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Sustainability related impacts of digitalisation on cooperation in global value chains: An exploratory study comparing companies in China, Brazil and Germany

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A R T I C L E I N F O

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A B S T R A C T

While digitalisation is reconfiguring global value chains (GVCs), the implications for sustainable development, especially in emerging economies, have not yet been thoroughly explored. In order to design more sustainable GVCs this gap must be addressed. This study examines two implications of digitalisation in value chains: first, how polarisation may lead to inequal development; and secondly, whether digital enhanced transparency can be an enabler of companies' environmental management systems (EMS). A survey-based approach is used to compare the developments of companies in China, Brazil and Germany and gain insights into countries that approach digital transformations from different starting points. The results indicate that polarisation tendencies on a country level are not as pronounced as experts predicted. Across all countries, less than 10% of companies reported that collaboration processes are being fully digitalised, while partial digitalisation is more common, ranging from 46% in Brazil ($n = 116$), to 61% in China ($n = 441$) and 63% in Germany ($n = 104$). Polarisation tendencies are stronger among small- and medium-sized companies (SMEs) across all countries. As SMEs form the backbone of countries' economies, this should be addressed by global governance. Digital enhanced transparency for EMS is not yet widespread, with only 9% of the German, 3% of the Brazilian and 6% of the Chinese companies integrating production data into their EMS in a fully digital way. The results of this study suggest that the automotive sector would provide a suitable object for future research, as it displays clear differences to other industries.

1. Introduction

The sustainable design and organisation of future GVCs is considered to be an important lever for efforts to achieve the United Nations Sustainable Development Goals (SDGs) (Della Navarrete et al., 2020; Fessehaie and Morris, 2018; Matheis and Herzig, 2019). The digital transformation of industry, often referred to as the 'fourth industrial revolution' or Industry 4.0, is predicted to transform GVCs in length and geographical distribution (Zhan, 2021). Given this, it is important to consider how digitalised GVCs will influence sustainable development. The concrete implications and consequences of digitalised value chains are not yet well researched or understood (Manavalan and Jayakrishna, 2019a).

Based on previously conducted studies (Beier et al., 2020, 2021) and a literature review, two main aspects are identified as playing an important role in the sustainability of future digital GVCs. The first is the threat of inequal development or digital divide(s) rooted in unequal access to technology, the uneven development of underlying

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infrastructure, and differences in the ability to apply technology (Andersen et al., 2021; Fessehaie and Morris, 2018; Song et al., 2020; van Deursen and van Dijk, 2019; World Bank Group, 2022). This could jeopardise the SDG of inclusive and sustainable industrialisation. Industry 4.0 provides opportunities to engage with new suppliers (Glas and Kleemann, 2016) but developing and emerging countries may struggle to meet higher quality standards and maintain a high-skilled workforce needed to operate in digitalised supply chains (World Bank, 2020). The slower adoption of digital technologies could also lead to inequalities and unsustainable development within countries, for instance between different sectors or large and small firms (Birkel et al., 2019).

The second aspect is to support environmental management along the supply chain through the use of digital technologies to improve transparency and provide reliable data in Industry 4.0 contexts (Chiappetta Jabbour et al., 2020; Esmaeilian et al., 2020; Hrouga et al., 2022; Manavalan and Jayakrishna, 2019a; Mangina et al., 2020; Nikolakis et al., 2018). Applied to this end, digital transparency could help to address known sustainability threats such as offshoring to countries with lower social and environmental standards (Clarke and Boersma, 2017) and accurately identify specific sustainability challenges faced by companies in GVCs (Muñoz-Torres et al., 2021; Shaikh et al., 2020). The transparency of an idealised digital GVC is based on a digital network connecting producers, customers, and end-users via information and communication technology (ICT), enabling a continuous flow of information between factories, manufacturing systems, and products. The availability of real-time information from the industrial internet of things (IoT) and advanced analytical capabilities (e.g. big data analytics) as well as improved reliability (e.g. through blockchain technology) facilitate the self-organisation of production processes and promote transparency, flexibility, and efficiency (Beier et al., 2020). Industry 4.0 technologies could document and analyse environmental data across the value chain. The topic of transparency is addressed by some studies from a technological perspective, discussing, for example, the potential of blockchain technology to improve supply chain transparency and support sustainability objectives such as product life cycle transparency (Esmaeilian et al., 2020; Nikolakis et al., 2018), transparency for resource management (Rejeb and Rejeb, 2020), transparency for compliance in the case of hazardous waste treatment (Hrouga et al., 2022) as well as barriers to transparency and sustainable blockchain adoption (Kouhizadeh et al., 2021; Saberi et al., 2019). Other studies discuss how platform-based solutions can enable environmental data sharing (Peukert et al., 2015; Xing et al., 2016), how digital sharing platforms can potentially support a circular economy (Schwanholz and Leipold, 2020) and how big data analysis can support sustainable supplier selection (Ghadimi et al., 2019; Liu et al., 2020) as well as reduce emissions and improve efficiency in logistics operations along the supply chain (Mangina et al., 2020). A small number of studies examine not only the technical opportunities and barriers, but also the attitudes that influence the use of digital transparency for corporate sustainability management (Niehoff, 2022).

While impacts on sustainable development are discussed in the literature on a theoretical level, there is little empirical research on the actual implementation of digital technologies and their impact on aspects of sustainable development. Moreover, only limited research investigates the nexus between digitalisation in the supply chain and sustainability in emerging economies and considers not only technological aspects but also the social and firm-specific contexts within which they are applied (Foster et al., 2018). The present study speaks to this research gap by empirically examining digital development in the emerging economies of China and Brazil and the industrialised economy of Germany, as viewed by employees of companies of different sizes and from various sectors. While the digital divide has often been measured using so-called first- and second-level indicators such as access to the Internet (first-level) and digital skills (second-level), more recent articles have also focused on third-level indicators related to Internet usage outcomes (Song et al., 2020; van Deursen and van Dijk, 2019). In this sense, a survey-based approach is employed that examines digitalisation from the perspective of corporate users of digital technologies. The chosen case countries of Brazil, China, and Germany provide insights into the development of digitalisation in countries with different preconditions for digital transformation. Building on an earlier study which compared Germany as a highly industrialised country with China as a major emerging country (Beier et al., 2017), the sample was extended with Brazil, an emerging country with high economic significance on the South-American continent. This study addresses the potential risk of inequal development between these countries as well as within the countries (e.g., between small and large companies). The aspect of transparency is explored by focusing on the data sharing and integration function enabled by digital technologies, as well as on the quality of collaboration along the supply chain. By combining different aspects and perspectives with regard to the complex linkage between sustainable development, digitalisation, and GVCs, the study provides a comprehensive basis and starting point for further research and policy development. This helps to capitalise on the window of opportunity for aligning digitalisation and sustainable development at a moment when digital transformation, with all its intended and unintended side-effects, is still fraught with many uncertainties.

