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Knowledge-sharing across supply chain actors in adopting Industry 4.0 technologies: An exploratory case study within the automotive industry

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ABSTRACT

This study investigates the role of knowledge-sharing between supply chain actors in facilitating their adoption of Industry 4.0 technologies, identifying factors that hinder or promote such knowledge-sharing. Drawing on an in-depth single case study, including 19 interviews with a manufacturing firm in the German automotive industry and five of the suppliers and customers in the focal firm's supply chain, the study identifies the following knowledge-sharing approaches that facilitate the adoption of Industry 4.0: 1) knowledge-sharing through principles; 2) upstream flow of knowledge; 3) strategic positioning; and 4) application-relatedness. These approaches are shown to be influenced both by company-related factors and relational factors. Applying a knowledge-based view of the firm, this study addresses a gap in current research by investigating the role of knowledge-sharing in adopting Industry 4.0 from the perspectives not only of a single focal firm but also of upstream and downstream suppliers and customers in the supply chain. In presenting approaches to knowledge-sharing that promote the implementation of Industry 4.0 based on a firm's existing resources, this study is also of direct relevance to practitioners.

1. Introduction

Industry 4.0 (I4.0) technologies have been transforming manufacturing since they became commercially viable in industrial applications (Strange and Zucchella, 2017). Comprising base technologies, such as cyber-physical systems, the Internet of Things, cloud computing and big data, to front-end technologies, such as smart working, smart manufacturing and smart products (Frank et al., 2019), 'I4.0' technologies are adopted by managers to optimize intra-company flows and to enhance inter-organizational integration across supply chains (Birkel and Hartmann, 2019; Chiarini et al., 2020; Müller et al., 2018). Interconnecting supply chain (SC) actors through the adoption of I4.0 technologies facilitates the generation and sharing of real-time data along the entire SC, enabling firms not only to track materials and goods but also to synchronize inter-organizational processes. Such data can further help firms forecast their resource needs, thereby reducing the risk of SC disruptions, increasing efficiency and lowering costs for multiple actors across SCs (Bär et al., 2018; Frederico et al., 2019).

Given the important advantages afforded by adopting I4.0 technologies, especially in an increasingly competitive global environment, it is a matter of considerable interest to researchers and practitioners alike that so many firms are still hesitant to implement these technologies more comprehensively (Chiarini et al., 2020; Koh et al., 2019; Tortorella et al., 2019). Instead, most firms still tend to confine themselves to experimenting with stand-alone I4.0 approaches for individual machines and in-house production steps (Bär et al., 2018; Pu et al., 2019), meaning they do not harness the full potential of interconnected systems (Fatorachian and Kazemi, 2018). This apprehension is largely due to the considerable upfront investment entailed in more comprehensive implementation of I4.0 technologies, as well as lack of knowledge and perceived uncertainties, including unclear break-even points and amortization periods (Horváth and Szabó, 2019; Kiel et al., 2017). In addition, manufacturing firms adopting I4.0 in their SCs must ensure interoperability between newly implemented technologies and traditional manufacturing procedures not only internally but also in their external SC processes (Zangiacomi et al., 2020). Integrating I4.0 into multiple existing structures and processes in this way entails establishing interfaces between all entities in an SC and thus cannot be undertaken by any single manufacturing firm in isolation but requires the involvement of all SC partners (Bär et al., 2018).

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In considering how firms can overcome these complex challenges, this study aligns with a growing recognition that collaboration is vital not only for optimizing the affordances of I4.0 in SCs but also for facilitating the large-scale adoption of these technologies in the first place. This starting point recognizes that it is only by collaborating in identifying and *sharing* the knowledge and skills needed to integrate I4.0 technologies throughout an SC that the potential of each actor along the chain can be fully leveraged to support the adoption and reap the benefits of these technologies (Zangiacomi et al., 2020).

While the importance of knowledge-sharing between SC actors has been widely acknowledged in previous studies, most research to date has examined its role primarily in the context of operational activities, such as the use of information exchange for better understanding customer demands, for tracking and forecasting inventory levels, for informing production plans, and for developing new products (Soosay and Hyland, 2015; Eslami et al., 2018). This prevailing focus has led researchers to overlook the vital supporting role that collaboration can play in the digital transformation of SCs. In particular, possible synergies between manufacturing firms and suppliers and customers to facilitate the adoption of I4.0 technologies between actors involved in the SC remain underexplored (Agostini and Nosella, 2020; Zangiacomi et al., 2020). In addition, because the focus of extant research on I4.0 adoption has typically been on single firms and/or their overall relationships to SCs (Sharma et al., 2021), little consideration has been given to the role of *dyadic* relationships between different entities in the SC.

