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Industry 4.0 in sustainable supply chain collaboration: Insights from an interview study with international buying firms and Chinese suppliers in the electronics industry

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ABSTRACT

With the proclaimed advent of Industry 4.0 in supply chains, digitalisation is expected to restructure the ways in which buying firms and suppliers in supply chains collaborate, including on sustainability issues. Digital technologies are expected to foster information exchange and facilitate collaboration on sustainability issues between firms. Yet, there is limited empirical evidence explaining the role of Industry 4.0 in the context of sustainable supply chain management. This qualitative, exploratory study examines digitalisation in the electronics supply chain and its implications for sustainable supply chain collaboration (SCC). We focus on environmental sustainability aspects, such as environmental data analysis and energy use in the supply chain. We conducted 18 interviews with representatives from international electronics buying firms and Chinese suppliers to explore a) how digital technologies are currently used in SCC, and b) which opportunities, risks, and obstacles are associated with digitalisation in sustainable SCC. Our results indicate that a broad range of digital technologies on different digital maturity levels (including Industry 4.0 technologies) are used in SCC, but their use for sustainability purposes is still underdeveloped. Digitalisation is expected by most firms to improve sustainability, e.g., using big data analytics for energy management or easing the transfer of sustainability knowledge in the chain (what we call "digital environmental upgrading"). We argue, however, that if firms do not prioritise addressing sustainability through digitalisation in collaboration, digitalisation-related sustainability potentials will either not materialise on the firm-level, e.g., due to data sharing concerns, or will tend to be overshadowed by the negative indirect effects of digitalisation, such as rebound effects. We propose three political and managerial levers to enhance the overall socio-ecological performance of the supply chain.

1. Introduction

Digitalisation, defined as the increasing development and application of information and communication technologies (or digital technologies), is expected to transform collaboration in global supply chains (IEA, 2017; WBGU, 2019). With firms along the supply chain using digital technologies, digitalisation can facilitate data and information exchange across company borders and enable better collaboration between supply chain partners (Vanpoucke et al., 2017). In recent years, research and business interest has shifted to advanced digital technologies, as envisioned in the concept of “Industry 4.0″. Industry 4.0 is characterised by the implementation of its core concepts, such as cyberphysical systems, the internet of things (IoT), big data analytics (BDA), artificial intelligence (AI), cloud computing, and additive manufacturing, in and across firms (Aoun et al., 2021; Han and Trimi, 2022; Li et al., 2020; Martinelli et al., 2021). Industry 4.0 technologies are expected to facilitate supply chain optimisation in real time, create interconnected production processes, and allow for customisation of production, products, and services along the supply chain (Bag et al., 2018; Bányai, 2018; Beier et al., 2020b; Birkel and Hartmann, 2019).

At the same time, firms are required to take more social and environmental responsibility along their entire supply chain. The German Supply Chain Act ratified in June 2021, for instance, obliges companies to improve human rights compliance in global supply chains and adhere to certain (although limited) environmental standards, i.e. the Minimata Convention on Mercury, the Stockholm Convention on Persistent

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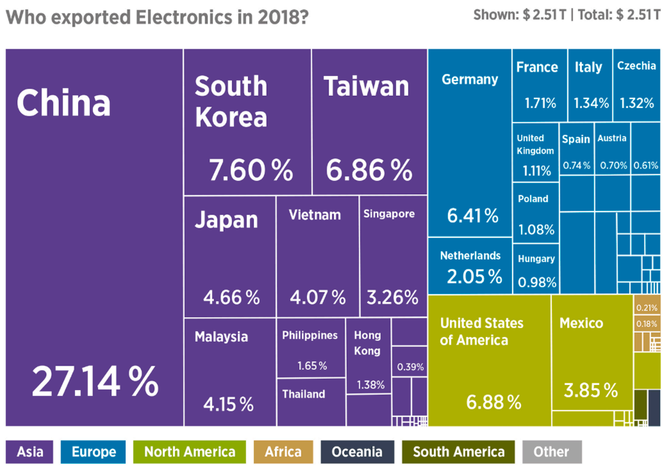

Fig. 1. Electronics exports in 2018; source: IASS illustration based on Atlas of Economic Complexity, 2020Atlas of Economic Complexity, 2020

Organic Pollutants, and the Basel Convention on Hazardous Waste (BMZ, 2021; Bundesregierung, 2021). Increasing accountability poses challenges to companies in supply chains, as compliance with regulations requires knowledge from different actors in the supply chain (Seuring and Gold, 2013). Collaboration can be considered a critical success factor for sustainable supply chain management (Tseng et al., 2019). Against this backdrop, stakeholders such as international organisations, private sector associations, and governments hope that digitalisation will contribute to more sustainable supply chains, e.g., by enhancing the monitoring of environmental performance and managing resource efficiency in value chains (UNCTAD, 2019).

Various disciplines examine the role of digitalisation in sustainable supply chain collaboration (SCC). In the supply chain management literature, risks and opportunities of digitalisation for sustainability on the firm and supply chain level (often in the Global North) are being investigated (e. g Bag et al., 2020.), as well as how firms collaborate on sustainability in the supply chain (e. g. Sellitto et al., 2019). In the global value chains literature, implications of digitalisation for production geography across the globe (Ferrantino and Koten, 2019; Ganne and Lundquist, 2019; Laplume et al., 2016.), as well as governance of value chains for (environmental) sustainability in the Global South (e. g Achabou et al., 2017.; Golini et al., 2018), are being scrutinized. Yet, there is little empirical evidence at the intersection of these research fields linking insights from supply chain management and the global value chains literature on digitalisation for sustainability in SCC. However, in our view, this intersection should receive research attention in order to specify the framework conditions that would allow expected potentials of digitalisation for sustainability to be realised and potential risks to be mitigated – along the supply chain in the Global North and the Global South.

In this qualitative, explorative study, we therefore analyse current digitalisation practices in the electronics supply chain and their implications for sustainable SCC from the perspective of both buying firms and suppliers. We focus on environmental sustainability aspects of sustainable SCC (for instance, energy and material use in the supply chain). Among the set of Industry 4.0 technologies, we chose to investigate interview partners' perceptions of big data analytics and artificial intelligence due to its associated functionalities. In the context of the analysis of heterogeneous data sources from complex value chains, technologies for the handling and (semi-)automatic recognition of patterns and relationships from large amounts of data appear to be particularly relevant (Beier et al., 2020a; Jeble et al., 2018; Mani et al., 2017). We pose two research questions of an explorative nature:

RQ1: How are digital technologies currently used in SCC?

RQ2: What are the opportunities, risks, and obstacles related to the use of digital technologies for sustainable SCC?

We conducted 18 expert interviews (eight written, ten in oral format) with supply chain managers from international electronics buying firms (headquartered in Europe, except for one Japanese firm) and Chinese suppliers. The focus on Chinese suppliers was chosen because China is the largest exporter of electronics (see Fig. 1). Moreover, Chinese firms are in a special position to harness digitalisation for sustainable SCC due to a conducive policy environment (Kunkel and Matthess, 2020). They are also likely to increasingly impact sustainability aspects in other emerging countries further upstream in the value chain.

This paper should make at least three contributions to the existing literature: First, we identify opportunities, risks, and obstacles related to digitalisation for sustainable SCC as perceived by practitioners in international buying firms and Chinese supplier firms in the electronics sector. Our aim is to contrast both perspectives and identify both sides' perceived opportunities of and obstacles to digitalisation for sustainable SCC. Second, we identify envisioned and implemented use cases from the interviews, e.g., of the application of big data analytics (BDA)[1] for sustainable SCC, and thereby contribute to the scarce literature on empirical examples of the use of Industry 4.0 technologies for sustainability in the supply chain. Last, by connecting two largely separate strands of literature, namely, on sustainable supply chain management and the global value chain, we link the perspective of management to foster sustainable SCC and the broader governance perspective of (digital) environmental upgrading.

2. Theoretical background: sustainability and digitalisation in supply chain collaboration

In this section, we first describe the theoretical lens through which we analyse environmental sustainability in SCC. Second, we present our concept of digitalisation in SCC by defining categories of digital maturity. Third, we link sustainability and digitalisation in SCC. Finally, we formulate our research questions.

2.1. Sustainable SCC and environmental upgrading

This study focuses on sustainable SCC (supply chain management literature) and integrates perspectives on environmental upgrading in global value chains (global value chains literature). We define sustainable supply chain collaboration (SCC) as interactions of two or more parties (mainly, but not limited to, firms) in the supply chain during processes of shared *planning, sourcing, making, delivering,* and *returning* of goods and services to improve performance in reaching sustainability goals. It comprises product- and process-related as well as organisational improvements (Blome et al., 2014; Vachon and Klassen, 2006). We define "environmental upgrading" as the process of enhancing the environmental performance of the value chain with regard to products and processes through changes on the technological, social, and organisational levels (Poulsen et al., 2018). The two literature strands identify similar and often mutually enriching perspectives on the risks and opportunities of digitalisation for more sustainable SCC. Arguably, sustainable SCC focuses more on the collaboration between firms in the supply chain, while environmental upgrading focuses on the broader governance and institutional conditions of value chains that need to be met to ensure better environmental performance of firms Fig. 2. shows a comparison of the two literature strands. Considering both perspectives should provide a theoretical lens through measures to foster Industry 4.0 for SCC at all levels - firm, supply chain and global level - can be

[1] We define BDA in our interviews as a technical means to gather, manage, and analyse large volumes of unstructured data (Leveling, Edelbrock, & Otto, 2021).