The research questions addressed in this study are:

1. To what degree is the concept of Industry 4.0 implemented and to what degree are collaborative value chain processes currently digitalised and interconnected in Chinese, Brazilian and German companies?
2. How has this changed the quality of cooperation and the number of partners in collaboration networks?
3. Are polarisation tendencies evident among:
    - o countries,
    - o companies of different sizes, or
    - o different sectors?
4. Are companies taking advantage of the transparency offered by Industry 4.0 to support sharing and integration of environmental data into environmental management systems?

The paper begins with a “Theory and Background” section that provides an overview of the state of digitalisation in the surveyed countries and summarises the literature review on digital GVCs and sustainability. The methodological approach is described in detail in the “Material & Methods” section. In the “Results” section the survey data is presented. In the “Discussion” the results are interpreted in light of the sustainability aspects inequality and transparency. The paper concludes (see “Conclusion & Outlook”) with an overview of the findings and areas for further research on GVCs, digitalisation, and sustainability.

2. Theory and Background

This section gives an overview of recent trends and developments in digitalisation in China, Brazil, and Germany in order to enable comparison of the findings within their different contexts. A short overview of the current scholarly discussion at the nexus of digitalisation, GVCs, and sustainability is also provided.

2.1. Digitalisation in China, Brazil, and Germany

Given their socio-economic and technological relevance and different preconditions for digitalisation, China, Brazil, and Germany are suitable case countries for assessing polarisation tendencies. China is the most populated country and the fourth largest country in the world in terms of its surface area. Its estimated GDP is 17,458 bn. US$ (Statista, 2022a). Brazil is the fifth largest country in the world, both in terms of area and population. Its estimated GDP is 1,608 bn. US$ (Statista, 2022a). Germany is the largest economy in Europe with a share of 21 percent of European GDP (Germany Trade and Invest, 2019). The country's estimated GDP is 4,226 bn. US$ (Statista, 2022b).

In all three countries, digitalisation is seen as an important vehicle for economic development and is supported by policies and investment. China has enacted a "Made in China (2025)" strategy to support relevant research and innovation; Brazil pursues a "Digital Transformation Strategy"; and Germany a "High Tech Strategy" (Federal Ministry of Education and Research, 2018; Ministry of Science, Technology, Innovation and Communications, 2018; State Council of China, 2015).

Different tools exist to predict and compare the progress of digitalisation in different countries. One of these tools is the Network Readiness Index (NRI), which is based on interviews with high-level experts. It evaluates the application and impact of ICT on different economies and their digital transformation potential (Portulans Institute, 2020). The NRI takes a holistic view of digital transformation and considers multiple variables (pillars) across the four dimensions: 1. technology (pillars: access, content, future technology), 2. people (pillars: individuals, businesses, governments), 3. governance (pillars: trust, regulation, inclusion) and 4. impact (pillars: economy, quality of life, SDG contribution) (Portulans Institute, 2020).

China's overall ranking in the NRI is 40th out of 134 countries but 2nd among the group of upper-middle income countries. Germany holds the 9th position out of the 134 economies and also the 9th position in the group of high-income countries. Brazil ranks 59th among the 134 countries and 12th in the group of upper-middle income countries. Fig. 1 gives an overview of the scores in each dimension for Germany, China, and Brazil (Portulans Institute, 2020). The indicator 'business use of digital tools' (People Dimension) is of special relevance for this study. In this indicator, Germany is ranked 10th and Brazil is ranked 39th. No data for China is available for this indicator (Portulans Institute, 2020).

Although the NRI does not look specifically at Industry 4.0 readiness, it provides a first impression of the countries' potential for digital transformation. The overall ranking shows a digital gap between Germany and the significant lower rankings held by China and Brazil. In particular, the category of technology development points to possible polarisation tendencies between China, Germany, and Brazil.

2.2. Links between digitalisation of GVCs and sustainability - current literature

'Sustainable supply chains' and 'industry 4.0' are both significant fields of literature, but research examining the relationship between the two is limited. We address two key themes that emerged from the literature review. The first is the potential for Industry 4.0 to harm social sustainability goals, such as the goal of fair and inclusive growth due to digital divides and polarisation tendencies between countries and/or within countries. The second is that digital technologies can facilitate transparency and validity for the purpose of environmental management. Each is discussed in turn, below.

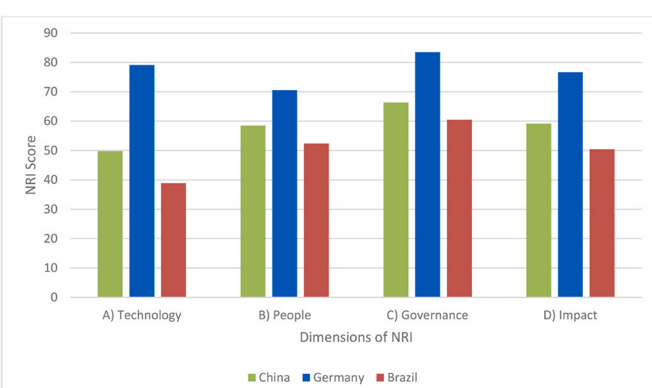

Fig. 1. Network Readiness Index Scores for China, Germany, and Brazil, based on Portulans Institute (2020)

2.2.1. Polarisation as a threat to sustainable development

Digitalisation is expected to influence market access and the positioning of companies in the value chain (World Trade Organization, 2019). This can contribute to inclusive economic growth by making it easier for firms to access value chains and develop new business opportunities, such as trading goods and services in online markets (World Bank, 2020). Chinese e-commerce companies, for example, have benefited from greater access to markets and are now among the largest and most innovative companies in the world (Lichtenthaler, 2018; Su and Flew, 2020). On the other hand, the digital global market, is still dominated by developed countries (Murthy et al., 2021). Digitalisation may further polarise economic access by creating obstacles for new entrants to value chains. Digital value chains may require infrastructure and investment in digital tools and knowledge that some developing countries currently lack (World Bank, 2020).

2.2.2. Digital supported transparency as a chance for sustainable development

The idea that digital technologies promote transparency in supply chains by sharing and integrating environmental data, in turn supporting collaborative value chains, is discussed in the literature from both a general perspective and in terms of specific technologies. A streamlined flow of information across the supply chain and effective communication among stakeholders enhances the effectiveness of sustainable practices (Bag et al., 2018; Ding, 2018) and allows the transfer of information on green initiatives (Luthra et al., 2020). Industry 4.0 technologies can also support circular manufacturing systems and the uptake of circular economy practices. Manavalan and Jayakrishna (2019b) note that IoT technologies can improve the visibility of the production process, enabling the re-use and re-design of waste products. Nascimento et al. (2019) note how digitalisation can support the shared aims of sustainable supply chain management and circular economy practices, particularly stakeholder cooperation and value co-creation.

Studies examining specific Industry 4.0 technologies reveal their potential to enhance the sustainability of supply chains. Chiappetta Jabbour et al. (2020) suggest that big data has benefits for each dimension of the triple bottom line in supply chains. Investigating the utilisation of IoT for supply chain transparency, Abdel-Basset et al. (2018) propose a website as a digital interface to integrate data stemming from radio frequency identification (RFID) along the supply chain. They highlight its applicability for tracing and analysing product data across companies.

