. 5. Relation between willingness to change production times depending on external factors and the current Industry 4.0 level of the respective company (ranging from "1 - Not digitally interconnected" to "5 - Fully digitally interconnected").

Table 10
Share of companies operating an environmental management system per company size.

Operating EMS	Germany	Brazil	China
1 < employees <250	20.5%	16.7%	59.0%
250 < employees < 5000	51.7%	55.4%	65.1%
5000 < employees	83.8%	83.3%	60.9%

ciation was found in Zhejiang (p = 0.0171), but not in Liaoning (p = 0.0556) or Jiangsu (p = 0.1382)

Looking at different sectors, the results show that the operation of environmental management systems is much more common in the automotive sector than in many other sectors. In China, 69% reported to operate an environmental management system in this sector (n = 64), slightly less frequently than in Germany (74%, n = 19) and in Brazil (83%, n = 30). In contrast, operation of environmental management systems differs greatly between countries in the plant construction and engineering sector. Only 35% of Germany respondents responded 'Yes' (n = 43), compared to 44% in Brazil (n = 16) and 65% in China (n = 144).

Question: Will 'Digitalisation and Interconnectedness' have an effect on the way this management system is operated? (Two nominal options: Yes | No)

Overall, there is great uncertainty amongst respondents concerning the impact of Industry 4.0 on the way that environmental management systems are operated. 24% of Chinese companies (n = 383) responded that they do not know its effect, compared to 32% in Brazil (n = 65) and 43% in Germany (n = 53). A similarity across countries is that more respondents believe that Industry 4.0 will impact the operation of environmental management systems (GER: 38%, BRA: 49%, CHI: 45%) rather than not (GER: 15%, BRA: 12%, CHI: 15%).

We implemented an open question to provide respondents the opportunity to specify the assumed impact of Industry 4.0 on the operation of EMS. Out of the 17 responses amongst German participants, 7 emphasize the impact of higher quality input data on improving operational performance. Out of 30 responses amongst Brazilian participants, the most frequent answer alluded to greater flexibility of operation in combination with greater control over relevant processes with environmental impacts, including risk assessments, as mentioned by a total of 11 respondents. Also, 30 out of 64 Chinese respondents highlight expectations regarding overall management efficiency. Moreover, noteworthy assumptions are that Industry 4.0 may impact the environmental management system by shortening the response time to issues or risks, by automating (responses to) energy efficiency measures, and by fostering standardization of data management.

Question: **To what extent can production related data already be integrated into your environmental or sustainability management system?** (Four nominal options: Fully integrated | Partially integrated | No integration yet, but planned | No integration)

Complementing our findings on the perceived Industry 4.0 level in companies, we aimed to specify how this relates to other indicators at the interface of Industry 4.0 and environmental sustainability. Thus, we asked participants to rate the extent to which production related data can already be integrated into their environmental management system, differentiating between "full integration", "partial integration", "planned integration", and "no integration".

Grouping "full integration" and "partial integration" on the one hand, and "planned integration" and "no integration" on the other hand, there is a tendency amongst the group with existing integration solutions ("Int") to report higher levels of Industry 4.0 (see Fig. 6). Accordingly, amongst those who are currently unable to integrate production related data into EMS ("No int"), relatively large shares report lower levels of Industry 4.0.

We performed Fisher's exact test to check for association between the Industry 4.0 levels of companies and the ability to integrate production related data into EMS. The analysis shows a significant association for China (p = 0.0000001), but not for Germany (p = 0.2642) or Brazil (p = 0.0599). Looking at the Chinese subsamples, a significant association was found in Liaoning (p = 0.0203), and in Zhejiang (p = 0.00005), but not in Jiangsu (p = 0.1162).

5. Discussion

Even though the results of our study draw a mixed picture, the overall impression suggests that the broad implementation of the concept Industry 4.0 can create opportunities for more environmental sustainability of companies.

5.1. Industry 4.0 and environmental sustainability

This impression was particularly strong, when we directly asked respondents about their expectations regarding the impact of Industry 4.0 on the respective company's environmental sustain-