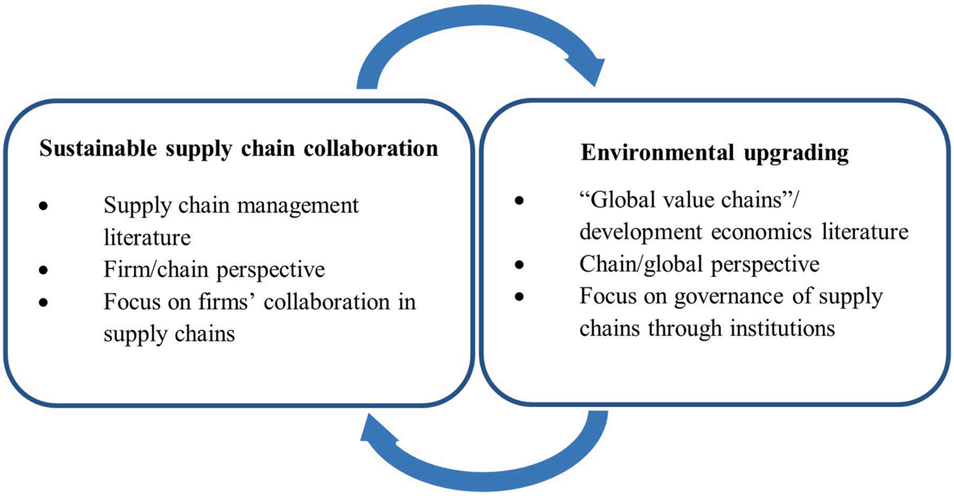

Fig. 2. Comparison between concepts of sustainable supply chain collaboration and environmental upgrading; source: own elaboration.

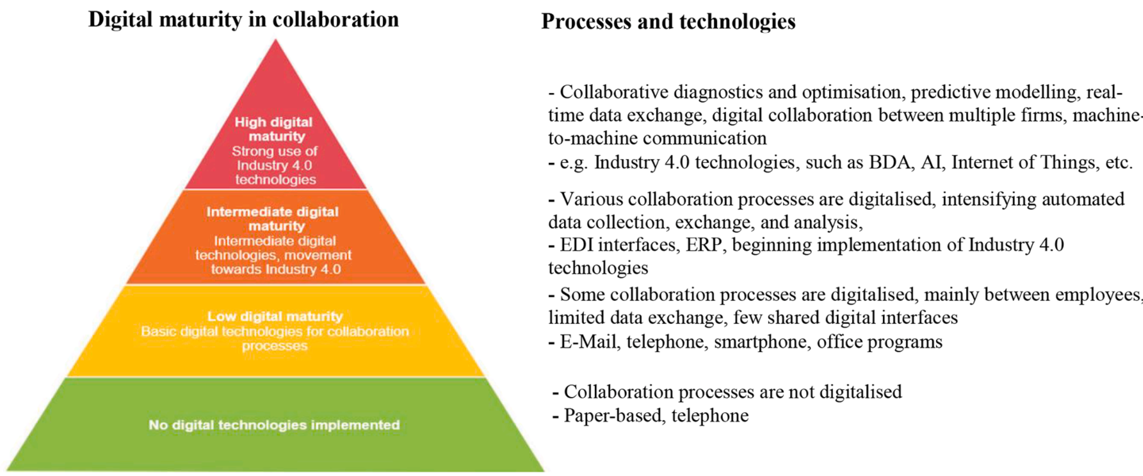

Fig. 3. Stylised categorisation of digital maturity in collaboration; source: own elaboration based on Bickauske et al. (2020) and Shao et al. (2021).
Note: At each digital maturity level, technologies used in the previous level are likely to continue being used, e.g., enterprises with high digital maturity are likely to continue using e-mail-based communication.

conceived.

Taking a supply chain perspective, Vachon and Klassen (2006; 2008) find that collaboration fosters inter-organisational learning and enhances sustainability capabilities. Sustainable SCC between supply chain partners usually includes an extensive exchange of information and knowledge, which is argued to contribute to the transmission of sustainability knowledge, standards, regulatory requirements, technology, and organisational practices between firms in the supply chain (Bai and Sarkis, 2010; Vachon and Klassen, 2006). However, supplier collaboration with sustainability aims does not necessarily lead to more sustainability in practice. In their analysis of 139 Dutch food and beverage processors, Grekova et al. (2016) found that collaboration with suppliers had not helped brand-name companies improve the sustainability of their internal processes. Yet, it had led to cost savings through the benefits suppliers gained from collaboration (e.g., lower prices of input materials). Thus, the positive effect of SCC on sustainability seems to be mediated by various factors, such as organisational and technological factors (Beltrami et al., 2021).

Taking a global value chains perspective, similarly, information and knowledge exchange between firms is argued to enable firms to environmentally upgrade to more environmentally friendly products, processes, and organisational practices (De Marchi and Di Maria, 2019). Particularly, there is a focus on the role of "lead firms", typically from the Global North, in transmitting technologies and knowledge about environmental standards and policies to suppliers as well as enforcing environmental governance strategies in global value chains, especially in the Global South (Khattak and Pinto, 2018). However, it has been argued that adopting standards and practices passed along the value chain may also lock suppliers into technologies and skills that do not support the development of strategic capabilities for environmental upgrading. Buyers may not want suppliers to build their own innovation capacity and obtain larger shares of added value along the value chain (De Marchi, Giuliani, and Rabellotti, 2018). Such challenges from the perspective of suppliers in countries in the Global South have only received limited attention in the literature (Khan et al., 2019).

In sum, there appear to be trade-offs between individual firms' interests in sustainable SCC and the optimal trajectory for environmental upgrading from a governance perspective. The existing literature points to diverse stakeholders' contexts and needs from the Global North and South that should be accounted for if sustainable SCC is going to lead to an overall improved socio-ecological performance of the supply chain. The next question is then: what role does digitalisation play in all this?

2.2. *Digitalisation in SCC*

To specify to what extent companies use digital technologies in SCC,

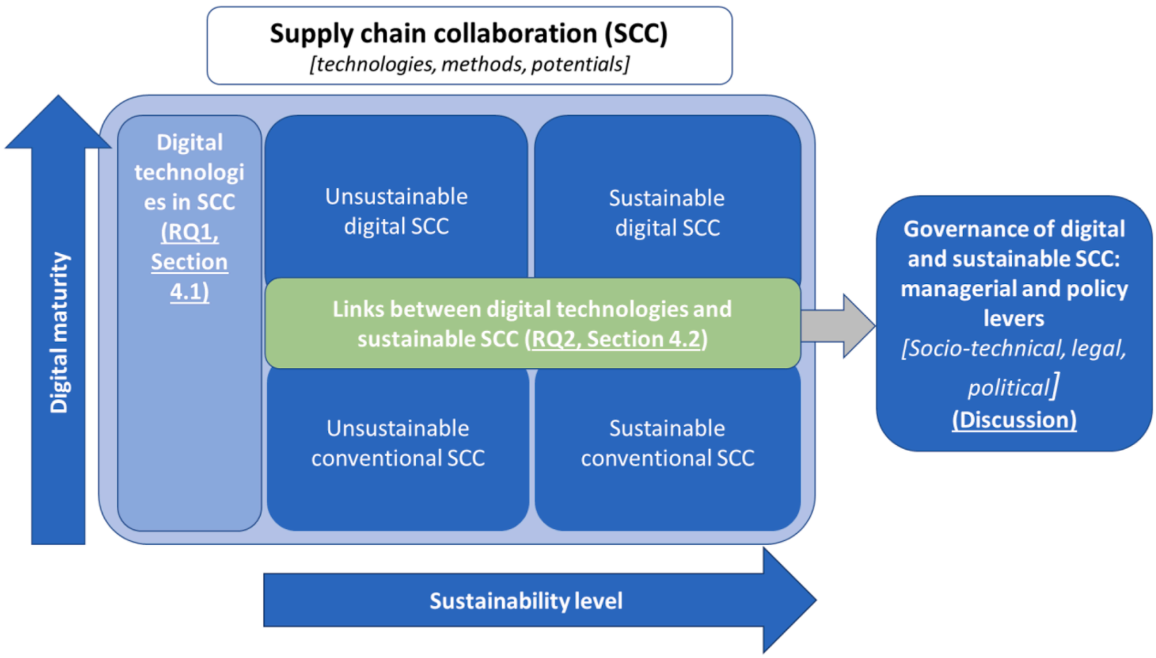

Fig. 4. Theoretical concepts and research questions in this article, source: own elaboration.
Note: The quadrants in the figure show four states of SCC in a firm: a situation, where there is low digital maturity and low sustainability level (lower left), low digital maturity and high sustainability level (lower right), high digital maturity and low sustainability level (upper left), and high digital maturity and high sustainability level.

we suggest a stylised categorisation of different levels of digital maturity. Digital maturity can be defined as "the status of a company's digital transformation" (Chanias and Hess, 2016). However, digital maturity models are generally not well scientifically founded (Thordsen et al., 2020) and lines between categories are blurry. In Fig. 3, we construct a stylised categorisation of digital maturity in collaboration. Differentiating between levels of digitalisation allows us to accommodate different types of digital technologies in further analyses, e.g., "basic" digital technologies, such as e-mail services, as well as (envisioned) "advanced" Industry 4.0 technologies, such as BDA and IoT.