This paper sets out to address these gaps in current research by drawing on findings from a single case study of a focal firm and its suppliers and customers to explore the role of knowledge-sharing in facilitating I4.0 adoption across several SC actors and the factors that hinder or promote such knowledge-sharing. In this investigation the concept of knowledge-sharing is applied to capture how the knowledge of individual firms can be distributed among upstream and downstream SC partners, showing how such sharing can not only increase the knowledge base of the SC as a whole (Suh et al., 2019) but also compensate for any knowledge gaps on the part of individual actors in the overall I4.0 adoption process (Mehdikhani and Valmohammadi, 2019; Wang and Hu, 2020). These benefits are attainable, it is argued, because knowledge-sharing can enable manufacturing firms to learn from the experiences of other companies in adopting specific I4.0 technologies. By enabling firms to explore possible synergies along the SC (cf. Zangiacomi et al., 2020), moreover, knowledge-sharing can support the development of a more favourable attitude towards I4.0 (Agostini and Nosella, 2020).

To identify the factors that influence knowledge-sharing along a manufacturing SC and the capacity of such sharing to support widespread transformation towards I4.0, this study examines the case of a manufacturing SC implementing I4.0 technologies not only from the perspective of the focal firm but also from the perspective of the firm's suppliers and customers. This inquiry is guided by the following two research questions:

RQ 1: *How can knowledge-sharing between a focal manufacturing firm and its first-tier upstream and downstream partners facilitate the adoption of I4.0?*

RQ 2: *Which factors influence knowledge-sharing between a focal manufacturing firm and its first-tier upstream and downstream supply chain partners in their adoption of I4.0?*

In drawing attention to underexplored processes and dynamics of multi-tier knowledge-sharing in SCs in relation to the adoption of I4.0 technologies, this study not only adds to theory but also offers highly relevant insights for practitioners, including manufacturing companies currently struggling with adopting and integrating I4.0 technologies across SCs.

The paper is organized as follows: Section 2 reviews the relevant literature on I4.0, SCs, and knowledge-sharing; Sections 3 and 4 present the research method and findings; and Section 5 presents the discussion of the study, following with theoretical and managerial implications and limitations and future research directions.

2. Literature review

2.1. Industry 4.0 and the supply chain

The term 'Industry 4.0' was first reputedly made famous in 2011 when the German government coined this term to announce a new high-tech economic strategy (Kagermann et al., 2011), thereby proclaiming the dawn of a 'new industrial age' (Xu et al., 2018). With growing evidence that adopting I4.0 technologies across SCs can significantly increase the capacities of companies to adapt to changing customer demands and fierce competition (Horváth and Szabó, 2019), I4.0 has evolved into a focal concept among firms within modern manufacturing industries (Bibby and Dehe, 2018). Encompassing a range of technologies that transform industry towards digital manufacturing (Hughes et al., 2020; Koh et al., 2019; Müller et al., 2018), I4.0 integrates people and physical objects such as products, electronic devices, machines, and production lines with the digital virtual world, thereby creating 'cyber-physical systems' (Agostini and Nosella, 2020; Chiarini et al., 2020; Devi et al., 2020). In combination, these multiple cyber-physical systems constitute an interconnected and decentralized network within which information and communication technologies, software and sensors enable the automatic collection of process data from connected devices and the communication of such data both within and across organizational boundaries in real time (Cisneros-Cabrera et al., 2021; Horváth and Szabó, 2019; Müller et al., 2018). By facilitating autonomous production systems in the manufacturing industry (Kamble et al., 2018; Tortorella and Fettermann, 2018), machine-to-machine communication affords multiple potential benefits, including in the form of greater transparency and traceability, enhanced information integration, and process optimization.

When adopted and applied to inter-organizational processes, I4.0 technologies can potentially yield even greater benefits. This is because the increased connectivity and automated real-time data-collection and analysis of embedded systems and devices afforded by these technologies can not only increase transparency and trust between different SC actors (Fatorachian and Kazemi, 2021; Ghadge et al., 2020) but also inform and improve decision-making and planning within and across company boundaries (Zheng et al., 2020). This increased transparency, as noted earlier, includes the capacity to trace and track parts, components, and products across SCs in real time (Xie et al., 2020), improving the capacities of multiple actors to forecast logistics operations, such as product flows and inventory planning, and thereby reducing inefficiencies. By increasing the capacity for coordination among SC firms, moreover, I4.0 adoption can increase the responsiveness and resilience of these firms to market fluctuations in demand (Fatorachian and Kazemi, 2021; Hofmann and Rüsch, 2017). In these ways, adopting I4.0 technologies can further help reduce information asymmetry between SC actors, enabling a better understanding of mutual requirements (Chauhan et al., 2021; Xie et al., 2020).