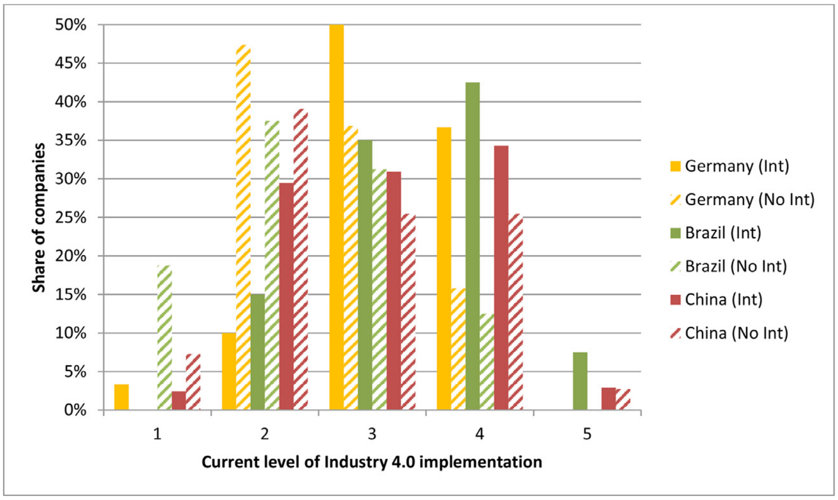

Fig. 6. Industry 4.0 levels of companies compared between those who are able to integrate production related data into EMS ("Int"), and those who are unable to do so ("No int").

ability. Respondents from all countries have in common that far greater shares expect (significant) improvements as opposed to (significant) deteriorations of environmental sustainability due to the implementation of Industry 4.0. Hence, there seems to be a shared assumption that the positive impacts will outweigh negative impacts associated with the proliferation and interconnection of digital technologies in companies concerning the overall environmental friendliness of industrial production. We have found a positive and significant association in Brazil and China between the current level of Industry 4.0 implementation of a company and the expectation to improve its environmental sustainability through the application of the Industry 4.0 concept - but not in Germany. Therefore our hypothesis H1 can only be partially confirmed.

This is in line with a broad strand of the current scientific discussion (Ghobakhloo and Fathi, 2021; Enyoghasi and Badurdeen, 2021; Bag et al., 2021; Gupta et al., 2021). Although empirical evidence is scarce, there are high hopes for Industry 4.0 to foster environmental sustainability within industry. For instance, the Global e-Sustainability Initiative (GeSI), aiming to promote sustainable practices within the ICT industry, expects significant improvements regarding carbon emissions. They project that until 2030, the abatement potential of Industry 4.0 will be seven times the size of the expected growth of carbon emissions in the ICT sector (GESI, 2019). However, the positive assessments we present should be viewed with caution, as the current levels of Industry 4.0 implementation are mainly reported to be mediocre, which is why we conclude that a significant share of these expectations are unlikely to be based on substantial individual experience with the concept Industry 4.0. Brazilian respondents do not report a significantly higher implementation of Industry 4.0, but a larger share expects significant improvements of environmental sustainability compared to their German and Chinese counterparts. Further analysis is needed to investigate factors which may influence differences in expected trajectories even though starting positions may be similar. Socio-economic framing conditions as well as political strategies and incentives may play a crucial role in this regard (Kunkel and Matthess, 2020; Yuan and Zhang, 2020).

Moreover, it is worth noting that especially in Germany and Brazil, there is a tendency that the expectations towards the environmental effects of Industry 4.0 are more optimistic in larger companies compared to the country average. More specifically, we have observed this effect with regard to the lower material use for German and Chinese companies and with regard to a lower energy use for Chinese companies. Conversely, there are different possible explanations as to why expectations may be less optimistic in smaller companies. Firstly, recent publications emphasise a number of barriers for SMEs with regard to integrating Industry 4.0 technologies into their manufacturing operations, such as limited financial means or a lack of human resources (Kumar et al., 2020; Amaral and Peças, 2021; Masood and Sonntag, 2020; Müller et al., 2017). Thus, SMEs may perceive a general lack of ability to benefit from technological advancements and digitalisation given low levels of implementation. This also relates to our finding that there seems to be a positive association between the level of Industry 4.0 implementation and optimistic expectations regarding environmental sustainability. Hence, the results suggest that companies may have to pass a certain threshold of Industry 4.0 implementation to reap the benefits. Secondly, smaller companies may have less resources to harvest from potential benefits concerning environmental sustainability, or strategic considerations regarding digitalisation may revolve around environmental sustainability less frequently (Kumar et al., 2020; Amaral and Peças, 2021). In general, Kouloukoui et al. (2019) find that environmental reporting – requiring the means and willingness to collect and analyse relevant data in the first place – is more common in larger companies.

Contrasting the findings concerning overall environmental sustainability, our results indicate mixed expectations regarding the effects of Industry 4.0 implementation on material and energy efficiency. Only amongst Chinese companies was there a substantial share expecting lower material use due to Industry 4.0. In contrast, Chinese respondents also expected a rise in energy use due to Industry 4.0 implementation more often than Brazilian and German respondents. Accordingly, our hypothesis H3 needs to be rejected as our data shows a significant but negative association between the current level of Industry 4.0 implementation of a company and its expectation to reduce its energy consumption due to Industry 4.0 technologies in China.