2.3. Digitalisation for sustainability in SCC

Digitalisation is argued to have a positive influence on sustainable supply chain management and collaboration (Bag et al., 2018; Dao et al., 2011; Mastos et al., 2020; Yadav et al., 2020). Digital technology can enhance the collaboration and operational performance of the supply chain by connecting supply chain partners and fostering more proactive supply chain planning, process harmonisation, decision making, and advanced delivery practices, as long as additional supply chain integration tactics are in place (Vanpoucke et al., 2017). Advanced Industry 4.0 technologies, in particular, are expected to solve some of the existing challenges of sustainable SCC, such as collaborating more easily with numerous supply chain partners on sustainability by managing data along supply chains through BDA (Bag et al., 2020). For instance, circular economy models are theoretically facilitated by the technological and organisational restructuring of companies and supply chains towards Industry 4.0 (Dev et al., 2020; Sousa Jabbour, Jabbour, Godinho Filho, and Roubaud, 2018). Several recent literature reviews give an analysis of the existing evidence regarding Industry 4.0 and sustainability in the supply chain, e.g., Beltrami et al. (2021). and Birkel and Müller (2020).

However, collaboration around sustainability, including the way in which digital technologies are used and sustainability-related data are gathered, assessed, and exchanged by firms in supply chains deserves more research attention. A recent review of empirical case studies on the organisational effects of Industry 4.0 for sustainability, for instance, indicates that only a minority of studies have looked at the organisational implications of Industry 4.0 for environmental sustainability (Margherita and Braccini, 2020). Often, environmental sustainability data, e.g., lifecycle data, are not collected on the organisational level or are not integrated in firms' existing internal information systems (Gandomi and Haider, 2015). For instance, energy-saving and emission-reduction evaluation technology has been found to be isolated from existing Enterprise Resource Planning (ERP), product data management, and customer relationship management, resulting in what have been termed "enterprise information islands" (Tao et al., 2014). Collaboration, in turn, is argued to facilitate the use of digital technologies. Inter-organisational collaboration has been found to enhance the effectiveness of ERP system implementation in a study on 283 Chinese firms (Li et al., 2017). Thus, there seems to be a critical link between the success of SCC and that of digitalisation. It is useful to understand how and with which tools enterprises collaborate along the supply chain in order to identify existing collaboration channels through which sustainability data could be exchanged.

Likewise, evidence demonstrating the link between digitalisation and sustainable SCC with a focus on the Global South is still scarce (Zeng et al., 2020). On the one hand, information technology can exacerbate existing disadvantages facing firms in emerging countries along supply chains. For instance, a lack of knowledge about data management, lack of understanding around decentralised organisational structures for chain collaborations, and high investment costs were found to be the largest hurdles for circular supply chain implementation in a study of manufacturing firms in India (Ozkan-Ozen et al., 2020). On the other hand, digitalisation may create new business opportunities for emerging countries, particularly in forming green supply chains (Luthra and Mangla, 2018). Yang et al. (2020) point to potential synergies resulting from linking information sharing, collaboration, and sustainable supply chain management in China. Surveying 300 Chinese organisations, they find that by combining approaches to green supply chain management and "green information systems" firms' economic, operational, environmental, and social performance can be enhanced.

However, the authors call for more empirical studies collecting observations from multiple countries with different cultural, political, legal, and economic contexts.

In conclusion, previous studies have reviewed the extant literature on sustainability and Industry 4.0 and have shown that opportunities for digitalisation may facilitate sustainable SCC, but have also identified risks associated with it. However, there are limited empirical studies on Industry 4.0 in supply chains focusing on the role of collaboration between supply chain partners in the Global North and Global South and relating these findings to the possibility of environmental upgrading along the value chain.

2.4. Conceptual framework and research questions

Following from the literature gaps identified in the preceding subsections, we formulate the following research questions (RQ):

RQ1: How are digital technologies currently used in SCC?
RQ2: What are the opportunities, risks, and obstacles related to the use of digital technologies for sustainable SCC?

Fig. 4 provides an overview of our research concept. With RQ 1, we aim to understand the use of digital technologies in SCC *in general* (unrelated to sustainability), in order to gain insight into the interviewed firms' digital maturity with respect to collaboration. Based on this knowledge of firms' digital technology use, RQ 2 serves to assess to what extent our interview partners perceive links between digital technologies and sustainability in SCC. We aim to identify not only explicitly stated opportunities and risks, but also opportunities and risks that might not yet be perceived by the interview partners regarding digital technologies and collaboration. Specifically, the literature describes several opportunities where an increased use of digital technologies can strengthen sustainable SCC, as well as possible negative impacts on environmental indicators associated with the large-scale use of digital technologies in SCC, such as an increased use of energy for digitising processes. Those opportunities and risks might emerge in the future due to the way digitalisation is currently envisioned and pursued in SCC. Whether and how the positive effects could outweigh the negative effects of digital technologies is rarely subject to scrutiny. In this study, mapping practitioners' views and contextualising these with theoretical considerations help us obtain a holistic view of the likeliness that possible opportunities and risks of digitalisation will emerge in SCC and what conditions have to be in place for more sustainable SCC. Therefore, in the discussion section we aim to develop governance measures for management and policy addressing the question of how to improve the socio-ecological performance of the supply chain. We structure the proposed measures along the dimensions "socio-technical", "economic", and "legal and political", adapted from Beltrami et al., (2021). The socio-technical dimension includes organisational and technological aspects, the economic dimension includes aspects related to firms' economic models, and the legal and political dimension includes regulatory actions and political support policies.

3. Methodology

In this section, we describe how we conducted our expert interviews and how we performed our data analysis.

3.1. Expert interviews

There is little data on the use of digital technologies, especially Industry 4.0 technologies, in sustainable supply chain management, particularly in emerging country contexts (Birkel and Müller, 2020). Therefore, we decided to do an exploratory study using semi-structured expert interviews as well as written expert interviews to obtain basic data and trends regarding our research objective. These results can pave the way for future in-depth studies with randomised samples. The exploratory nature of our study should be considered when interpreting our results.

We conducted interviews with two groups of companies in the electronics sector that we refer to as:

- "buying firms" and
- "suppliers".[2]

This approach helped us to gather perspectives from different groups of actors in the supply chain, i.e. international buying firms and Chinese suppliers, and contrast these perspectives to increase validity, reduce bias, and obtain a more nuanced picture from our research results.

With the buying firms, we conducted 10 semi-structured expert interviews among international buying firms (nine European, one Japanese) following a tested interview guideline (see Appendix A). The interviews took between 41 and 101 min. To reach a wider range of participants under the circumstances of the Covid-19 pandemic, we used online conferencing software to conduct the interviews. With the suppliers in the electronics sector in China, we conducted 8 interviews in written form (see Appendix B). We chose to collect written responses to avoid language barriers. The questions in the supplier questionnaire corresponded to the questions asked of the buying firms, translated into Mandarin and with minor adaptations to the specific role of suppliers, which we wanted to investigate. For instance, for some questions on the supplier questionnaire, we inquired about assessments of downstream customers and upstream suppliers. The "expert" status of our interviewees was assessed by the firms we contacted that chose their colleagues based on the introductory information we communicated.

The interviews covered the following areas:

- First, we investigated how supply chain processes are organised regarding the identification and selection of, as well as collaboration with, suppliers.
- Second, we investigated to what extent digital technologies were used in supply chain management. Specifically, we were interested in the tools used to exchange data and information and collaborate with other firms in the supply chain.
- Third, we dedicated a section of our questionnaire to the use and potential of BDA and AI in SCC, as two exemplary technologies for Industry 4.0.
- Fourth, we investigated the perceived and expected risks and opportunities of digital technologies in supply chain management for social and environmental sustainability.
- Last, we added a set of quantitative questions for which the respondents were required to assess the influence of digitalisation on sustainability aspects on a scale from -5 ("probably very negative") to 5 ("probably very positive").

3.2. Choice and characteristics of interviewees and firms

In the case of buying firms, we aimed for a systematic selection of interview partners but bias was introduced through the irregular replies by the selected firms. In the case of suppliers, we chose convenience sampling to identify our interview partners. Although convenience

[2] It should be noted that there are no definite boundaries that distinguish the two groups due to the complexity of supply chains, e.g., buying firms can be suppliers to other buying firms and suppliers can be buying firms to the upstream and downstream companies they sell products to. Moreover, in the case of Chinese suppliers, some firms combined business activities as both suppliers and final sales companies. We also point to the fact that buying firms were not willing or able to bring us into contact with their direct suppliers, so we analysed suppliers in the electronics sector more broadly. Thus, the "suppliers" were not necessarily supplying the interviewed "buying firms".

sampling is likely to introduce bias to the interview results, we believe that the convenience sampling approach can be justified. It is often the only way to identify recent trends in firms, where time to participate in studies is limited and other barriers, such as confidentiality requirements, exist. We discuss the limitations of this approach in more depth in the discussion section.