At the level of single firms, the implementation of I4.0 technologies not only enables better monitoring of production through the continuous capturing of data pertaining to machinery and the production process but also the remote execution of preventive maintenance, significantly increasing manufacturing efficiency by reducing downtimes (Masood and Sonntag, 2020; Müller et al., 2018). Because such production-related data enables early problem identification, moreover, it can also be used to forewarn a firm's SC partners of expected bottlenecks, thus also increasing delivery reliability (Ghadimi et al., 2019; Müller et al., 2018; Xie et al., 2020). By diminishing intra- and inter-organizational boundaries, digital integration can further help strengthen SC partners' collaborative relationships (Xie et al., 2020; Xu et al., 2018).

In sum, prior research has envisaged the adoption of I4.0 technologies to facilitate enhanced SC integration by providing instant connectivity and accessibility throughout the chain (Müller et al., 2018). Sharing resources and data related to devices and units while also executing inter-organizational transactions between SC partners can help achieve optimal integration by assisting in the tracking of movements of goods, the creation of uniform administrative platforms, making business processes more mobile, and lowering overall manufacturing costs (Büyüközkan and Göçer, 2018). Despite these potential benefits, many manufacturing firms still struggle to implement I4.0 technologies on any scale commensurate with their potential (Birkel and Hartmann, 2019). Research has shown that many firms are reluctant to invest in these technologies due to perceived obstacles to knowledge-sharing, adoption, and implementation (Frederico et al., 2019). The key challenges the literature has identified to the adoption of I4.0 across SCs can be categorized as economic, technological, and organizational (Fatorachian and Kazemi, 2018; Moeuf et al., 2020; Srivastava et al., 2022).

Economic challenges relate to the costs associated with the replacement or upgrading of existing systems and machinery and the investment in new infrastructure capable of supporting I4.0 (Masood and Sonntag, 2020; Sharma et al., 2021). Additional costs are further incurred by the need for technical training (Moeuf et al., 2020; Müller et al., 2018). Due to the pace of technological developments and uncertain market developments, moreover, these investments tend to be seen as too risky (Birkel and Hartmann, 2019; Horváth and Szabó, 2019; Kumar et al., 2020).

Technological challenges arise from the need to integrate and align I4.0 technologies with the existing infrastructure of firms and SCs (Horváth and Szabó, 2019; Xu et al., 2018). These challenges apply not only to the adoption of I4.0 across organizations in a chain but also span across different hierarchical levels and departments within each organization (Kiel et al., 2017). Attaining compatibility between different systems and IT infrastructures must thus be achieved both in-house and with external actors, increasing the complexity of the IT system (Ehie and Chilton, 2020; Frederico et al., 2019; Müller et al., 2018). With each connected machine there comes a corresponding increase in the amount of available real-time data to be processed, creating the need for high data-storage capacity (Horváth and Szabó, 2019). Scalability issues may arise, therefore, as the amount of data transacted increases and as more machines are connected to the I4.0 network (Xu et al., 2018). Unless companies have the necessary tools and capacities to analyze these vast and proliferating quantities of newly generated data, the potential benefits of I4.0 technologies may remain under-exploited (Fatorachian and Kazemi, 2018). Another pressing technological challenge for companies adopting I4.0 is cybersecurity (e.g. Hofmann and Rüsch, 2017; Kiel et al., 2017; Moeuf et al., 2018). This challenge arises because I4.0 technologies require the storing and partial sharing of companies' proprietary and confidential data, including customer and production data, making organizations more vulnerable to cyber-attacks. To avoid disruptions or shutdowns of interconnected machines that could potentially affect the entire production system (Kiel et al., 2017; Müller et al., 2018), companies thus also need to have sufficient protections in place against cybercrime, data theft, and unauthorized interference in production systems and other business processes, including industrial espionage (Fatorachian and Kazemi, 2018; Xu et al., 2018).