Overall, we cannot support the notion that practitioners echo overly optimistic expectations that were raised in the scientific discussion on related topics. Moreover, we find deviations to a preceding study by Beier et al. (2017) who reported more optimistic expectations of practitioners in the past. In accordance with our further findings, higher levels of Industry 4.0 implementation seem to be associated with more pessimistic expectations regarding energy efficiency. This is also a contrast to the positive association between Industry 4.0 implementation and expectations for overall environmental sustainability that we found. Against this backdrop, more in-depth analysis is required to assess the relevance of different indicators of environmental sustainability that practitioners aim to optimise through digitalisation. Leverage points to foster environmental sustainability through digitalisation do not necessarily lie within the company's boundaries and may require a supply chain wide perspective (Manavalan and Jayakrishna, 2019). Furthermore, heterogeneous expectations found in different sectors indicate varying potentials to improve resource efficiency through Industry 4.0. Both Chinese and Brazilian companies showed great optimism in the automotive sector, for which to our knowledge only very few isolated positive examples exist in the literature (Riazi et al., 2017; Hacksteiner et al., 2019).

We find great differences between countries regarding their openness to practice Demand Response management. More specifically, only a minority of German companies already adapts production times flexibly to reduce energy costs. Similarly low shares of German respondents indicate a willingness to do so in the future. Accordingly, we have found no significant association between the current level of Industry 4.0 implementation of a company and its participation in Demand Response Schemes in Germany, Brazil or China. Therefore, hypothesis H4 cannot be confirmed.

The International Energy Agency highlights great potential of digitalisation to foster Demand Response management and thus optimise renewable energy usage in the grid (IEA, 2017). However, our results do not suggest an association between the level of Industry 4.0 implementation and the willingness to practice Demand Response management. This may imply that reduced energy costs are not a sufficient incentive for companies to change production times accordingly due to limited financial benefits (Guo et al., 2017). Looking at China, respondents' positive assessment of Demand Response management can be related to recent endeavours of developing a wholesale energy market in the country, further stressing the importance of facilitating boundary conditions (Guo et al., 2017). In conclusion, there is a lot to be gained to improve environmental sustainability in industry by fostering this approach, especially because large shares of Brazilian and German respondents are still undecided regarding the implementation of Demand Response management, but also because renewable energy production has steadily increased in both countries in recent years (IRENA, 2021).

We also find that especially Brazilian companies report positive impacts of Industry 4.0 implementation on their ability to match supply with demand. Interestingly, large shares of Brazilian and Chinese respondents report improved matching abilities at low levels of Industry 4.0 implementation already. Overall, hypothesis H2 can only be partially confirmed as our data suggests a significant association between the current level of Industry 4.0 implementation of a company and its capability to match its supply with the actual demand through Industry 4.0 technologies in Germany and China, but not in Brazil. Moreover, greater benefits were reported in serial production as opposed to single item production. It has often been emphasised that digital integration of supply chain partners provides mutual economic benefits, for instance by sharing production plans and forecasts to reduce inventory and optimise transportation (Vanpoucke et al., 2017). Our results indicate that even with a low level of Industry 4.0 implementation some "low hanging fruits" seem to be within reach, which would allow to improve environmental sustainability by preventing surplus production and by using transportation modes efficiently.

5.2. Industry 4.0 potentials for environmental management system

The majority of companies surveyed in all three countries state that they already have an environmental management system (EMS) in place. The implementation of EMS appears to be particularly widespread in the automotive sector. Moreover, we find a positive and significant association between the level of Industry 4.0 implementation and the likelihood for operating an EMS in Germany, Brazil and China. We have also found a positive and significant association between the respective company size and the likelihood for operating an EMS in Germany, Brazil and China. Therefore, our hypotheses H5-a and H5-b can both be confirmed.

This highlights the benefits of digital solutions for the collection and analysis of data to improve corporate environmental management. For instance, Belhadi et al. (2020) show that Big Data analytics provides the means to analyse complex environmental data which is generated at different nodes in the company. Additionally, a set of use cases of how Big Data analytics can support EMS in the automotive industry is presented in Beier et al. (2020a). Against this backdrop, it is important for companies to not only consider the implementation of Industry 4.0 to acquire large amounts of data. It is equally important to strategically consider how this data can be transformed to support decision-making and thus improve transparency (Morgan et al., 2018) and ultimately contribute to improvements of environmental performance. This trend is likely to be accelerated by current developments in legislation and jurisdiction, in which compliance with the SDGs is interpreted as a mandatory activity for all stakeholders. However, as Shao et al. (2017) highlight, many companies are inexperienced applying modelling techniques in production facilities, which impedes the detection of issues with regards to e.g. energy usage optimisation.