Regarding buying firms, we systematically contacted companies who were affiliated with the German digital association "Bitkom". Initially, we contacted a total of 68 companies directly via email or telephone. We reached further companies by contacting 10 associations and corporate networks in the electronics industry as well as six civil society organisations and individuals working in the field. We usually sent/made at least one follow-up email/call if there was no response in the first round. We conducted interviews in all companies that responded positively to our request. A total of 11 companies responded positively to our request, but one company was excluded after the interview due to a lack of fit between the interviewee's position and the firm. Within each firm, we talked to leading employees from the field of supply chain management, including "Head/Director of Supply Chain Management", "Head/Director of Manufacturing Solutions" or senior management positions in SMEs/start-ups. Our oral interviews took place between July and November 2020.

Regarding suppliers, due to the language and geographic barriers, we relied on contacts from within our research team. First, based on local statistical information, we asked potential corporate contacts whether interviews and surveys could be carried out, and then based on the response opinions we further selected companies in which to conduct interviews and collect data. The interviewees from among the suppliers had more diverse occupations in the firms, namely automation engineer, purchasing/supply chain director, smart city responsible, finance and business manager, product manager, and general manager in a family-run private enterprise. However, in contrast to the buying firm interviews, the interviewees informed us that they had consulted colleagues, e.g., from the PR and OEM departments for questions they could not answer. We collected the written replies from supplying firms between November 2020 and February 2021. A detailed list with information on the interviewees and firms can be found in Appendix B.

The results from buying firms' interviews in languages other than English, i.e. German, were translated into English by the authors. Regarding the interviews conducted with supplier firms, the written interview results were translated from Chinese into English with online translators (DeepL, Bing Translator). The results of the translation were double checked and corrected where necessary by a native speaker of the Chinese language.

3.3. Qualitative content analysis

We used the software "MaxQDA" to conduct a qualitative content analysis following Saldana (2013) to transcribe and analyse the interviews. First, buying firms' interviews were transcribed from recordings taken during the interviews. Suppliers' interviews were already in written form. Second, after having obtained both sets of interviews in the form of typed documents, we proceeded equally with both groups. The intention behind using qualitative content analysis was to describe the phenomena in our research focus using categories identified in our interviews. Thus, we used content-structuring content analysis (Schreier, 2015). In the first step, based on the theory-driven interview guideline, we deduced the main categories that were aligned with our research questions. In the second step, two researchers coded the passages independently and induced sub-categories where the initial scheme needed more detailed categories (Saldana, 2013). After this round of coding, the coded passages of each researcher were compared and grouped in order to identify common coding patterns. Agreement amongst researchers also increases the reliability of the coding scheme and the data analysis (Carter and Easton, 2011). Where no shared understanding of a category was reached or an initial theory-driven category was not able to accommodate certain codes identified by the research team, the researchers developed further categories, and consolidated similar sub-categories. We applied the same category system to the data from the suppliers but allowed for the possibility to add categories where necessary. A final check against the theory helped us to increase the validity of our category system (Potter and Levine--Donnerstein, 1999). The final category system was used to structure the results to address our two research questions. The emergent category system can be found in Appendix C. A more detailed explanation of how the research results emerged from the coding scheme can be found in Appendix D.

4. Results

In this section, we first describe the research results related to research question 1 focusing on digitalisation in SCC (section 4.1). Subsequently, we describe the research results related to research question 2 focusing on sustainability opportunities, risks, and obstacles related to digitalisation in sustainable SCC (section 4.2).

4.1. Digital technologies in SCC

In line with earlier findings, a range of digital tools are used in SCC, e.g., basic technologies such as e-mail and Excel tables, as well as more advanced digital technologies such as ERP and Electronic Data Interchange (EDI) systems. The usage of specific tools in buying firms was reported to depend on the respective supplier (II, III, IV, VI). For instance, one company reported that there was an automated, standardised data exchange with some suppliers and manual, and even paper-based, data exchange with other suppliers (IV). To determine the digital maturity level of suppliers, the use of digitalisation assessment handbooks was reported by two large buying firms (I, II). The handbook is used to assess digital maturity across different domains, such as factory operation, product tracking, general connectivity, and the adoption of IoT (I). For instance, suppliers are asked how many laptops they have on the shop floor and how many IT trainings their employees receive (I, II).

One factor in determining which digital tools are used seems to be the type of relationship the firm has with its suppliers. In transactional, loose relationships, the role of digital technologies was reported to be smaller (V, VI) than in "partnerships" where "trust" was important (I) and suppliers were also considered to be "customers" (VI, VIII). Regarding transactional relationships, digital interfaces with suppliers may not amortise the necessary efforts and costs (VI), so the question was raised whether "more digitalisation" was desirable for all suppliers (III). Regarding partnerships, two interview partners were positive about the enhancement and intensification of relationships through digitalisation (IV, VIII). In these cases, entire products may be produced for the buying firms, and innovation may be carried out together with suppliers (V).

Among the more advanced digital technologies used in buying firms, there are databases for supplier data following different approaches to optimise "source-to-contract" procurement processes and "purchase-to-pay" integration (i.e. electronic supplier integration) (VI). The company used both "classical EDI" and "web-EDI", offering different platforms with different levels of sophistication for varying types of orders (e.g., paper supply vs. more complex parts) (VI). Some platforms can be used for free by the suppliers, while other more sophisticated platforms, e.g., to exchange design plans, have to be paid for by the supplier (VI). Suppliers additionally frequently referred to the use of commercial cloud services (A, C, E, F) (depending on the confidentiality agreements (A, F)), and the use of "WeChat" or "QQ" (both instant messaging software services owned by the Chinese firm Tencent) for non-confidential data. In the case of confidential data, "offline" USB flash drives or paper-based data exchange were reported to be used for data safety reasons (A, H).

Asked about the use of BDA and AI, limited uptake of BDA and AI

Table 1
Digital technologies used in the interviewed firms in SCC.

Digital maturity	low	Intermediate	high
Technologies	Email (II, III, VII, IX, X, A, B, C, D, E, F, G, H), excel tables (I, II, III, VIII, IX, X IV, V, B, C, D, E, G), video telephony (VII)	ERP (II, III, IV, VI). Purchase-to-pay integration, (web-)EDI (II, IV, VI) "WeChat" or "QQ" (both instant messaging software services by Chinese firm Tencent) (A) cloud services (A, C, E, F)	Big data analytics (I, II, A, B, C, E) AI (V, A) IoT (I, F) Blockchain (VI)

Table 2
Assessment of the influence of digitalisation in sustainable SCC on two environmental upgrading indicators.

	Buying firms	Suppliers
Green innovative ability	3.8 (N = 9)	3.3 (N = 8)
Transfer of knowledge about the use of energy- and resource-efficient manufacturing technologies and processes	3.6 (N = 9)	4.2 (N = 8)

Note: Scale ranges from -5 (very negative influence) to +5 (very positive influence); one buying firm interview participant did not answer the above assessment questions.

solutions in SCC was reported by the interviewed firms. BDA (and sometimes AI) was mentioned as a means used, e.g., in marketing (E), (predicting) market trends (I, B, C), screening the competitive situation (A), understanding the use of companies' products by customers (A), and quality management (I, B), but to a lesser extent in direct collaboration with the supplier. One such example was the analysis of output fluctuation at the suppliers' plants. BDA was used to suggest correlations between variations in outputs and other indicators, such as the level of experience of employees working at a machine (I). However, two reasons for low uptake of BDA and even lower uptake of AI reported by firms was the lack of a unified understanding of what BDA and AI actually are (I, D) and, in the case of suppliers, a lack of internal capacity to conduct BDA and use AI techniques (C, D, F, G) was mentioned. Table 1 provides a summary of technologies the interview partners reported using for each digital maturity category.

4.2. Opportunities, risks, and obstacles related to digitalisation for sustainable SCC

4.2.1. Perceived opportunities for environmental upgrading but few implemented use cases

Buying firms and suppliers alike expected several opportunities for sustainable SCC to arise from digitalisation. For a high number and variety of suppliers, data management could be improved by digitalisation in the future (X). Moreover, firms expected to be able to measure how energy is used in collaborating firms and which efficiency measures are in place (I, II, VI, E, F). In a few cases, energy data were already analysed for and together with the supplier to detect savings potentials (I, II). Several interview partners suggested opportunities for digital technologies to enable better collaboration on material circularity in the supply chain (II, VIII, IX, B, C, G). Digitalisation was expected to enable tracking of resources (IX, VIII, B, G), predicting sustainability risks for suppliers in the supply chain through big data analysis (V) and machine learning (VI), and reducing paper-based communication (VI, F). One buying firm, for instance, reported the development of a blockchain to track and trace emission data (VI) and others reported placing great hopes on blockchain technology for transparency (VIII, IX).

Our quantitative question regarding the effect of digitalisation in sustainable SCC on environmental upgrading (see Table 2) supports our impression that firms perceivea potential created through digitalisation for more environmental sustainability in the supply chain. When asked about the effect of digitalisation on firms' capacity to create environmentally friendly innovation, both buying firms and suppliers expected a moderately positive effect (3.8 and 3.3, respectively, out of 5). The influence of digital technologies on the transfer of knowledge about the use of energy- and resource-efficient manufacturing technologies and processes was assessed even more positively by suppliers than by buying firms (4.2 and 3.6, respectively), indicating that firms expect a facilitation of "green" knowledge transfer through digitalisation.