Organizational challenges include employee-level concerns regarding job security and increased work surveillance, as well as concerns at managerial level about changes in their functions that might trigger their resistance to the adoption of I4.0 (Horváth and Szabó, 2019; Kamble et al., 2018; Moeuf et al., 2020). Another organizational challenge of adopting I4.0 technologies is the need to ensure the availability of adequate digital competence and technological expertise (Kumar et al., 2020; Masood and Sonntag, 2020; Sharma et al., 2021). Such competence is required not only to run I4.0-supported SC processes but also to choose appropriate tools and designs and to implement the processual set-up aligning company-specific systems with their SC partners' systems (e.g. Müller et al., 2018). Any shortfall in managerial competence regarding I4.0 technologies might lead to inadequate planning of change processes and resources and the lack of a clear and feasible strategy (Horváth and Szabó, 2019; Salo et al., 2020; Zangiacomi et al., 2020). As a further key inter-organizational challenge, SC partners must be willing to collaborate closely with each other, which requires a level of shared understanding of potential I4.0 benefits and challenges, shared trust in I4.0 technologies, and trust in the necessary technological capabilities of the partner organizations (Birkel and Hartmann, 2019; Müller et al., 2018; Sharma et al., 2021).

Notwithstanding all these economic, technological and organizational challenges, the most critical impediment to successful I4.0 adoption has been identified as a lack of commitment on the part of firms in partnerships (Horváth and Szabó, 2019; Salo et al., 2020). All these factors thus need to be carefully considered before embarking on I4.0 implementation. In particular, manufacturing firms must gain sufficient *knowledge* of I4.0 in order to identify which capabilities are required to overcome challenges that may arise as they proceed with I4.0 adoption. Accordingly, this study starts from the contention that knowledge-sharing is the most viable solution for encouraging and facilitating I4.0 adoption. This is because sharing knowledge and working together can reduce the burden on individual manufacturing companies and their SC partners and better equip them to overcome the challenges of I4.0 implementation. This contention is supported by evidence from prior studies which have shown that knowledge-sharing throughout an SC has the potential to strengthen relationships between SC actors and lead to better overall performance of the chain as a whole (Handoko et al., 2018; Mehdikhani and Valmohammadi, 2019). For example, Zangiacomi et al. (2020) have argued that mutual knowledge-sharing can serve not only to enhance the level of readiness for I4.0 implementation but also to facilitate possible synergies between suppliers and customers.

2.2. Knowledge-sharing in supply chains

In SC contexts, knowledge-sharing facilitates the establishment of interactive connections among different actors, primarily through dyadic relationships, enabling firms to transfer, combine, and enhance their knowledge (Pihlajamaa et al., 2019; Szulanski, 1996). By enabling firms to acquire and assimilate external knowledge in this way, knowledge-sharing can serve as a viable solution to many issues arising in supply chains, including the adoption of I4.0 technologies (Lee and Ha, 2018; Zangiacomi et al., 2020). This study therefore adopts a knowledge-based view of the firm to examine and elucidate how knowledge-sharing can increase the capacities of firms to adopt I4.0, applying this lens to the case firm and its SC partners in the German automotive industry.

In the knowledge-based view of the firm, knowledge is conceptualized as the key strategic resource by which companies can gain a competitive advantage, primarily because the internal, specialized knowledge accrued by firms is difficult to imitate (Grant, 1996; Kogut and Zander, 1992). This, in turn, is because knowledge resides within the individuals working for a firm, meaning that effective internal knowledge-sharing strategies are needed to transfer knowledge from individual level to organizational level in order for such knowledge to benefit the firm (Kogut and Zander, 1992). In addition to such internal organizational knowledge, firms also need to create and obtain knowledge from external resources to improve their performance (Nonaka, 1994). As multiple studies have shown, an effective way of obtaining external knowledge is though the adoption of voluntary knowledge-sharing with other SC actors such as direct suppliers and customers (Grant and Baden-Fuller, 2004; Kogut and Zander, 1992).

For instance, Jayaram and Pathak (2013) and Eslami and Lakemond (2016) have found that by sharing knowledge with its customers a focal firm can alter its manufacturing capabilities to ensure its products better meet customers' needs, while Lin (2014) has shown that knowledge-sharing can enable companies to modify and synchronize processes within their SCs and thus ensure long-term effectiveness.

2.2.1. Types of knowledge

In discussing knowledge-sharing, especially in the context of SCs, a vital distinction must be drawn between *explicit* and *tacit* types of knowledge. Explicit knowledge here refers to codified knowledge, such as facts and symbols that can be stored and accessed in different ways and is thus easily transferable (Polanyi, 1966; Spekman and Davis, 2016), whereas tacit knowledge denotes knowledge possessed by firms' employees that is difficult to codify, complicated to understand, and challenging to transfer (Li, 2020; Polanyi, 1966). While explicit knowledge can be shared effectively among large impersonal groups, sharing tacit knowledge needs to be facilitated by intensive interactions based on personal contacts in familiar groups (Alavi and Leidner, 2001; Li et al., 2017). In the context of SCs, therefore, it is important to note that while explicit knowledge is easier to share with suppliers, the focus of knowledge-sharing involving customers is on the more complex and challenging exchange of tacit knowledge (Vanpoucke et al., 2017; Wagner and Bukó, 2005).