Blockchain is the Industry 4.0 technology that has received a lot of attention in the literature. Saberi et al. (2019) note that "blockchains, as distributed, immutable, transparent, and trustworthy databases, shared by a community, can also influence sustainable supply chain networks", because they promote openness and transparency (Saberi et al., 2019, p. 2124). They highlight blockchain's potential to verify the origins of the materials and resources which constitute a product and the ability to accurately trace the carbon footprint of a product across the supply chain (Saberi et al., 2019). Esmaeilian et al. (2020) argue that the capacity for blockchain technology to enhance transparency is an incentive for green behaviour and will foster sustainability monitoring and reporting. Nikolakis et al. (2018) suggest blockchain can withstand the complexity of GVCs and help to address fragmented sustainability regulatory regimes in different countries.

There are no studies yet on the extent to which companies are already using digital technologies to exchange environmental information or on the extent to which production data can be automatically integrated into an environmental management system (EMS).

3. Material & Methods

A jointly-developed questionnaire was used as the method of choice for data acquisition to ensure companies in all three countries faced the same questions and answer options.

3.1. Questionnaire design

The questionnaire was iteratively developed in multiple video conferencing sessions by the authors (conducted in English) and begins with a brief explanatory text describing the main characteristics of the Industry 4.0 concept to ensure that participants share a common understanding. The questionnaire covered the following aspects: personal characteristics, company characteristics, implementation of 'Digitalisation and Interconnectedness', and effects of 'Digitalisation and Interconnectedness' on cooperation with external partners.

To ensure validity of the analysis, different measures were taken that are in line with previously described design principles of questionnaire studies (e.g., Drost (2011)). For instance, the construction of items is based on experience from prior studies (Beier et al., 2017) as well as a literature review, as partially summarised in Section 2. A review of relevant scientific literature led to the identification of a set of indicators that play a role in the debate around Industry 4.0 but also have relevance for sustainable production. Variables were mainly measured through a 5-point Likert-type scale, multiple nominal (verbally described) options or, in few instances, with a free text response. Additionally, the first two variants of questions also provided the two answer options "Don't know" and "No Answer". An overview of the relevant questions addressed in this paper is provided in Appendix I.

As a thorough pre-test, the preliminary questionnaire was discussed with potential interviewees in China and Germany to ensure its quality and relevance. Their feedback and comments were collected before the questionnaire was revised to ensure its validity. The final version was translated into German, Chinese and Brazilian Portuguese by professional translators and subsequently retranslated into German or English by native speakers not involved in the study in order to verify the quality of the translation.

3.2. Data acquisition and analysis

Generally, the sampling methods used were a combination of a) direct contacting of practitioners through telephone or email and b) spreading information about our study within networks linked to industrial associations. Using a web search, companies were identified in sectors seen as suitable for applying the concept of Industry 4.0 (such as manufacturing or plant construction and engineering) and contacted directly. In China, a professional agency was additionally contracted to contact companies for this purpose. In Brazil and Germany, all respondents provided their data through an online survey, while in China the extra mode of a paper-based questionnaire was additionally offered. Both the questionnaire and online survey had identical contents.

The questionnaire was distributed in the official language of the respective country by separate teams in China, Brazil, and Germany. Data was collected in three different Chinese provinces: Zhejiang, Jiangsu, and Liaoning. Some key information regarding the data acquisition process (such as the chosen format and time span) in all three countries is 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. In order to statistically test for an association between variables we performed a Chi-square test. In cases of statistically significant Chi-square values, we additionally calculated Spearman's ρ to test rank-order correlation. All tests have been calculated with Monte Carlo simulation of Fisher's exact test based on 10.000 samples.

Table 1
Format, duration and achieved sample size of the data acquisition process per country.

Country	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

3.3. Data set

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

3.3.1. Personal characteristics

Regarding the respondents' age: the difference between the youngest sample, Liaoning, and the oldest, 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, the samples in Germany and Zhejiang feature a much higher proportion of managers than those in Brazil, Liaoning, and Jiangsu.

Table 2 shows the key personal characteristics per country sample.

3.3.2. Company characteristics

Participants were asked about predefined categories related to the number of employees (see Appendix A: Questionnaire) and the groups were later classified based on the German definition of SMEs and large enterprises. In terms of company size, the German and Chinese samples most prominently include companies with less than 250 employees. At the same time, whiles companies with 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, considerable variation between the samples can be seen with regards to this indicator in Table 3.

The samples also diverge with respect to the sectors to which the companies are attributed. In four of the five samples, one third of the companies are involved in plant construction, but the other sectors differ in weight across the samples (see Table 4).

For all countries except Brazil, the largest group included in the sample are suppliers, with original equipment manufacturers (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

The following results describe a) the current status of Industry 4.0 implementation and the digitalisation of collaboration networks, and b) the sharing of environmental data with external partners and its integration into environmental management systems.

4.1. Industry 4.0 levels

Full implementation of the Industry 4.0 concept is still rare in all surveyed countries. With 30% (n = 440), China represents the highest rate of companies which consider themselves as "4 – highly digitally interconnected" or "5 - fully digitally interconnected" with Brazil following closely (28%, n = 116). In Germany about one fifth of all participants state that their company is fully or highly digitally interconnected (21%, n = 104). A weighted sum (S_w) per national economy was calculated, which for all rating options i is the sum of 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:

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

Country/Province	Age		Sex			Position in Company		
	Mean	Median	Female	Male	Other	Management	Operational	Other
Germany (n = 104)	45	46	15%	85%	0%	71%	23%	6%
Brazil (n = 83)	37	34	16%	84%	0%	45%	30%	25%
Liaoning (n = 145)	36	35	38%	62%	0%	39%	49%	13%
Jiangsu (n = 125)	41	42	42%	58%	0%	38%	51%	10%
Zhejiang (n = 171)	39	38	45%	55%	0%	78%	14%	8%

Table 3
Company size.

	Germany	Brazil	Liaoning	Jiangsu	Zhejiang
<250	37%	20%	53%	69%	37%
250-1000	18%	19%	9%	24%	31%
1000–2500	8%	13%	4%	1%	13%
2500–5000	2%	12%	20%	3%	5%
>5000	35%	35%	14%	3%	14%

Table 4
Sector.

	Germany	Brazil	Liaoning	Jiangsu	Zhejiang
Automotive	18%	29%	20%	10%	12%
Plant construction	41%	13%	28%	36%	35%
ICT	8%	5%	28%	33%	9%
Electronics	8%	4%	7%	19%	11%
Other	26%	49%	16%	2%	33%

Table 5
Supplier/OEM.

	Germany	Brazil	Liaoning	Jiangsu	Zhejiang
Supplier	40%	33%	45%	40%	43%
OEM	30%	36%	30%	37%	26%
Both	16%	17%	16%	22%	23%
Other	13%	14%	8%	2%	8%

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

In this weighted sum Brazil leads with a combined score of 1.85. China scores 1.73 and Germany a value of 1.62.