Generally, however, sustainability concerns played a subordinate role as a determinant, or driver, of digitalisation in SCC in all our interviews. While general statements about the positive (economic) effects

Table 3
Use cases of Industry 4.0 technologies for sustainable SCC identified by our interview partners.

	Environmental data gathering and analysis on platforms	**Managing energy use and environmentally optimising logistics chains**	**Improving material circularity**
Measure implemented in a specific case	Establishing firms' own data platforms to collaborate with suppliers (IV, VI) and to measure CO2 emissions along the supply chain (II) Predictive risk assessment through BDA: assessing parameters as to whether companies are at high risk of not meeting their sustainability targets, subsequent selective and risk-driven collaboration with suppliers (V)-	Detecting savings potentials in suppliers' plants by measuring machine energy use data through sensors in the machines (IoT) (I) Using BDA to optimise truck fleet routes in logistics processes of buying firms and suppliers (I) Using IoT and BDA to reduce energy consumption in production lines, reported effect of reducing energy consumption per product unit by 3% compared to the previous year (F)-	Tracking & tracing containers and reusable packaging material, reported to reduce the amount and cost of packaging (II)
Measure envisioned	Linking and analysing previously unrelated databases through BDA and machine learning in the company to identify supplier sustainability risks (V) Anticipating sustainability risks in the supply chain through BDA: Analysing data on companies that have signed a code of conduct over a time span of three to five years, suggesting correlations on whether firms from different regions face higher or lower risks of breaching sustainability regulations in the future; analysing the likeliness and effects of extreme weather events such as hurricanes in the supply chain (VI) Preventive maintenance of wind energy turbines through machine learning (VI)	Calculating Product Carbon Footprint along the chain (VI) Determining the closest location of production facilities to retailers, i.e. choosing where to produce according to expected buyer locations (I) Determining the use of data centres and servers according to where renewable energies are available (VIII) Optimising logistics chains (D, F)	Using digital imprint of material information to learn why a produced product had failed and improve product development processes accordingly (IX) Improving recycling collaboration supported by digital technologies, contributing to recycling of discarded appliances (B, C, G) Tracking and tracing of packaging material (C, G) Using big data analysis to gather recycling information of scrap products (B)

Table 4
Perceived obstacles to digitalisation for sustainable SCC.

Perceived obstacles to digitalisation for sustainable SCC		
Socio-technical	**Technology and data availability** **Engagement and role of suppliers** **Lack of expertise in technology implementation**	No tool and no data available to calculate, e.g., emissions of delivery trucks in the entire logistics chain (VI) no habit of data collection among (second-, third-, … tier) suppliers (A), especially on environmental and social indicators, e.g., no measurement of emission data by suppliers (VI) a lack of internal capacity to conduct BDA and use AI techniques (C, D, F, G)
Economic	**Internal resources in firms (increasing) cost**	Insufficient resources to obtain sophisticated software for supplier management (III) insufficient resources to actively foster sustainability practices by suppliers, as this is labour-intensive and expensive (III) expectation of increasing costs of raw material used to produce digital technologies (VIII) and thus of an increasing need to use refurbished hardware (VIII)
Legal and political	**Weak regulations** **Data confidentiality requirements and lack of trust in secure infrastructure**	Dispersed social and environmental reporting landscape, no globally binding supply chain sustainability standards, suppliers report having few or no requirements for sustainability from the buying firms' side (A, G, H) data confidentiality poses challenges to data sharing among firms, secure transmission channels might be lacking (VIII, F, G)

Table 5
Levers for more socio-ecologically sustainable supply chains.

Goal: Overall improved socio-ecological performance of the supply chain Managerial and policy levers		
→ Socio-technical Use digital technologies adapted to diverse firms' (country) contexts to enable 'digital environmental upgrading'	**→ Economic** Explore economic-environmental win-win situations to amortise investments in digitalisation for sustainable SCC	**→ Legal & Political** Create open, secure, and conducive environments for gathering, sharing, and analysing sustainability data

of digitalisation for SCC were common, e.g., regarding BDA and AI to enhance the logistics efficiency of multiple sources and materials (D) or the synchronisation of supply and demand (I), few interview partners pointed out specific sustainability purposes of digitalisation. Currently, buying firms often request that suppliers provide certificates about meeting specific regulations but do not manually or digitally verify this information, e.g., by collecting real-time data on energy efficiency and use at collaborating firms. Granular sustainability information (beyond certificates) is reported to be less relevant and difficult to obtain at the moment (III, IV, V, VI, VII, VIII). Thus, at the time of the interviews only few firms had already realised some of the expected sustainability opportunities of digitalisation, and none of them had implemented system-wide Industry 4.0 solutions for this purpose. However, there were a few implemented use cases of digital technologies for sustainable SCC. A list of implemented and envisioned use cases of digital technologies for sustainable SCC can be found in Table 3.

4.2.2. Little awareness of environmental risks

Our analysis indicates that there are several blind spots in the interview partners' awareness of adverse direct and indirect effects of digitalisation in SCC. Direct effects comprise increased energy and material use through digital technology use. An indirect environmental risk can arise, when increases in efficiency (material, energy) create rebound effects (Kunkel and Tyfield, 2021). Environmental risks of digitalisation in SCC were not mentioned frequently by our interview partners. Interview partners briefly touched upon the issues of material use of digital technologies, high return rates induced by digital ordering, increased use of batteries in the IoT, and disposal of products in the supply chain (II, VIII, IX, B, C, G). One supplier spoke of the high velocity of changes and customisation of products in the electronics sector, possibly leading to negative environmental effects (C). Moreover, one supplier recognised that environmental challenges in the supply chain and digitalisation were systemic challenges that can only be solved by including all supply chain partners (D).

4.2.3. Several obstacles to digitalisation for sustainable SCC

Several obstacles have been identified by our interview partners that currently hamper digitalisation for sustainable SCC. These obstacles are summarised in Table 4, structured along the dimensions "socio-technical", "economic", and "legal and political".

5. Discussion: Managerial and policy levers to improve the socio-ecological performance of the supply chain through digitalisation

The aim of our study was to explore the current use of digital technologies in SCC, as well as the opportunities, risks, and obstacles related to digitalisation for sustainable SCC. In this section, first, we propose two hypotheses to explain our observations arising from the analysis. Second, we suggest three levers with which to improve the socio-ecological performance of the supply chain through digitalisation in sustainable SCC.

5.1. *Hypothesis 1: Relationship between firms determines the degree of digitalisation in sustainable SCC – and the success of sustainable SCC*

We inferred from our interviews that the relationship between firms in the supply chain seems to be an important influencing factor in digitalisation for sustainable SCC. Usually, supply chain firms are hesitant to share more information than needed (Voigt et al., 2019). This tendency is supported, e.g., by statements of concerns about data safety in our interviews. However, to harness the proposed opportunities for sustainability (section 4.2.1), extensive data collection and exchange by different supply chain actors is fundamental. Even if Industry 4.0 technologies were to be used, such as sensors measuring machine energy use and providing real-time energy use information (Liang et al., 2018), a compatible technological infrastructure and a high level of trust would probably be needed between firms to enable mutual access to this information by supply chain partners. In this regard, two large firms mentioned that they assess the digital maturity of suppliers with a handbook upon establishing the business relationship. However, if suppliers can be replaced easily, if the interaction with a higher number of suppliers through digitalisation becomes feasible (VI), and thus there is less potential for a long-term partnership, then firms might be less likely to engage in their partners' (digital) internal processes and environmental data management, and instead switch to another supplier if any sustainability issues arise or sustainability targets are not met.

While in our interviews, suppliers did not report technological barriers to collaboration with buying firms, there is a risk that powerful firms (be it buying firms or suppliers) in the supply chain when advancing Industry 4.0 technologies solutions, even for *sustainable* SCC, force less powerful firms to implement compatible hardware and software systems and provide data, while not necessarily obtaining useful data themselves. This might happen, for instance, if sustainability platforms are exclusively managed by a small number of powerful firms, or if digitalisation solutions are too advanced for a specific country context (Luthra et al., 2020; Ozkan-Ozen et al., 2020).

5.2. Hypothesis 2: Digitalisation and sustainability management are not linked in firms

In our interviews, we gained the impression that especially large firms have achieved maturity in using digital technologies for business-related functions in SCC, such as order transmission between companies. However, little collaboration on *environmental sustainability*-related topics using the companies' digital technologies in the supply chain was reported by our interview partners - an observation that is supported by the focus of applying Industry 4.0 technologies for economic rather than environmental benefits (Margherita and Braccini, 2020). The use of Industry 4.0 technologies for sustainable SCC in the interviewed firms did not appear to be widespread, as showcased by the low adoption of BDA and AI solutions for sustainable SCC. Some implemented examples of advanced technology use mentioned by our interview partners include online collaboration platforms, predictive analyses of sustainability risks with suppliers, and optimisation of truck routes. We conclude that either there is little existing sustainable SCC realised through the main digital information and communication systems used in supply chain management by the firms we interviewed, or else sustainability collaboration is detached from the broader supply chain management in the company and therefore beyond our interview partners' awareness. In support of the latter notion, earlier research has already identified the problem of "enterprise information islands" regarding sustainability data (Tao et al., 2014). Moreover, we were rarely able to identify an expert on both sustainability *and* digitalisation in supply chain management in any company, possibly indicating a lack of awareness and expertise at this intersection.