2.2.2. Challenges associated with knowledge-sharing in supply chains

The probability of achieving successful knowledge-sharing in SCs has been shown to increase if all parties involved are willing to dedicate time and resources to this process (Li et al., 2012). Attaining such a collective commitment of resources is inherently challenging, however, not least because committing to such a long-term undertaking may seem counterintuitive to some employees given the typical focus in most settings on the competitiveness of *individual* companies (Suh et al., 2019). Studies have further shown that firms may be reluctant to apply external knowledge even if they are reassured it is valid, since they have not been involved in creating that knowledge (Cohen and Levinthal, 1990).

2.2.2.1. Maintaining the effectiveness of partnership over time. Once a knowledge-sharing partnership has been developed among SC actors, a further challenge is to maintain a reciprocal flow of knowledge among actors in the chain that facilitates *mutual* benefits and not just individual gains (Suh et al., 2019). This challenge arises from the tendency of companies, for various reasons, to be protective of internal knowledge, thereby precluding reciprocal knowledge-sharing (Lawson and Potter, 2012). This tendency may be justified insofar as the leakage of knowledge – both intentional and non-intentional – has been widely identified in the literature as the main risk associated with knowledge-sharing (Colicchia et al., 2019). If customers are overly focused on minimizing the risk of knowledge leakage, however, this will significantly impede knowledge-sharing, and in particular the exchange of tacit knowledge (Qiu and Haugland, 2019). Similarly, if suppliers strive to acquire each other's knowledge without reciprocating, the wronged party will likely respond to such attempts by limiting future knowledge-sharing (Lawson and Potter, 2012). In general, regardless of the reasons for such protective behaviour, "the more protective partners are of the knowledge they possess, the less effective the transfer will be" (Spekman and Davis, 2016, p. 51).

2.2.2.2. Self-interest. Opportunistic behaviour is also detrimental to knowledge-sharing (Singh and Power, 2014) and likewise can arise due to a variety of factors. For example, Vázquez-Casielles and Iglesias (2013) have attributed such self-interested behaviour primarily to information asymmetries and power inequalities between supplier and customer firms, while Suh et al. (2019) have argued that opportunistic behaviour can arise from disparities in the relative applicability of the knowledge gained inside and outside of a partnership insofar as such knowledge may open up multiple options for the receiving firm but not for the other partner and thus jeopardize the continuity of the partnership. By contrast, relationship-specific knowledge tends to nurture a long-term perspective (Suh et al., 2019). Given the evidence that opportunistic behaviour can lead to knowledge leakage, research on "trustworthiness in knowledge transfer and leakage in alliances" (Qiu and Haugland, 2019) has concluded that firms need to choose their suppliers and customers cautiously to pre-empt such behaviour and its negative consequences.

2.2.2.3. Relational challenges. Relational challenges to knowledge-sharing can again arise from multiple factors, including perceptions of cultural distance on the part of employees in respective firms of a partnership, potentially leading to lack of trust, insufficient behavioural transparency between individuals, and inadequate communication (Mol and Brandl, 2018; Rungsithong and Meyer, 2020). Such risks may also arise if one of the partners enhances their competitive position and no longer sees knowledge-sharing as beneficial (Cheng, 2011). Insofar as transferring internal knowledge to suppliers or customer tends to be a highly sensitive issue (Spekman and Davis, 2016), moreover, knowledge-sharing is inherently difficult to achieve in practice.

To pre-empt or manage these various types of challenges, therefore, firms seeking to engage in knowledge-sharing need to consider not only supporting factors, such as power equality, mutually perceived justice and trust in partnerships but also ways of mitigating any obstacles to increasing their chances of success both in knowledge exchange and in adopting I4.0 (Cheng, 2011).

2.2.3. Factors influencing knowledge-sharing in supply chains

In seeking to establish knowledge-sharing networks across SCs, the most critical factor for success and for increasing the scale of knowledge-sharing has been identified in the literature as the facilitation of close and trusting relationships among the parties (Spekman and Davis, 2016; Yang et al., 2016). In evaluating the factors influencing knowledge-sharing across SCs, therefore, the role of 'relationship-related modifiers' must be considered in addition to the factor of 'company readiness'.