In this context, our findings provide valuable insights regarding data integration from the shop floor. We find that the ability to integrate production related data into EMS is positively associated with the level of Industry 4.0 implementation, at least in China. Hence, as companies' ability to integrate data along the product lifecycle increases, sharing EMS data along the supply chain becomes more feasible through Industry 4.0. Thus, Industry 4.0 provides an opportunity to overcome challenges of traditional IT systems concerning the integration of largely isolated lifecycle data being collected by different actors along the supply chain (Gandomi and Haider, 2015).

We emphasise some limitations of our study. Firstly, sample sizes between countries differed, causing low numbers of respondents amongst surveyed German and Brazilian companies for some answer categories of the contingency tables, which limits generalisability of some findings. Moreover, high shares of respondents stating "Don't know" or "N/A" can be associated with the survey design, especially because open questions require more effort to answer. We also recognise potential impacts of cultural differences – an effect that cannot be neglected especially as we have chosen self-assessments as the method of choice for our survey. These could have affected the general attitude towards the expression of opinions and knowledge but may have also determined associations with certain terms and issues, although we initially defined their context. Future studies could address this uncertainty by reflecting on cultural differences especially with regard to the understanding of the term environmental sustainability and its underlying concepts.

6. Conclusions

Digital technologies can potentially drive the transformation of industrial production towards a more sustainable economy, which is a prerequisite if the UN Sustainable Development Goals shall be met. Two objectives are essential to make industrial production more environmentally sustainable: decarbonisation and dematerialisation on a global level. For these reasons our study has empirically investigated the potentials to reduce resource (dematerialisation) and energy demand as well as opportunities to couple the industrial with the energy sector (decarbonisation) through the broad application of Industry 4.0 technologies looking at Brazil, China and Germany. Comparing these potentials from a multi-country perspective is novel to this emerging research field. A first finding shows that ten years after the introduction of the Industry 4.0 concept the current level of its implementation in industry is still mediocre, with German companies slightly trailing behind their Brazilian and Chinese counterparts.

Furthermore, our analysis shows that the positive attitude that digitalising production processes in accordance with Industry 4.0 will be automatically leading to efficiency gains, is also common amongst industrial practitioners. The majority of respondents expects an improvement of the environmental sustainability of their respective company due to the broad application of Industry 4.0 technologies. At the same time, expectations regarding improvements in resource efficiency are cautious. In contrast to the expectations expressed in vast parts of the literature, practicioners' expectations regarding energy savings may decrease with an increasing level of Industry 4.0 implementation, which the growing experience with this technological concept could possibly explain. Reasons for these observations can be manyfold: an increase in production in absolute terms, a tendency to focus on process instead of resource efficiency, and a failure to take full advantage of the potentials of digitalisation for corporate sustainability management.

These findings are a strong indication for policy makers and practitioners that Industry 4.0 will not automatically lead to environmental improvements, instead this transformation towards a more sustainable economy needs to be accompanied by supporting measures such as a regulation that includes clear targets and according incentivisation. From a managerial perspective, it is important to critically reflect in how far specific digital technologies will actually serve strategic purposes of the organisation before deciding for their implementation. Managers must therefore consider how they want to bring their company in line with the goals of sustainable development and strategically decide what role digital technologies should play in it and where other supplementary measures may be necessary. To do this, the corporate goals must be critically mapped with the respective possibilities of digital technologies (taking into account the specific application context) and the measures decided upon must be implemented consistently across the entire organisation. Synergies and potential contradictions between broadly defined economic goals and increasingly important environmental goals should also be explored for different time spans, bearing in mind near- and long-term impacts of the respective technology implementation.

On the side of the positive findings, it should be noted that the higher the Industry 4.0 level of the companies, the greater their ability to match their supply with the actual demand as well as their likelihood for participating in Demand Response schemes and operating environmental management systems. This finding holds a promising lesson for policy makers, as it shows that the potential to fulfil an essential prerequisite for the stabilisation and efficient use of future renewable energy systems is given, which needs suitable framework conditions to materialise.