4.1.1. Company size

The self-assessed implementation of the Industry 4.0 concept varies between different company sizes and across countries. In Small and Medium-sized Enterprises (SMEs, having less than 250 employees) in all three countries, low levels of Industry 4.0 implementation (sum of answers in categories "1" and "2") were mentioned more frequently compared to the overall national average of all participants, 56% (n = 39) in Germany (average: 38%), and 58% (n = 24) in Brazil (average: 37%). The difference is less pronounced in China, where 43% (n = 229) of SMEs report low levels of Industry 4.0 implementation (average: 40%). Interestingly, 5% of German SMEs (average: 2%), and 2% of Chinese SMEs (average: 2%) report that their companies are "5 – fully digitally interconnected", while in Brazil 13% of Brazilian SMEs (average: 4%) report this rating.

A Chi-square test and a Spearman's rank correlation (through a Fisher's exact test) were performed to check for a correlation between the company size and the current level of Industry 4.0 implementation of the respective company (see Table 6). A significant correlation was found in Brazil, China, and Germany: larger companies show higher levels of Industry 4.0 implementation.

Table 6
Values for Chi-square test and Spearman's rank correlation for the correlation between the company size (5 categories: <250 | 250–1000 | 1000–2500 | 2500–5000 | > 5000) and the current level of Industry 4.0 implementation.

Country	Number of valid cases	Chi-square value	Chi-square significance	Spearman correlation	Correlation significance
Brazil	113	41.101	**0.000**	0.328	**0.000**
China	411	29.822	**0.009**	0.114	**0.020**
Germany	95	53.650	**0.000**	0.525	**0.000**

4.2. Digitalisation of collaboration processes

4.2.1. Country overview

The Industry 4.0 concept assumes that data is continuously and seamlessly exchanged between value creation entities within factories as well as across factory borders with external cooperation partners. Therefore, it was asked if collaboration processes with partners (suppliers or OEMs) are currently being digitalised and interconnected, and in case of "no digitalisation", if there were collaboration processes at all. Across all countries, less than 10% reported that collaboration processes are being fully digitalised. A partial digitalisation of collaboration processes was the most frequent answer in all three countries, with results ranging from 46% in Brazil (n = 116), to 61% in China (n = 441) and 63% in Germany (n = 104). In Brazil, however, no digitalisation of these processes was much more prevalent than in Germany and China: 45% compared with 21% and 17%, respectively. Further, a very limited number reported no collaboration processes being in place at all (2–3% on average, see also Fig. 2).

4.2.2. Effects on collaboration network through digitalisation – number of partners

Digitalisation and interconnectedness of collaboration processes can cause further changes in the value creation network, such as the number of partners a company cooperates with and/or the quality of cooperation between companies. The questionnaire accordingly asked if changes in the quantity or quality of cooperation were caused by digitalisation.

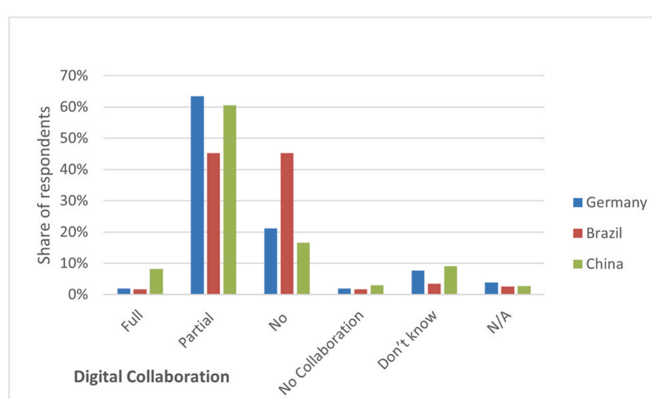

Fig. 2. Degree to which collaboration processes are currently digitalised.

In an interconnected and digitalised environment, most Chinese respondents indicated a higher (43%, n = 438) or much higher (13%) number of partners, whereas 22% reported no change in the number of partners. Germany and Brazil present more ambiguous results. In Germany, 39% (n = 100) reported no change in the number of partners and 23% reported a higher or much higher number of partners. In Brazil, 40% (n = 111) described no change at all and 31% a higher or much higher number of partners. Participants in all three countries reported that only a minority of companies cooperate with a lower or much lower number of partners in a digitalised environment. In Germany and Brazil, they account for 10% and in China for 15%. A relatively high number of respondents chose the "do not know option" in Germany (20%), compared to Brazil (9%) or China (5%). The results are illustrated in Fig. 3.

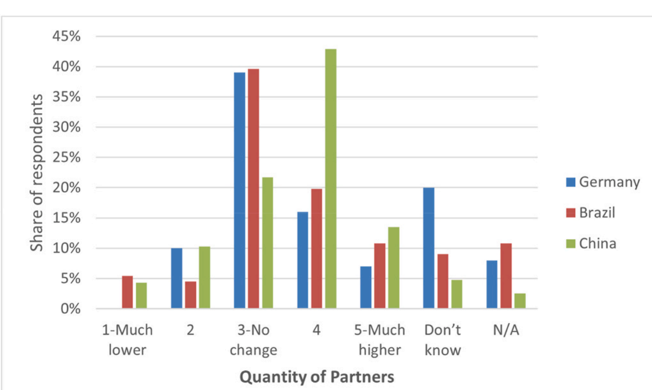

Fig. 3. Change in the number of cooperation partners in an interconnected and digitalised environment.

4.2.3. Effects on collaboration network through digitalisation – quality of cooperation

Digitalising cooperation processes between partners from different organisations can alter the quality of cooperation. Gains in efficiency and leaner processes are often identified as benefits, whereas common drawbacks include threats to intellectual property or the often unclear reliability of provided data (e.g. when the data acquisition process is not well-defined between partners) (Stjepandić et al., 2015; Chhetri et al., 2018; Shrouf et al., 2014; Bai et al., 2020; Lazarova-Molnar and Mohamed, 2019). With respect to the quality of cooperation, the majority of respondents in all countries indicated that it is higher or much higher in a digitalised and interconnected environment. The highest numbers of reported quality improvements were found among Chinese respondents, where 27% (n = 438) indicate a much higher and 41% a higher quality of cooperation, while only 8% estimated a lower and 3% a much lower quality of cooperation. The Brazilian results were very similar with 17% declaring a much higher quality of cooperation (n = 111) and 38% a higher quality, with only 3% seeing a decline in quality. In Germany, the numbers were slightly lower with only 5% (n = 100) indicating a much higher cooperation quality and 44% a higher one. Nevertheless, here none of the respondents indicated a lower or much lower quality. In all three countries the surveys also showed a notable proportion of respondents who do not see any changes in cooperation quality due to digitalisation at all, with 24% in Germany, 14% in China and 21% in Brazil (see Fig. 4).

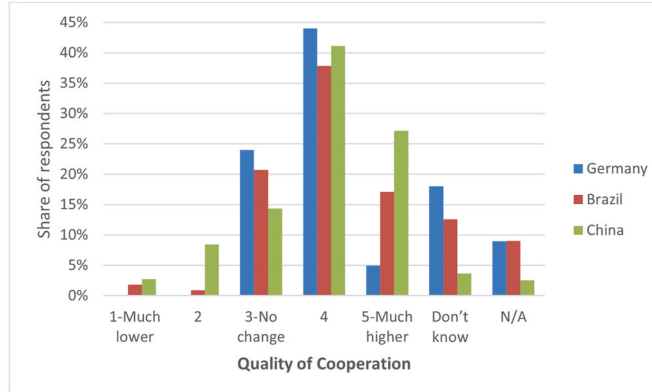

Fig. 4. Change in the quality of cooperation with partners in an interconnected and digitalised environment.