2.2.3.1. Relationship-related modifiers. Research has shown that strong relationships between SC partners directly facilitate knowledge-sharing, including by reducing opportunistic behaviour (Chesbrough, 2003; De Vries et al., 2014). Here, the behaviour of the respective partners in the SC in terms of levels of interaction and the flow of knowledge among partners has been shown to be an essential factor, with extensive interaction and communication between SC partners tending to nurture relationships conducive to knowledge-sharing processes (Li, 2020; Spekman and Davis, 2016; Wagner and Bukó, 2005). Among the factors proposed to nurture such relationships and thus encourage a knowledge-sharing culture among diverse SC partners is the adoption of shared behaviour and etiquette (Li et al., 2012). Such mutual adaptation is needed, it is argued, because knowledge-sharing is invariably enacted within socially embedded relationships based on mutually established norms (Vázquez-Casielles and Iglesias, 2013).

Mutual trust plays a significant role in this process as a key driver for effective knowledge-sharing and for building complementary capabilities across SC actors (Cai et al., 2013; Qiu and Haugland, 2019). As Spekman and Davis (2016) have shown, mutual trust is typically the outcome of *long-standing* relationships between SC actors, again implying that the careful selection of suppliers and customers is a crucial factor in effective knowledge-sharing. Implicit in this argument is that the benefits gained through knowledge-sharing processes, especially in the form of competitive intelligence, must be perceived by the partners as exceeding the risks associated with such knowledge-sharing (Vázquez-Casielles and Iglesias, 2013). Closely related to trust, *commitment* has also been shown to influence the success of knowledge-sharing initiatives by positively influencing "relationship performance" (Cai et al., 2013; Morgan and Hunt, 1994). Given that power can lead to commitment based on dependency rather than trust, however, the power balance in knowledge-sharing partnerships needs to be carefully considered to avoid the coercion of weaker parties (Cai et al., 2013).

2.2.3.2. Company readiness. To benefit fully from knowledge-sharing, companies first need to be *capable* of sharing knowledge (Li et al., 2017). This capacity requires *learning intent*, i.e. sufficient motivation to integrate external knowledge (Lawson and Potter, 2012). Knowledge asymmetry by individual parties needs to be carefully balanced, therefore, since all parties involved must perceive knowledge-sharing as beneficial to their professional development and productivity (Spekman and Davis, 2016). Furthermore, because the willingness of companies to share knowledge is often people-dependent, it is essential to empower and incentivize employees to pursue knowledge-sharing with external SC partners (Mehdikhani and Valmohammadi, 2019).

Overall, knowledge-sharing with SC members has been shown to help firms compensate for lack of internal expertise (Moeuf et al., 2020). Here it is crucial to note that one firm in an SC often has more knowledge and a higher level of I4.0 maturity than other firms in the chain (Sharma et al., 2021). Such *knowledge asymmetry* need not be an impediment, however, and can be overcome if firms with greater I4.0 maturity share their knowledge and best practices with less experienced partners to enable I4.0 adoption across organizational boundaries and combine expertise from different perspectives (Bibby and Dehe, 2018; Zangiacomi et al., 2020). As emphasized above, such transfer requires commitment and trust, which may take time to develop and thus prevent firms from benefitting from the external competencies of their SC partners (Moeuf et al., 2020). This calls for a proactive approach to knowledge-sharing to accelerate the process of trust building among SC partners in adopting I4.0.

Even with sufficient commitment, however, firms in SCs will nonetheless face their own and interdependent challenges regarding I4.0 adoption. Proceeding from the premise that knowledge-sharing can potentially overcome these challenges, this study aims to identify and elucidate how such sharing can facilitate I4.0 adoption from both an intra-company and supply-chain-wide perspective.