5.3. Managerial and policy levers to improve the socio-ecological performance of the supply chain through digitalisation

We structure the suggested measures around three levers: socio-technical, economic, and legal & political measures (Table 5).

From a socio-technical point of view, support structures from more digitally mature companies, governments, and/or non-firm actors for less digitally mature firms are needed that create possibilities for "digital environmental upgrading" for firms. **Digital environmental upgrading** means a continuing digital innovation process where socio-technical knowledge regarding digitalisation is co-produced and applied among supply chain parties to achieve environmental goals. Cheap and context-dependant, (possibly low-tech) solutions to collaboration between supply chain partners should be explored, especially further upstream, in order to overcome the problem of proposing ever more technologically sophisticated technologies that fail due to organisational, financial, and other non-technological problems across the supply chain (Luthra et al., 2020; Yadav et al., 2020). Sustainability indicator performance will need to be measured along the supply chain in order to critically assess the effectiveness of any Industry 4.0 measure towards more sustainable supply chains. In this regard, a combination of several technologies could create synergies. For instance, a blockchain-based information storage in trustworthy, public cloud infrastructures (such as proposed by the GAIA-X project), could enable the more independent evaluation of environmental parameters along the supply chain, with the aid of algorithms developed collaboratively among supply chain partners. Collaboration with non-firm actors in the supply chain, e.g., government agencies, sectoral business associations, specialised service companies, or utility providers, could facilitate this task. Several initiatives and solutions work at this nexus, such as the private sector initiatives "Global e-Sustainability Initiative (GeSI)", the Responsible Business Alliance (RBA), and service providers such as "Sustainabill" or "CircularTree".

From an economic point of view, firms should aim to create economic and environmental win-win situations. Taking the examples of using Industry 4.0 technologies in supplier collaboration on energy, material use and waste, we concur that the interviewed firms did not yet fully take advantage of the existing and anticipated possibilities of digitalisation for such win-win situations in sustainable SCC (e.g.Dev et al., 2020). For instance, one supplier expected logistics platforms supported by BDA and artificial intelligence to solve the problem of the complexity of supplier evaluations (D) but did not yet take sustainability parameters in supplier evaluation into account. However, choosing suppliers with advanced energy management systems might enable the identification of energy savings potential and associated cost reduction in the future. Furthermore, data analysis to make the sampling of suppliers for audits on sustainability more efficient and effective (VI), could also help to reduce the costs of such audits – a potential that is not yet widely exploited.

We argue that firms' approaches to energy use reduction and material circularity could be incorporated as an additional selection criterion in the selection of collaborating firms, including upstream suppliers beyond the first tier. This is important, as suppliers further upstream run an even greater risk of not meeting sustainability standards (Villena and Gioia, 2018). To this end, organisational and strategic priorities should be shifted towards sustainability, e.g., by employing a digital sustainability expert who explores the potential of digitalisation for sustainable SCC and its economic benefits. This could also help to amortise investments associated with digitalisation in sustainable SCC.

From a legal and political point of view, policymakers should create both constraining and enabling legal environments within which companies have a clear mandate to create sustainable supply chains. On the enabling side, secure legal frameworks for gathering, sharing, and analysing sustainability data have to be created by addressing Intellectual Property and data safety concerns and incentivising collaboration across the supply chain. National (industrial) policies should incentivise the adoption of digital sustainable SCC between buying firms and suppliers. Public funding should be dedicated to public digital infrastructure, such as secure cloud services, and digital environmental innovation in the supply chain, that meets the conditions for wide-spread adoption in upstream countries and contributes to environmental upgrading along the supply chain in the Global South (De Marchi et al., 2013).

On the constraining side, supply chain-wide governance measures, such as carbon pricing and circular economy approaches aimed at environmental sufficiency and questioning (solely) efficiency-enhancing digitalisation measures, could help to prevent digital rebound effects (Kunkel and Tyfield, 2021). In the case of optimising truck routes through BDA, for instance, more efficient logistics routes may increase the total amount of logistical operations as the price of truck transport decreases (becoming more efficient and driving less unnecessary miles). Such rebound effects in transport have been documented in the literature (e.g.Hymel et al., 2010; Tooraj Jamasb and Manuel Llorca, 2021). More generally, when a firm can materialise cost savings using BDA, it is also likely to be more competitive vis-à-vis other firms in the market and offer services and products at cheaper prices. If demand is elastic, this can entail more demand for a service or product and increase its use or production volume. Eventually, digitalisation-related efficiency gains might be overcompensated by the scale effect (rise in overall use/production). Thus, containing rebound effects in the face of digitalisation, is a necessary condition for any digitalisation measure to contribute to sustainability.

6. Limitations

Our study suffers several limitations. We aimed to reach high-level employees responsible for electronics companies' supply chains in a period of global uncertainty and supply chain distress. Consequently, we were not able to interview a representative number of interview partners from buying firms and suppliers, which hampered the external validity of our study. The small number of participants and our convenience sampling approach did not allow us to derive statistically verifiable results. Our results should therefore be viewed as indications for phenomena that have yet to be further validated in future studies, including for other sets of companies and in other geographical contexts . However, we consider the exploratory approach of the study to be an interesting way to touch upon a variety of digitalisation topics and draw links between research and practice. We are able to provide insights into the otherwise largely obscure firm-internal initiatives and expectations regarding digitalisation for sustainable SCC.

Another limitation of interview studies like ours is that interview partners might be biased, or have had incentives to answer in socially desired ways, not wanting to expose possible deficiencies in their companies, e.g., with regard to digital maturity or sustainability. One attempt to validate our findings to some extent was to include two perspectives on SCC, i.e. both buying firms' and Chinese suppliers' perspectives, and match buyers' and suppliers' questions, as well as to employ a theory-driven qualitative analysis approach (Yin, 2003). Because buyers and suppliers were randomly chosen without having a direct business relationship with one another and because interviewees remained anonymous, there was little risk of firms answering in socially desirable ways in an attempt to maintain old or attract new business contacts. However, this is also why it is not possible to derive conclusions as to the specific relationships between the interviewed buying firms and their suppliers in the analysed regions or countries.

To reduce the impact of researcher bias and increase the comprehensibility of our interview questions, we performed a pre-test of our interview guideline with an industry practitioner in the field of supply chain and information systems who gave us an external perspective on the interview questions we chose and the interview process. As a consequence, we adapted the formulation of the interview questions to our target group of supply chain experts, avoiding using conceptual terms such as 'Industry 4.0′, 'cyberphysical systems' or 'connectivity' in our interviews and choosing in our view more practically relevant terms in the field of SCC related to Industry 4.0. Nonetheless, other sources of subjectivity remain in the interviewing and qualitative content analysis. For instance, despite attempts to increase reliability, coding remains a subjective process. There is always leeway in the interpretation of interview partners' statements and in categorising them. We tried to reduce this bias by working together among two coders in this study, discussing with colleagues working in the field, and drawing from theory and prior empirical studies for the establishment of our category system. Agreement amongst researches can increase reliability of the coding scheme and the data analysis (Carter and Easton, 2011).

Lastly, in the Chinese supplier data we chose to conduct written interviews and had to translate Chinese to English and vice versa. Therefore, cross-cultural and language barriers may have influenced the results from our analysis of the Chinese interviews. However, with the support of a native speaker of Chinese who reviewed the translations we were able to identify and eliminate some of the uncertainties around interviewees' responses and thus counter such issues.

7. Concluding remarks: Some suggestions on fostering Industry 4.0 *for* sustainable supply chains

While digitalisation, and Industry 4.0 in particular, offers opportunities for sustainable SCC and environmental upgrading, it is not a sufficient condition for sustainability along the supply chain. Socio-technical, economic, legal, and political hurdles also have to be overcome (Luthra et al., 2020). We posed two research questions. First, how are digital technologies currently used in SCC? Second, what are the opportunities, risks, and obstacles related to the use of digital technologies for sustainable SCC?

Our results indicate that a broad range of basic digital technologies are used in SCC, with fewer cases of advanced Industry 4.0 technologies' application. However, most of the digital technologies in SCC mentioned by our interview partners were not focused on sustainability-related applications. Digital technologies are mainly envisioned to enable a more frictionless supply chain, e.g., BDA for synchronising supply and demand between firms and analysing (future) customer preferences. Sometimes digital technologies were reported to offer additional sustainability use cases, e.g., reducing energy consumption in production lines by using Internet-of-Things technologies. With regard to the opportunities, risks, and obstacles of digitalisation for sustainable SCC, digitalisation was generally viewed as positive for economic and environmental sustainability by most firms we interviewed, e.g., through its potential to induce energy efficiency gains, and only a few risks, such as increasing resource demand, were mentioned. However, several hurdles, including socio-technical, economic, and legal and political ones, need to be addressed in order to harness the potential of digitalisation for sustainable SCC.