4.2.4. Effects of company size and sectors on digitalisation of collaboration

4.2.4.1. Company size. Differences in the digitalisation of collaboration processes become apparent when company sizes are taken into consideration. Although similarly low shares of respondents in all countries reported that collaboration processes are being "fully digitalised and interconnected", "partial" digitalisation of collaboration processes was mentioned more frequently in larger companies (>5000 employees) than in SMEs (<250 employees), especially in Germany and in Brazil (see Fig. 5). Moreover, "no digitalisation of collaboration processes" was reported by larger shares of SMEs (Germany 34%, n = 38) than within the group of larger companies (Germany 3%, n = 37).

Moreover, the distribution of values indicates a U-shaped correlation, where smaller and very large companies seem to display above average levels of digital interconnectedness in their cooperation processes with their partners, while especially the category containing companies with 2500–5000 employees offers very heterogenous data.

Therefore, a Chi-square test and a Spearman's rank correlation (through a Fisher's exact test) was performed to check for a correlation between the company size and the level of digitalisation with regard to the collaboration processes with partners of the respective company (see Table 7). A significant correlation was found for Germany, where larger companies cooperate with their partners in a more digitalised and interconnected manner, but not for Brazil and China.

The data also revealed a tendency among bigger companies to judge the quality of cooperation in a digitalised and interconnected environment more positively compared to smaller companies. This applies to Germany and China for companies with 250–5000 employees, whereas in Brazil, only companies with more than 2500 employees stated more quality in cooperation.

Therefore, a Chi-square test and a Spearman's rank correlation (through a Fisher's exact test) was performed to check for an association between the company size and the quality of cooperation with partners in a digitalised and interconnected environment (see Table 8). In Brazil in particular, and to a limited extent also in China, there is a (weak) association between the two variables (that could be random).

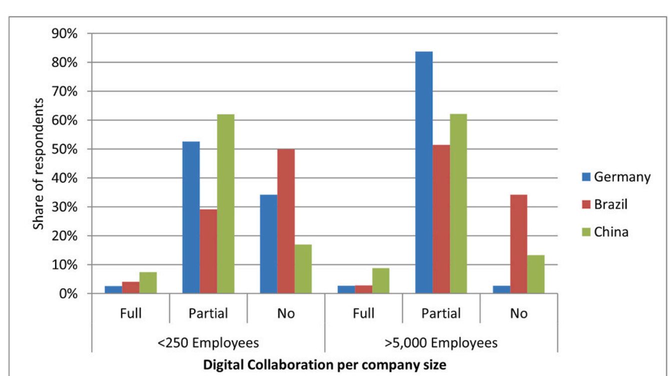

Fig. 5. Degree of digitalisation of collaboration processes in small vs. large companies.

Table 7
Values for Chi-square test and Spearman's rank correlation for the correlation between the company size (5 categories: <250 | 250–1000 | 1000–2500 | 2500–5000 | > 5000) and the digitalisation level of collaboration processes with partners (3 categories: 1 = fully digitally interconnected | 2 = partially digitally interconnected | 3 = not digitally interconnected).

Country	Number of valid cases	Chi-square value	Chi-square significance	Spearman correlation	Correlation significance
Brazil	106	5.747	0.675	−0.151	0.123
China	376	11.664	0.151	−0.047	0.358
Germany	90	21.098	**0.002**	−0.315	**0.002**

Table 8
Values for Chi-square test and Spearman's rank correlation for the association between the company size (5 categories: <250 | 250–1000 | 1000–2500 | 2500–5000 | > 5000) and the quality of cooperation with partners in a digitalised and interconnected environment (5 categories: 2 = Much lower .. 0 = No change ..+2 = Much higher).

Country	Number of valid cases	Chi-square value	Chi-square significance	Spearman correlation	Correlation significance
Brazil	87	20.155	0.121	0.265	**0.015**
China	411	19.084	0.208	0.072	0.141
Germany	73	8.011	0.446	0.073	0.539

Interestingly, the scatter plots for the distribution of the values show that small and very large companies are far above average in terms of the self-assessed quality of digitalised cooperation. However, no statistically significant association could be found for any of the three countries.

In contrast to the quality of cooperation, the number of partners a company cooperates with hardly varies in the results regardless of the size of the company. The Chi-square test as well as the Spearman's rank correlation also reveal no association between the company size and the quantity of cooperation partners in a digitalised and interconnected environment.

4.2.4.2. Sectors. In the automotive sector, firms from all countries reported above average digitalisation of collaboration processes. In Germany, 84% (n = 19) of respondents from this sector reported at least the partial digitalisation of collaboration processes, compared to 72% (n = 64) of Chinese and 62% (n = 29) of Brazilian companies. Additionally, more than a quarter of German respondents (26%, n = 19) from the automotive sector stated that digitalisation has led to a decrease in the number of partners, 32% see no change, while only 11% indicated a higher number of partners. This deviates from the average across all sectors, where a majority stated that they had not experienced changes in the number of partners. In all countries the assessment of the quality was above average in the automotive sector (see Fig. 6).

Differences can also be found within the plant construction & engineering sector. Here 63% (n = 16) of Brazilian respondents mentioned no digitalisation of collaboration processes, far more than in Germany (30%, n = 43) and China (24%, n = 144). In the Chinese plant construction & engineering sector, not only was improved quality of cooperation reported by 74% (n = 143) across all branches but also the number of partners has increased significantly due to interconnectedness and digitalisation (64%, n = 143). However, this is not the case in Brazilian or German companies.

4.3. Digital sharing of environmental data

More than 35% of the companies in all three countries share environmental information with external partners, with Chinese firms far outperforming their German and Brazilian counterparts (CHI: 60%, BRA: 42%, GER: 35%). However, fully automatic digital sharing of

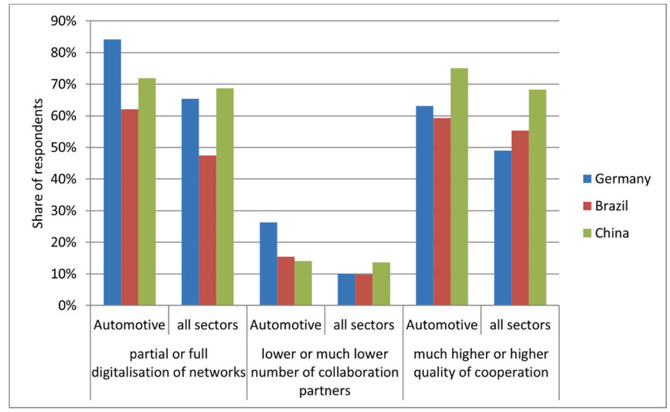

Fig. 6. Comparison of the characteristics of digital collaboration processes in the automotive sector with the average of all sectors.

environmental information with external partners hardly exists in any of the three countries (see Table 9).