3. Methodology

In exploring the role of knowledge-sharing in facilitating the adoption of I4.0 technologies across SCs, it is crucial to consider the different perceptions of the SC parties involved. Accordingly, the approach taken in this study aligns with a relativist ontology that does not strive for any single truth but rather acknowledges the validity of different perspectives held by diverse actors (Easterby-Smith et al., 2018). Since the goal of this research is to understand a complex phenomenon and explore its pertinent information regarding the particular elements along the SC that influence knowledge-sharing and the adoption of I4.0, an exploratory research design is adopted, applying a single case study approach to gain more in-depth insights into these elements than would be possible if several different cases were analysed (Doz, 2011; Yin, 2018). This case study is *embedded*, with primary data mainly provided by representatives of the focal manufacturing firm and by five members of the chain in which this firm operates, namely three of its upstream suppliers and two of its downstream customers. The broad perspective afforded by this approach is best suited to yielding maximum insights from a single case (Yin, 2018). Nevertheless, the unit of analysis of our study always remains at the firm level since the inter-firm relationships take a central role in this study. The focal firm is a German metal-forging and processing company operating in the automotive industry. With almost 6000 employees, it is one of the industry's leading suppliers and operates in at least ten manufacturing locations worldwide. This company was selected as the case firm for the following three reasons. Firstly, this firm afforded a valuable opportunity to capture knowledge-sharing across an SC as being positioned *within* rather than at either end of a chain. Secondly, examining a firm operating in the German automotive industry is relevant in addressing the research question because this highly competitive and innovative industry has been at the forefront of I4.0 developments worldwide. Thirdly, the focal firm collaborates with several external partners that differ in their respective stages of adopting I4.0 technologies while the firm itself is at development stage of I4.0 adoption and has so far experimented mainly with internal stand-alone solutions linking its ten production plants. However, the focal firm has clear aspirations to expand the use of these technologies across organizational boundaries and strives to take advantage of knowledge-sharing with its well-established SC partners.

In addition to the perspectives of the focal firm itself, this study also considers the viewpoints of upstream and downstream actors in the chain, including two of its customers, two of its equipment suppliers, and one of its raw material suppliers. While the focal firm has a pre-existing knowledge-sharing partnership with one of these customers, no such long-term partnership has been previously established with suppliers. All of the companies encompassed in the case study are located in Germany.

Primary data regarding the case was obtained through interviews with participants selected through a purposeful sampling approach (Saunders et al., 2016). This sampling began with a stakeholder analysis of the focal firm's SC to identify a list of its SC partners that might be relevant for the purpose of the study. This list was then discussed with the contact person in the focal firm responsible for managing I4.0-related topics to identify the most suitable participants. The final selection of interviewees was guided by three criteria: (i) the interviewees had to have a direct business relationship with the focus firm, either as employees or as part of the SC; (ii) the interviewees had to be working with I4.0 topics in their daily work and proactively involved in the potential integration of these technologies into their work processes; and (iii) the interviewees had to have sufficient decision-making power to take independent operational decisions regarding the adoption and development of I4.0.

The preparations undertaken for these interviews included initial familiarization with essential information about the focal firm and the case at hand, including some of the secondary data already obtained at this stage in the form of annual reports, company webpages, and industry press releases. The themes developed at this stage informed the questions used to guide the semi-structured interviews, helping to ensure a clear sense of direction by having the participants focus on those aspects identified as most relevant from the preceding literature review and familiarization with the case firm and context (Yin, 2018). As a final preparatory step, the developed themes and corresponding example questions were sent to the participants prior to the interviews. Providing this content in advance enabled the participants sufficient time and opportunity to reflect on the selected themes, with the aim and expectation being that this would lead to more in-depth discussions about their perceptions and experiences. This preparatory process and transparent communication with the study participants further served to increase the credibility of the research project and authors and thus gain the confidence of the interviewees (Yin, 2018). Later, the transcripts of the audio-recorded interviews were provided to the participants to ensure their views had been accurately captured.

In total, 15 h of interview data were collected (excluding the duration of the introduction and explanation of the topic at the start of each interview). Table 1 shows the list of interviewees including their roles and responsibilities. Due to Covid-19 restrictions, the interviews were all conducted via video link. The language used was German, which is the mother tongue of three of the authors. In addition to interviewing each supplier and customer firm, their perceptions related to knowledge-sharing for the adoption of I4.0 with the focal firm employees are used to provide complementary insights.

To gain a greater empirical understanding of the context and case, the interview data was subsequently triangulated with secondary data obtained over the duration of the study (Doz, 2011). Important additional secondary data was obtained through access gained to the focal firm's internal documents, reports and presentations concerning I4.0

Table 1
Sample characteristics.