We therefore argued for a targeted effort by industry and policy makers to foster (existing) digitalisation initiatives along the supply chain for sustainable SCC in an inclusive way to achieve high uptake and gains particularly among suppliers globally along the supply chain, as showcased by the example of China. We suggested three levers for business and policymakers to improve the overall socio-ecological performance of supply chains through digitalisation: using digital technology adapted to diverse firms' (country) contexts, exploring economic-environmental win-win situations for digitalisation in sustainable SCC, and creating secure legal frameworks for gathering, sharing, and analysing sustainability data. The ultimate goal of any such measure should be an *overall improved socio-ecological performance of the supply chain*.

Despite several limitations of our qualitative, exploratory study, such as limited generalisability, we believe that insights from this study contribute to link the intertwined, but often separated research fields of sustainable supply chain management, global value chains, and digitalisation/Industry 4.0 in order to understand digitalisation from the perspective of collaboration along the supply chain. From a practical point of view, this study enabled us to suggest policy and managerial levers taking into account firm, supply chain, and governance aspects of sustainable SCC. These levers can give hints to policymakers and managers on how to create framework conditions that enable sustainable SCC and (digital) environmental upgrading. From a research point of view, our study yielded indications at the intersection of these research fields that build a basis for future research.

Specifically, the issue of how digitalisation enables sustainability learning in (electronics) value chains deserves more research attention. First, it will be helpful to investigate how sharing environmental data, knowledge, and innovation along the supply chain can be improved despite existing concerns about intellectual property sharing amongst firms. Studies could investigate, e.g., how existing technology transfer licenses could be adapted to privilege 'green innovation' or include sustainability requirements. Second, it will be insightful to scrutinize more in-depth first-tier suppliers and collaboration with further upstream suppliers, also from a broader range of countries. For instance, large suppliers were suggested to sometimes have a stronger leverage for sustainability vis-à-vis small buyers than the other way round. It will be interesting to learn more about first-tier suppliers' own motivation and ability to achieve (digital) sustainability innovation and how they could contribute to fostering environmental upgrading along the supply chain. Likewise, researchers can engage with second-tier, third tier, and further upstream suppliers about their perception of the opportunities and risks of sustainability in the supply chain through digitalisation. Doing so would also enable us to draw parallels and find distinctions between the specific Chinese context and other low- and middle-income country contexts. For instance, in the discussion around its integration into electronics supply chains, Vietnam has managed to attract production capacities (World Bank, 2020), while high logistics costs due to their distance from Asian production hubs make it difficult for African countries to participate in electronics value chains. An intriguing question for future research would be to investigate whether digital technologies have any effect on these geographical differences and what this would mean for (environmental) sustainability.

Sustainability and digitalisation in supply chains are two complex transformation processes. In light of the European “green and digital twin transitions”, commitments to carbon neutrality in the EU and China within decades, and existing trade relationships, it will become ever more important to govern both digitalisation and sustainability across borders going forward. This will likely require immediate intervention *and* long-run strategic planning of policy makers, civil society, academia, and companies. To deal with the challenges and dilemmas that arise, solutions should be developed through a broad, science-based dialogue with all relevant stakeholder groups, orientated by the normative goal of enhancing the socio-ecological performance of supply chains. If guided by sustainability values, digitalisation can certainly help to achieve this goal.

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CRediT authorship contribution statement

Stefanie Kunkel: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Marcel Matthess:** Conceptualization, Data curation, Investigation, Writing – review & editing. **Bing Xue:** Resources, Validation. **Grischa Beier:** Supervision, Validation, Writing – review & editing.

Declaration of Competing Interest

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

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Appendix

A. Interview guidelines

Interview guideline development

The interview guideline was developed in a theory-driven, collaborative process starting in April 2020 including several rounds of internal group revision. In order to ensure validity, we performed a pre-test of the guideline in July 2020 by conducting an interview with an industry expert. The pre-test led to some adjustments, accounting especially for the feedback that, according to the expert, the desired information and knowledge was likely to be spread out amongst various experts and that we would need to tailor our guideline more towards the target group of supply chain managers (in contrast to, e.g., IT or sustainability experts). We also discussed and revised the guideline together with colleagues working in the field and drew from prior studies that chose similar approaches in order to increase validity (Busse et al., 2016).

Interview guideline (buying firms)

1. Please describe your position in the company and your responsibilities and your disciplinary background.
2. What do your supply chain (SC) processes look like regarding procurement (and reverse logistics) and cooperation with suppliers?
   - How do you proceed in terms of:
     - Identification of suppliers
     - Choice of suppliers
     - Other collaborative processes with supplying companies
   - Can you tell us what current challenges you are facing with regard to these processes?
3. How many suppliers does your company have and how are they geographically distributed?
4. Estimate / Please rate: How important are the following aspects to you regarding the suppliers’ performance on a scale from 1 to 10, 1 being not important at all, 10 being very important?
   - Transparency
   - Price
   - Quality
   - Compliance with scheduled delivery dates
   - Recommendation from other partners
   - Digital equipment and know-how
   - Willingness to exchange data on the part of the suppliers for their integration into the supply chain
5. What data do you collect in the course of procurement?
   - What data do you collect on environment and social indicators?
   - Is there also a mutual exchange of data between your suppliers and your company?

6 Which tools do you use in detail for the collection and assessment of data (Excel, e-mail, ERP, EDI, others…)?
  - Do you use any specific tools for the storage and analysis of data on social and environmental indicators?

7 What are obstacles in the collection and assessment of data?
  - Are there any specific obstacles when it comes to the collection and assessment of data on social and environmental indicators?

8 Do you already use big data analytics (and artificial intelligence) to generate information about your suppliers? If so, for what purposes?
  - Just to clarify: We view big data analytics as a technical means to gather and analyse large amounts of unstructured and heterogeneous data.

9 If not: Do you already use big data analytics in other SC processes?

10 Can you imagine using (other) digital technologies in SC management in the future?
  - For instance, can you think of instances in which algorithms could optimise decision-making processes? Are there cases in which tools that are able to give meaning to existing data would assist your work?

11 Which economic, ecological, and social effects of the use of digital technologies do you observe or do you expect to observe in the future in your company or your suppliers?

12 Estimate: How will the use of digital technologies influence the below aspects? Please rate on a scale from −5 to 5 (−5 probably very negatively, 0 probably neutral, 5 probably very positive).

- Exchange of data on the environment and social issues (transparency)
- Transfer of knowledge about the use of energy- and resource-efficient manufacturing technologies and processes
- "Green" innovative ability
- Compliance with legal and voluntary reporting standards on environmental and social aspects
- Involvement of (new) suppliers in the value chain
- Employment and wages in supplier companies

13 Imagine you could reinvent the existing SC processes in the area of sourcing (and possibly reverse logistics): Which processes would have to change and which tools and technologies would be needed to make processes more ecologically and socially beneficial?

Interview guideline (suppliers, translated into Mandarin)

1 Welcome, thank you for your willingness to participate, reminder of the goals of the study, **permission to record?**
1.欢迎, 感谢您的参与, 提醒您此次研究目的, **是否允许会议记录∝**

2 Please describe your position in the company, your responsibilities, your age, and your disciplinary background, and particularities of supply chain management in the electronics branch.
2. 请描述您在公司的职位, 您的职责, 您的年龄以及学术背景, 电子行业供应链管理的特性

3 How many branded firms does your company supply and how are they geographically distributed?
3. 贵公司共供应多少品牌公司∝他们的地理分布是怎样的∝

4 How many suppliers does your company have and how are they geographically distributed?
4. 贵公司有多少的供应商∝他们的地理分布是怎样的∝

5 What do your supply chain (SC) processes look like regarding cooperation with both branded firms/OEMs and your suppliers?
5. 对于品牌公司/原始设备制造商与贵公司供应商之间的合作, 您的供应链流程是怎样的∝

6 Please rate each on a scale from 1 to 10: How much do the branded firms that you supply value the following aspects in you:
请按1至10比例评分:您供应的品牌公司在以下方面对您是怎样评估的∝

Transparency 透明度
Data availability 数据可用性
Price 价格
Quality 质量
Sticks to delivery dates 确保交货日期
Recommendation from another firm 其他公司推荐
Digital equipment and know-how 数字化设备及专业技能
Willingness to exchange data 交换数据的意愿

1 What data do branded firms demand from you, including about environmental and social indicators?
7. 品牌公司需要您提供哪些数据∝包括环境及社会指标∝

2 What data do you demand from your suppliers?
8. 您需要从供应商那里得到哪些数据∝

Do you also collect data on environmental and social indicators?
您也需要收集环境及社会指标数据吗∝

1 Which tools do you use in detail for the collection, transmission, and assessment of data (pencil & paper, excel, e-mail, ERP, EDI, others…)?
9. 您在收集, 传输及评估数据时使用了哪些工具∝ (铅笔和纸张, excel, 电子邮件, ERP, EDI, 或其他…)

If you collect data on environmental and social indicators: Which tools do you use for that?