In Germany and Brazil, none of the surveyed companies with less than 5000 employees use digital technologies to share environmental information. The ratio of Chinese companies that use digital technology to partially share environmental information is relatively constant regardless of the size of the companies (ranging between 36% and 43%), while in Brazil and Germany, this ratio grows with the size of companies (less than 250 employees: BRA: 17% (n = 24), GER: 5% (n = 37); 250–5000 employees: BRA: 24% (n = 55), GER: 14% (n = 28); more than 5000 employees: BRA: 35%, GER: 27%). Generally, there is a relatively high share of participants in Germany (20%) and Brazil (19%), who do not know whether their company is sharing environmental information with external partners. This problem is especially apparent in large companies with more than 5000 employees (GER: 35%, BRA: 26%).

A Chi-square test and a Spearman's rank correlation (through a Fisher's exact test) was performed to check for an association or correlation between company size and the level of digitalisation in which the respective company is sharing their environmental data with partners (see Table 10). No significant association was found for any of the three countries.

4.4. Sharing and integration of data into an EMS

Achieving modern and comprehensive management of environmental data in complex GVCs requires continuous, digital capture of relevant parameters along the entire product life cycle and the seamless integration of environmental data provided by partners. Integrating production data automatically into an EMS would help to run it efficiently and ensure the validity of the data. To avoid simply shifting the problem across the supply chain, it would be most effective and efficient to share environmental data across the supply chain and integrate these data automatically into the EMS of respective partner organisations.

Table 9
Quality of sharing environmental information digitally with external partners.

Sharing of Environmental Information	Germany (n = 102)	Brazil (n = 113)	China (n = 418)
Fully automated	1.0%	0.9%	2.9%
Partially automated with manual data preparation	15.7%	25.7%	33.3%
Manual data preparation	18.6%	15.9%	23.7%
No sharing of environmental information	40.2%	36.3%	31.3%
Don't know	19.6%	18.6%	7.4%
N/A	4.9%	2.7%	1.4%

Table 10
Values for Chi-square test and Spearman's rank correlation for the association between the company size (5 categories: <250 | 250–1000 | 1000–2500 | 2500–5000 | > 5000) and the quality in which the respective company is sharing their environmental data with partners (3 categories: 1 = fully automated | 2 = partially automated | 3 = not digitally).

Country	Number of valid cases	Chi-square value	Chi-square significance	Spearman correlation	Correlation significance
Brazil	48	5.313	0.907	−0.133	0.37
China	258	8.898	0.310	−0.077	0.218
Germany	36	6.913	0.836	−0.231	0.184

The survey data show that currently only a few companies fully digitally integrate production data into their EMS: five German (9%), two Brazilian (3%) and 23 Chinese (6%) companies. Of these, all German, 50% of the Brazilian and 70% of the Chinese companies take advantage of this technological capacity and share their environmental information in a fully or partially digital manner with their partner organisations. Of the companies which currently manage to integrate production data into their EMS in a partially digital way (GER: 25, BRA: 37, CHI: 187 companies), 24% of German, 43% of Brazilian and 47% of Chinese companies share their environmental information fully or partially digitally with their partner organisations. These values decrease significantly among those companies that do not integrate production data into their EMS or currently only plan to do so.

Regarding their willingness to share environmental data, according to the survey, German and Chinese companies that do not integrate their production data into their EMS also tend not to share environmental information with their partners. In Germany, this combination of no EMS integration and no sharing of environmental information can be observed in 7 out of 11 companies and in China in 22 out of 44 companies. Surprisingly, in Brazil the opposite trend can be observed, with 6 out of 10 companies (of those that do not integrate production data into their EMS) sharing environmental data in different ways (digital, partially digital and manually) while only 2 companies do not share this kind of information at all.

A Chi-square test and a Spearman's rank correlation was performed (through a Fisher's exact test) to assess the ability of a company to digitally integrate production data into their EMS and the level of digitalisation in which the respective company is sharing their environmental data with partners (see Table 11). A highly significant correlation was found in Brazil and China, while the values for Germany are close to being statistically significant. Subsequently, it can be concluded that companies with a higher degree of automation in integrating product-related data into their EMS are more likely to use digital technologies to share their environmental data with partners.

5. Discussion

The results of the survey underscore the observation that the digital transformation of industrial processes is still at an early stage. The low number of respondents indicating full digitalisation does not only relate to collaboration processes with external partners but also to the bigger picture of the current implementation level of the concept of Industry 4.0.

Table 11
Values for Chi-square test and Spearman's rank correlation for the association between the ability of a company to digitally integrate production data into their EMS (4 categories: fully digital| partially digital | planned integration | no integration) and the quality in which the respective company is sharing their environmental data with partners (3 categories: 1 = fully automated | 2 = partially automated | 3 = not digitally).

Country	Number of valid cases	Chi-square value	Chi-square significance	Spearman correlation	Correlation significance
Brazil	29	14.895	**0.005**	0.464	**0.012**
China	207	21.989	**0.001**	0.295	**0.000**
Germany	26	8.626	0.170	0.392	0.052

5.1. Differences in digitalisation between countries

While German and Chinese companies indicated a comparable level of fully or partially digitalised collaboration processes (around 70% of respondents), in Brazil less than half of the companies reported that their collaboration processes are digitalised. In addition, almost half of the Brazilian companies indicated no digitalisation of cooperation processes at all – far more than in Germany or China. While the digital gap between Germany and China is smaller than anticipated on the basis of benchmarks like the NRI, the results indicate a tendency toward polarisation for Brazilian companies in the digitalisation of the value chain.

Interestingly, our calculations show that Brazil leads the field when it comes to the implementation of Industry 4.0. This suggests that the digitalisation of internal processes is prioritised over collaboration processes in Brazil, whereas in Germany and China both digitalisation areas are developed in parallel. Additionally, a significant correlation in all three countries can be observed, showing that larger companies have higher levels of Industry 4.0 implementation.

5.2. Higher quality in cooperation with external partners but their overall number is not increasing in digitalised networks

The results show an improved quality in how companies cooperate with external partners in digitalised and interconnected networks. In Germany (39%, N = 100) and Brazil (40%, N = 111) a large share of participants states no change in the number of partners, and as the second most chosen option, an increase in the number of partners. Even though the study did not explicitly address this issue, this could be an indication that in these two countries digitalisation does not lead to completely new and extended value chains but instead is used primarily to improve the quality of cooperation. If this holds true, it might be more difficult for emerging companies to access very stable networks in comparison to more flexible ones with more partners. Chinese companies indicate a higher degree of transformation in cooperation processes due to digitalisation with an increase in quality as well as in number of partners. However, it is not clear if this would mean greater chances for all companies to be part of a digital value chain since "there is a downside risk to growth if China decides to respond to Western protectionism regarding its digital companies with further protectionist measures at home" (Nguyen, 2020, p. 2).