Our results also provide valuable insights concerning the operation of environmental management systems. While the association between Industry 4.0 implementation and operation of environmental management systems suggests an even greater application of such systems in the future, we emphasise the importance for further consideration of the prerequisites and consequences of digitally-enabled data integration into environmental management systems. Drawing connections to our other findings, Beier et al. (2020a) highlight the need to integrate separately conducted energy optimisation measures both within companies and in the supply chain. Thus, significant efforts for organisational coordination are needed to leverage digital approaches for goals of corporate environmental sustainability (Beier et al., 2020a). Whereas digitalisation will undoubtedly improve the ability to generate data, accompanied measures need to ensure the establishment of data processing capabilities as well. Thus, to improve decision-making on various issues of corporate environmental sustainability, data integration efforts need to be supply chain wide, a task yet to be fulfilled by the majority of companies in the light of limited transparency, especially at lower tiers (Grimm et al., 2016). Besides data integration, this may also entail standardisation of environmental indicators and their measurement between firms (Zhou et al., 2016).

Given the scarce empirical evidence regarding the impacts of Industry 4.0 on corporate environmental sustainability, our study makes a contribution to overcome this gap by investigating practitioners' expectations and experiences. We conclude that there are a number of key factors covered by our study that seem to be vital in order to improve environmental sustainability in industrial production through Industry 4.0 technologies, which are summarised in the following framework (Fig. 7).

This study can help Industry 4.0 stakeholders – especially policy makers and practitioners but also fellow researchers – to better understand the current trends in the implementation of this technological concept and in how far this development is supporting the transformation towards more sustainability. In the ongoing transition to a digitalised economy, a stronger research focus

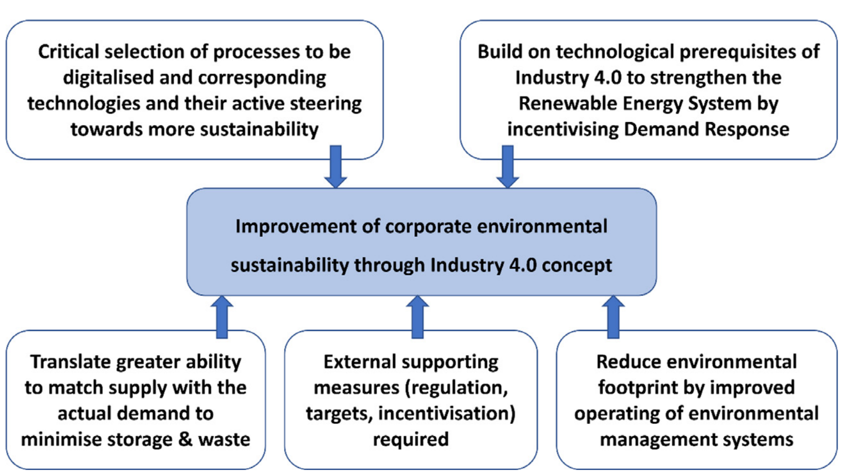

Fig. 7. Framework to improve corporate environmental sustainability through the Industry 4.0 concept.

on the nexus of digitalisation and sustainability must be supplemented by setting binding targets for saving energy and material and reducing non-recyclable waste. Such research should also address the question how regulations and incentivisation can be most effectively balanced. The implementation of the Industry 4.0 concept should not be understood as a benefit in itself, but always be critically evaluated against the background of the SDGs instead. Only then will a digitalised industrial production be able to serve the people without harming the environment.

Funding information

Funding body	Grant number	Recipient
Alexander von Humboldt foundation	3.4 - 1149468 - CHN – IP	Ting Guan, Grischa Beier
The Fundamental Research Funds for the Central Universities	2020NTSS33	Ting Guan
Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES)	Finance Code 001	David Iubel de Oliveira Pereira Grudzien
Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq)	308137/2018–3	Edson Pinheiro de Lima
German Federal Ministry of Education and Research	01UU1705A	Grischa Beier
National Natural Science Foundation of China	41971166	Bing Xue
Liaoning XinLiaoRenCai Program	XLYC2007201	Bing Xue

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We would like to express our sincere gratitude to Simon Terhorst and Luke Shuttleworth for their tireless efforts and incredible work during the data collection phase. We would also like to thank our respondents for taking the time to participate in the survey – as well as our partners who supported us in the distribution of the survey. These include the Bundesverband der Deutschen Industrie e.V., Plattform Industrie 4.0, a number of Mittelstand 4.0 competence centres, VDI Zentrum Ressourceneffizienz, econsense, Verband für Nachhaltigkeits- und Umweltmanagement e.V., and the competence platform nachhaltig.digital.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.spc.2022.02.015.

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