如您收集了环境及社会指标数据:您使用到了哪些工具∝

1 What are obstacles in the collection and assessment of data?
10. 在收集及评估数据方面有哪些障碍∝

What are specific obstacles around data on environmental and social indicators?
在收集环境及社会指标数据时有哪些具体障碍∝

1 Do you already use big data analytics and/or artificial intelligence in the cooperation with branded firms? If so, for what purposes? Descriptive or prescriptive? Also for ecological or social purposes?
11. 在与品牌公司合作时您是否已经运用到了大数据分析和/或人工智能∝如果是, 您的目的是∝描述性还是规定性∝为了生态还是社会目的∝
2 If not: Do you already use big data analytics in other SC processes?
12. 如果没有:您是否已经在其他供应链流程中使用到大数据分析∝
3 If not: Can you imagine using specific digital technologies in SC management in the future?
13. 如果没有:您能想象在未来的供应链管理中会使用到的特定的数字技术吗∝

Do you use other tools to assess large amounts of unstructured data?
例如:您使用过其他工具来评估大量的非结构化数据吗∝
Do you use algorithms to optimise decision processes?
您使用过算法来优化决策过程吗∝

1 Which ecological and social effects of the use of digital technologies do you observe or do you expect to observe in the future in your company/ at the branded firms that you supply, e. g. with respect to energy use, resource use or wages in your company?
14. 您在贵公司/供应的品牌公司中观察或未来期望观察到哪些使用数字技术的的生态和社会影响∝例如:能源的运用, 资源运用或公司工资方面∝
2 Estimate: How will the use of digital technologies influence the below aspects? Please rate on a scale from -5 to 5 (-5 probably very negatively, 0 probably neutral, 5 probably very positively).
15. 请预估:数字技术的使用会怎样对以下几个方面产生影响∝请按-5至5分段评分 (-5 可能非常消极, 0 可能中立, 5 可能非常积极).

Exchange of data on the environment and social issues 环境和社会问题的数据交换
Transfer of knowledge about the use of energy- and resource-efficient manufacturing technologies and processes 关于能源及资源高效制造技术和过程的知识转换
In your company 对您公司
At your suppliers 对您的供应商
"Green" innovative ability "绿色"创新能力
In your company 对您公司
At your suppliers 对您的供应商
Compliance with legal and voluntary reporting standards on environmental and social aspects
遵守环境和社会方面法律及自愿报告标准
In your company 对您公司
At your suppliers 对您的供应商
Involvement and realised gains of your own company in the supply chain
您自己公司在供应链中的参与及收获
Involvement of (new) suppliers in the value chain（新）供应商在价值链中的参与度
Employment and wages in your own company 贵公司的工作及薪资
Employment and wages at your suppliers 您的供应商的工作及薪资

1 Imagine you could reinvent the existing SC processes in the area of sourcing: Which processes would have to change and which tools and technologies would be needed to make processes more ecologically and socially beneficial?
16. 设想一下您能在采购中重新设计现有的供应链过程:哪个过程是必须改变的∝哪些工具及技术会使整个流程更具生态及社会效益∝
2 Optional: What are your current challenges in supply chain management?
17. 可选:您目前在供应链管理方面面临的挑战是什么∝
3 Are there any other aspects that we haven't mentioned yet but which you would like to add because you think they are important?
18. 有没有其他方面我们没有提及, 但您认为较重要并愿意补充∝
4 Do you have contacts who might be willing to talk to us and share their expertise?
19. 您有愿意与我们交流并分享他们专业知识的联系人吗∝

B. *Statistics about buying firms and suppliers*

Table A1 and A2.

Table A1
Statistics about buying firms.

Interviewee (Position)	Size of firm	No. of suppliers	Location of suppliers	Sub-sector / product type
I (Director Advanced Manufacturing)	Large	~30 000	Globally distributed (~60 countries)	Multimedia, Automotive electronics
II (Smart Logistics Manager)	Large	"10, 000s"	Globally distributed with clusters in Europe, Asia (China), North America	Smart home & household appliances
III (Supply Chain Manager)	small/ medium	~25	10 biggest ones in Asia, 10–15 in Europe	Consumer electronics peripherals
IV (Director Supply Chain Management)	Large	–	Concentrated in Germany; China, Romania, US, Mexico	Electrical connectors
V (Director Supplier Sustainability)	Large	4500	33% Asia (majority in China), 33% in Americas (mostly North America), remaining Europe clustered around Poland, the Netherlands, and Germany	Household appliances, multimedia
VI (Procurement Manager)	Large	–	–	Household appliances
VII (Supply Chain Manager)	Large	–	Concentrated in China, significantly smaller in India, Vietnam, local services from Switzerland	Telecommunication equipment
VIII (Procurement & Manufacturing Manager)	small/ medium	100–150	Concentrated in Germany, smaller clusters in China	Data centre equipment
IX (Business Development Manager)	–	50–100	Concentrated in Germany, rest of Europe	Smart sensors
X (Sustainable Sourcing Manager)	Large	>20,000	Clustered around Asia for hardware and components, services all around the world	Multimedia, mobile phone

Note: "Size of firm" is defined in our paper according to the number of employees: small/medium (1–500 employees), large (501–500,000 employees); "-" indicate gaps in information; in the first column, where two positions are mentioned, two persons were interviewed.

Table A2
Statistics about suppliers.

Interviewee (Position)	Production location	Size of firm	No. and location of customers (buying firms)	No. and location of 2nd tier suppliers	Sub-sector / product type
A (Supply Chain Manager)	Shanghai	small/ medium	~3000 – 4000 customers, largely SMEs and a few brand-name companies. High concentration in China, Taiwan, Hong Kong, few customers in Japan and the EU.	~50 suppliers, mainly from Europe, US, Japan, Taiwan, China	Unspecified intermediate components
B (Production Director)	Suzhou	large	Unspecified customer base and location	Unspecified (large) and global supply base, concentrated in China	Laptops
C (Procurement Manager)	Nanjing	large	~100 customers, mainly located in Europe, America, and Southeast Asia	~320 suppliers, unspecified location	Household appliances
D (Production & Planning Manager)	Shenyang	large	~70 customers, largely located in China, Latin America	~100 suppliers, largely located in China, Europe, US	Smart measurement tools
E (Supply Chain Director)	Shanghai	large	Unspecified customer base, concentration in China	~100 suppliers, concentrated in China	Household appliances
F (Production Manager)	Guangdong	large	~200 customers, concentrated in SE Asia, India, the Middle East, North America, China	~200 suppliers, concentrated in China, Japan, South Korea, US, Germany	Air conditioners
G (CEO)	Shenzhen	large	~ 100 customers, all located in China	~20 suppliers, concentrated in China	Unspecified intermediate components
H (Production Line Development Manager)	Taizhou	large	~40 customers, concentrated in China	~10 suppliers, concentrated in China	Unspecified intermediate components

Note: "Size of firm" is defined in our paper according to the number of employees: small/medium (1–500 employees), large (501–500,000 employees); "-" indicate gaps in information; in the first column, where two positions are mentioned, two persons were interviewed.

C. Category system for the qualitative content analysis

List of codes that were developed in the collaborative coding process
1. Interviewee information
2. Information on electronics supply chain
3. Supply Chain Collaboration processes
3.1 Identification of suppliers
3.2 Choice of suppliers
3.3 Collaboration with suppliers
4. Data exchange and analysis
5. Digital tools & technologies
5.1 BDA & AI
6. Supplier collaboration use cases
7. Supply chain use cases
8. Sustainability implications
8.1 Supply Chain Collaboration sustainability conception
8.2 Observed impacts of digitalisation in SC Collaboration

(*continued on next page*)

(*continued*)

8.2.1 Economic
8.2.2 Environmental
8.2.3 Social
8.3 Envisioned impacts of digitalisation in SC Collaboration
8.3.1 Economic
8.3.2 Environmental
8.3.3 Social
9. Obstacles to digitalisation
10. Opportunities & risks of digitalisation in sustainable Supply Chain Collaboration
10.1 Opportunities
10.2 Risks

D. From category system to research results

After the coding and discussing the researchers' codes, we reviewed all interview fragments that a) reported on the digital technologies that are used in the SCC of the respective firms, and b) linked digital technology use in collaboration to environmental sustainability, according to our research questions. We sorted digital technologies according to our digital maturity scheme. All reported digital technologies used in collaboration were accordingly reported in section 4.1.

With regard to the link between digital technology use in collaboration and sustainability, we differentiated between observed and envisioned impacts, as well as the triple bottom line of sustainability categories – social, economic, and environmental – to get an overview of all the sustainability aspects mentioned. Since this analysis focuses on the environmental dimension, we concentrated on the mentioned environmental aspects to further differentiate between "opportunities" and "risks" in these interview fragments. We report these in section 4.2. We further added opportunities and risks that emerged as a combination of the way firms collaborated digitally (research question 1) and the way they reported currently handling sustainability (mentioned during the interview).

We report the use cases in section 4.2 merged by clustering the reported sustainability applications of digital technologies along three specific environmental sustainability aspects in the supply chain, namely: environmental data gathering and analysis on platforms, managing energy use and environmentally optimising logistics chains, and improving material circularity in the supply chain. Our approach aims at including *all* information that is relevant to either research question 1 or 2 in order to achieve our goal of obtaining a broad scope of digitalisation for sustainable SCC in the interviewed electronics firms.

In order to improve the validity of our findings, we conducted an additional interview with the representative of an electronics association who was responsible for increasing sustainability in the sector by using digital technologies. This interview was not used in the results section but helped to validate our coding decisions and identified foci for the results and discussion (Potter and Levine-Donnerstein, 1999).

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