5.3. Polarisation tendencies: larger vs. smaller companies

The degree of digitalisation in cooperation with partners differs between companies of different sizes. The results indicate that very large companies with 5000 or more employees are more advanced in digitalising their external processes than smaller companies with less than 250 employees. The transformation to digitalised production and processes is time and cost-intensive and requires special skills and knowledge. Chen et al. (2021) identify lack of funding, lack of digital capability, lack of human resources, and technical barriers as the four main barriers to digitalisation in SMEs, suggesting that governments play a crucial role in supporting SMEs to overcome those barriers.

In China, SMEs "account for more than 90 percent of firms, employ more than 80 percent of total urban workers, and contribute more than 60 percent of GDP" (The World Bank, 2020, p. 97). The digital divide between very large companies and SMEs with respect to the digitalisation of collaboration processes is not as pronounced in China as in the other countries, although it is still easier for larger companies to access financing options. The Chinese Government has released several policies to specifically address the issue of SME financing (The State Council

China, 2020). Hence, further convergence of digitalisation between larger firms and SMEs in China is a reachable goal.

In Germany, 99.5% of all companies are SMEs (defined as having up to 500 employees there). Together, they account for over 50% of GDP and almost 60% of the jobs in Germany (BVMW, 2021). In the data set, over a third of small companies with less than 250 employees in Germany reported no digitalisation of collaboration processes, compared to only 3% of very large companies with more than 5000 employees. The European Commission (European Commission, 2020a, 2021) and the Federal Ministry of Economic Affairs and Energy in Germany (Bundesministerium für Wirtschaft und Energie, 2021) have developed and rolled out a variety of financing and support programmes for the digital transformation of SMEs. Despite this, the data for Germany proves a significant correlation, where larger companies cooperate with their partners in a more digitalised and interconnected manner. This could reflect an emerging digital divide between SMEs and large companies. However, it could also imply that the impacts and benefits of digitalisation do not materialise immediately but rather take time to significantly influence collaboration with value chain partners.

In Brazil, SMEs account for 62% of total employment and 50% of national value added (OECD, 2020a). According to the OECD "productivity gaps between SMEs and large companies are wider in Brazil than in the OECD area, and especially so in industry" due to "little innovation and export propensity among Brazilian SMEs" (OECD, 2020b, p. 15). Additionally, GVC integration levels are low across the Brazilian economy, resulting in the near exclusion of very small and small companies from foreign trade (OECD, 2020a). Brazilian policymakers recognise the relevance of digitalisation for GVC integration, as reflected in the Brazilian Digital Strategy, which aims "to facilitate the inclusion of Brazilian businesses, particularly small and medium enterprises (SMEs), in global markets" (Ministry of Science, Technology, Innovation and Communications, 2018, p. 69)

Against this background, the empirical results show low degrees of digitalisation in collaboration processes in Brazil, suggesting that the threat of being excluded from GVCs may be exacerbated. However, the results of the statistical analysis only indicate a significant risk for German SMEs. Even though the findings addressing SMEs must be interpreted with caution - due to the fact that micro and small enterprises are only represented through a small sample size, both results emphasise the conclusion that SMEs are most at risk of being excluded from future GVCs.

5.4. Polarisation tendencies: the automotive industry as a frontrunner in digitalisation?

The automotive industry is one of the sectors that stood out in the results. In all countries the digitalisation level of collaboration processes is higher in this sector compared to the average calculated across all sectors. The automotive industry has faced several challenges that have put pressure on the sector to transform its business models. On the one hand, emissions regulations are getting stricter "leading to pressure for new technologies in body and powertrain" (Peters et al., 2016, p. 1). On the other hand, customers are seeking new and more flexible forms of mobility and new competitors from the ICT sector are entering the market (Peters et al., 2016; PricewaterhouseCoopers, 2021). One way to react to these pressures is to optimise processes and gain more efficiency along the value chain, because "with a digital supply chain and the resulting closer cooperation, material lead times can be reduced, replenishment techniques streamlined, inventory planning improved, and visibility increased" (Kern and Wolff, 2019, p. 5). Moreover, the digitalisation of collaboration processes could help to alleviate the pressure to innovate by enabling new forms of product planning in cooperation with partners (collaborative engineering) or by potentially opening up new business relationships and sales markets.

Based on car registrations, Brazil is the sixth largest car market in the world but is still recovering from the country's 2014 economic crisis (Alves, 2021; OECD, 2020b). While in China, the market is still growing, in Europe the number of cars is expected to decline after 2025 (PricewaterhouseCoopers, 2021). This development will increase pressure on the German automotive sector and might explain why the digitalisation of its collaboration networks has advanced faster, as indicated by the results. Notably, in Germany the higher digitalisation rate is accompanied by a decrease in the number of partners, but additional research with greater sample sizes would be needed to verify this connection. Thus, the results suggest that the companies in the sample of the German automotive sector do not strive for integration into new value chains, but rather utilise the digitalisation of collaboration to strengthen existing relationships, as indicated by an increase in the quality of cooperation.

5.5. The use of digital enhanced transparency for environmental management

The potential benefits of using digitalisation to facilitate the sharing of environmental data across the value chain as well as the automated integration of such data in the EMS of the respective companies was examined. Both can potentially improve transparency along the whole value chain and offer opportunities to optimise production processes with a view to reducing negative environmental impacts.

5.5.1. Digital sharing of environmental data and integration into an EMS

In the recent past, legal requirements have become stricter, especially for large companies, with regard to the obligation to monitor and report on their environmental impacts. Current legislation aims to ensure that activities in other parts of the value chain are also integrated into these considerations. One example at the national level is the German Supply Chain Act, passed in June 2021 to ensure compliance with human rights and environmental standards along the supply chain (Federal Government, 2021). This necessarily leads to the cooperation partners having to agree on a way of exchanging their environmental data. A variety of options with different degrees of IT integration exist for the sharing of relevant data between and across corporate IT landscapes.

The results indicate that sharing environmental information with partners is not yet the norm. However, it is much more common among Chinese companies compared to their German and Brazilian counterparts. A differentiated view of the data by company size reveals that, among the large companies, a larger proportion shares environmental information with their partners in Germany and Brazil, but no statistical association could be found for any of the three countries regarding these two variables.

While negative effects on the environment might increase with the size of the individual company, there is a considerable cumulative environmental impact of all SMEs, as stated by the European Commission (European Commission, 2021). This is also the case for China and Brazil, where SMEs have a similar importance for the national economy (see 5.3). From a sustainability point of view, it would therefore be expedient if SMEs were to also share relevant data. But SMEs are often reluctant, as Kern and Wolff (2019) have shown for the automotive industry, since "increased transparency could be employed in shadow calculations and would give an OEM customer potentially advantages in price negotiations" (Kern and Wolff, 2019, p. 12). In to overcome reluctance within the SMEs, it will be important to communicate the shared benefits of information sharing (Müller et al., 2020), which may relate to both economic and environmental outcomes, emphasising the importance of trusting relationships.

Very few of the surveyed companies (five German (9%), two Brazilian (3%) and 23 Chinese (6%) companies) integrate production data into their EMS in a fully digital way. Companies could benefit from digitalisation and automation because it potentially simplifies environmental compliance issues as well as the process of environmental certification for companies and regulating bodies, which often require value chain-wide analyses (Blass and Corbett, 2018). In the European Union, many regulations require the sharing of environmental data. For example, the REACH Directive, which also applies to companies from non-EU countries operating in the European market, regulates potentially harmful substances and follows the principle of "no data, no market" (European Commission- Environment -, 2020b). This general assumption is also reflected in the data, which shows a significant correlation that companies with a higher automation degree for the integration of product-related data into their EMS are more likely to share their environmental data with partners in a digital manner. In this sense, the increasing degree of digital interconnectedness could open doors to a broader sharing of environmental information along GVCs. Still, significant obstacles should be kept in mind, such as the interoperability of automation technologies (Weyer et al., 2015).

5.6. Limitations

This study has several limitations that must be considered. As the digitalisation of internal and external processes is still at an early stage, it is difficult to fully predict future developments on the basis of these findings. The study also relies on the assessments of interviewees who might have divergent ideas and definitions of the concept of digitalisation (despite a definition being included in the survey).

Moreover, although respondents were asked to provide company-wide expectations and experiences, it cannot be ruled out that personal characteristics influenced responses. Further analyses may include differences in expectations with regards to tenure, employee occupation, age, and so on. We also recognise the 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.

Given that the sample is not representative of all sectors in each country, it is only possible to identify tendencies on country levels. Absolute statements about the current levels of digitalisation cannot be made on this basis. The ICT and electronics sectors were underrepresented in the German and Brazilian sample as well as companies with a size of 2500 up to 5000 employees in the German sample. When interpreting the results, it is important to account for the different sample sizes for each country.

To address the topic of inequality in a comprehensive way, future research must address more than three cases, especially in developing and least developed countries.

6. Conclusion & Outlook

The study presented looked at the consequences of the digitalisation of GVCs for sustainable development. The focus was on two sustainability aspects: the threat of an inequal development and the potential of improved transparency of Industry 4.0. In this sense, the contribution of the study is threefold. First, the study provides insights into the current digitalisation status of GVCs in Brazil, China, and Germany and the consequences thereof for the quality of cooperation as well as the quantity of partners. Second, these results were evaluated with a focus on inequalities or polarisation tendencies, which could potentially threaten the achievement of the SDGs. Third, the potential of digitalisation to support the sustainability management of companies based on environmental data sharing and integration into EMS was investigated.

The methodological approach involved the development of a questionnaire with researcher based in all three countries. The questionnaire was distributed in the official language of the respective country by the separate teams in China, Brazil, and Germany. Data was collected in Germany and Brazil as well as in three different Chinese provinces Zhejiang, Jiangsu, and Liaoning. The German sample comprised 105 completed questionnaires, the Brazil sample 117, and the Chines sample 445.

With regard to the aspect of inequality, the results suggest that although the level of digitalisation within surveyed companies and their value chains is still quite low, some polarisation tendencies are indicated. Differences in the digitalisation of GVCs were less pronounced than expected at the country level. However, the study showed clear differences with a statistically significant correlation in the digitalisation level of companies depending on their size, with smaller companies trailing behind. These polarisation tendencies can be seen in all countries studied but are more pronounced in Brazil due to less favourable (economic, social, and technological) starting conditions. At the same time, the effect of these polarisation tendencies is likely to be more severe, possibly leading to parts of the Brazilian economy becoming (or staying) disconnected from GVCs. With regard to the second aspect of transparency, the results indicate potential for the sharing of environmental data via digital technologies where digitalisation is more advanced. Thus, with the advancing implementation of Industry 4.0 in companies and value chains, there is a window of opportunity to strategically link and establish digitalisation and environmental management goals as key aspects of the concept. Even though there are currently only very few companies which integrate production data into their EMS in a fully digital manner, the study has proven that this would significantly improve their probability to share this type of information with their partners in a digital way.

Certain implications for future research emerge from the findings. First, further research is needed to assess the impact of potential digital gaps between large and small firms in countries participating in GVCs. Research should also focus on potential causalities between economic conditions and polarisation trends to clarify the basis for policy development. With respect to transparency, data sharing, and integration, future research should focus on identifying technical barriers to the use of digitalisation for corporate environmental management, as well as barriers related to the lack of awareness of how digital technologies can be used to improve environmental management. A particular focus should be on potential concerns and barriers for SMEs related to environmental data sharing and integration.

The results also suggest that the automotive sector provides an interesting field for further research on the drivers of digitalisation, such as economic pressures. Nevertheless, the study points to some interesting trends that could provide a starting point for further research in this sector. First, the results suggest a trend toward improved quality of collaboration in digitally networked environments, but not a statistically relevant change in the number of partners. This argues against a complete disruption of value chains and for a stabilisation of existing chains, regardless of individual changes in current partnerships. Second, the affinity for sharing environmental data is higher in the automotive sector in all countries studied, providing a good test case for the feasibility of digital technologies to support EMSs.

Policymakers will play a crucial role in promoting the sustainable development of digital GVCs. This study can provide starting points for the development of policy recommendations. The complexity of digitalisation processes requires a solid empirical basis as well as a normative framework such as the SDGs and a participatory approach involving practitioners, academics, regulators, and stakeholders (Renn et al., 2021). This means that policies to reduce polarisation trends should be supported by cross-country studies of countries in different positions in GVCs and accompanied by continuous monitoring and evaluation. The transnational nature of value chains requires the involvement of global organisations such as the UN Global Compact or the UN Department of Economic and Social Affairs (UNDESA) in policy making for the sustainable development of GVCs. The already existing discourse on the linkages between the SDGs and digitalisation must be advanced and expanded with all relevant stakeholders.

Future digitalisation policies should also support exchange between practitioners of environmental management in companies and with researchers to identify barriers and solutions for the digital support of EMS. The inclusion of other stakeholders in such projects should ensure that the urgent issues related to managing sustainability in supply chains are identified and tackled.

Managers can benefit from such an exchange of best practices with other companies, but also from a close exchange between all relevant departments in the companies. In addition, managers can use the data to develop an understanding of where to expect challenges in international comparisons and carry out sector-specific exchanges to develop the best (sustainable and digital) practices for their respective sectors. Digitalisation needs to be recognised as an integral part of environmental management to ensure that digitalisation is aligned with sustainable development. Furthermore, as sustainable supply chain management requires collaboration across company boundaries, it is crucial to involve all relevant actors in the supply chain in the development of digital solutions.

CRediT authorship contribution statement

Silke Niehoff: Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Visualization. **Marcel Matthess:** Validation, Data curation, Formal analysis, Writing – original draft. **Claudia Zwar:** Writing – review & editing. **Stefanie Kunkel:** Writing – original draft. **Ting Guan:** Conceptualization, Methodology, Investigation. **Ling Chen:** Conceptualization, Methodology, Investigation. **Bing Xue:** Conceptualization, Methodology, Investigation. **David Iubel de Oliveira Pereira Grudzien:** Conceptualization, Methodology, Investigation. **Edson Pinheiro de Lima:** Conceptualization, Methodology, Investigation. **Grischa Beier:** Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing, Visualization.

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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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2022.134606.

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