Nr.	Number of interviewees	Position	Department	Company	Length (min)
1	1	Head	Production systems	Focal firm	49
2	1	Manager	Sales	Focal firm	53
3	1	Manager	Quality management	Focal firm	47
4	1	Team Leader	Production systems (strategic)	Focal firm	51
5	1	Head	Logistics	Focal firm	51
6	1	Manager	Forging	Focal firm	42
7	1	Team Leader	Production systems (operative)	Focal firm	57
8	5	Head, Team Leader, Operative Specialist Operative Specialist Operative Specialist	IT	Focal firm	63
9	4	Manager Team Leader Operative Specialist Controller	Purchasing	Focal firm	41
10	1	Manager	Production systems	Focal firm	57
11	1	Team Leader	Production systems	Focal firm	38
12	1	Manager	Purchasing and logistics	Focal firm	57
13	1	Manager and Team Leader	Digital sales	Supplier A	65
14	1	CEO	CEO	Supplier B	41
15	1	Manager	Sales	Supplier C	37
16	1	Head	Supplier development	Customer A	58
17	1	Manager	Production systems	Customer A	47
18	1	Manager	Supplier development	Customer A	48
19	1	Manager	Transport planning, Control and digitalization	Customer B	47
SUM	27				949

and related projects undertaken in the past (a list of the secondary data is displayed in Table 2.). Also, the authors had the possibility to attain the perspective of the customers and suppliers using secondary data. The adoption of I4.0 was a high priority for the focal firm and resulted in documents that contained perspectives from the suppliers' and customers' representatives. Further insights into the research topic were gained through attending a bi-annual meeting between the focal firm and the first-tier customer with whom it maintains a knowledge-sharing partnership (cf. Easterby-Smith et al., 2018). In addition, to interviewing each firm, the suppliers' and customers' perceptions related to knowledge-sharing for the adoption of I4.0 with the focal firm employees were used to providing complementary insights.

Table 2
List of secondary documents.

Company	Type of secondary data
Focal firm	Articles about this company, internal PP, webinar documents, notes from meetings between focal firm with partners, annual report, company webpage,
Supplier A	Internal PP, website, potcast
Supplier B	Website, annual report
Supplier C	Website, annual report
Customer A	Internal PP, notes from meetings with suppliers
Customer B	Website, annual report

Last but not least, the study benefited from feedback and insights obtained through continuous communication and numerous informal discussions about the emerging findings with the assigned representative of the focal firm.

Fig. 1 depicts the SC investigated in this study. In this depiction, Suppliers A and B denote the two equipment suppliers that maintain a strategic relationship with the focal firm and thus represent the upstream end of the chain, while Supplier C is a raw material supplier and thus represents one upstream endpoint of the SC. The downstream end of this chain is represented both by Customer A, a first-tier automotive component supplier that maintains a strategic relationship with the focal firm, and Customer B, one of the biggest car manufacturers in Germany, which has the role of OEM in relationship to the focal firm. At the time of the study, both customers were already engaged in knowledge-sharing with the focal firm to facilitate their adoption of I4.0 technologies.

The data analysis followed five sequential steps, beginning with open coding of the interviews, and proceeding to the identification of recurring codes and sub-codes. After the first three transcripts had been independently coded by two of the authors, a final codebook was agreed upon (Kurasaki, 2000). Inter-coder reliability was continuously checked throughout the remaining coding process by double-coding excerpts of the interview data and by jointly discussing any ambiguities arising along the way. Then patterns in the resulting codes and collated them into sub-categories were identified. In a re-coding step of second-cycle coding, the authors then went back to the raw data to deepen their understanding of emerging sub-categories, resulting in a higher-level pattern of overarching categories, based on which the main categories of knowledge-sharing in I4.0 adoption were identified. As elucidated below, these categories included internal readiness, exchange composition, and partner selection. Fig. 2 illustrates the example of process of data coding and structure.

4. Findings

4.1. Case description

The focal firm of the SC in this case study is one of the largest globally operating automotive manufacturing companies in the forging and machining sector and a technology leader in its industry. To ensure the firm remains competitive, its management has recently taken the strategic decision to make more extensive use of I4.0 technologies. However, the firm is still at an early stage in adopting these technologies and has thus far mainly used real-time data to increase internal transparency regarding each step in its production processes and between its production plants, focusing primarily on (1) automating information flow for smart communication and improved decision-making, (2) improving process efficiency through data analysis and event prediction, (3) increasing the efficiency of material flows by using adaptive and autonomous automation, and (4) increasing customer satisfaction through digitized services. As part of its I4.0 adoption, the firm is now beginning to integrate its SC partners into this process.

The focus of this study is on the role of knowledge-sharing in the efforts of the focal firm to enhance its I4.0 adoption in collaboration with five external SC actors, namely three suppliers and two customers. Supplier A is also at an early stage in its adoption of I4.0, which has so far been confined to connecting internal processes across subsidiaries. Supplier B already considers I4.0 an integral part of its core feature and selling proposition; indeed, its representatives argue that interconnecting SCs through I4.0 technologies is vital to remain competitive in the

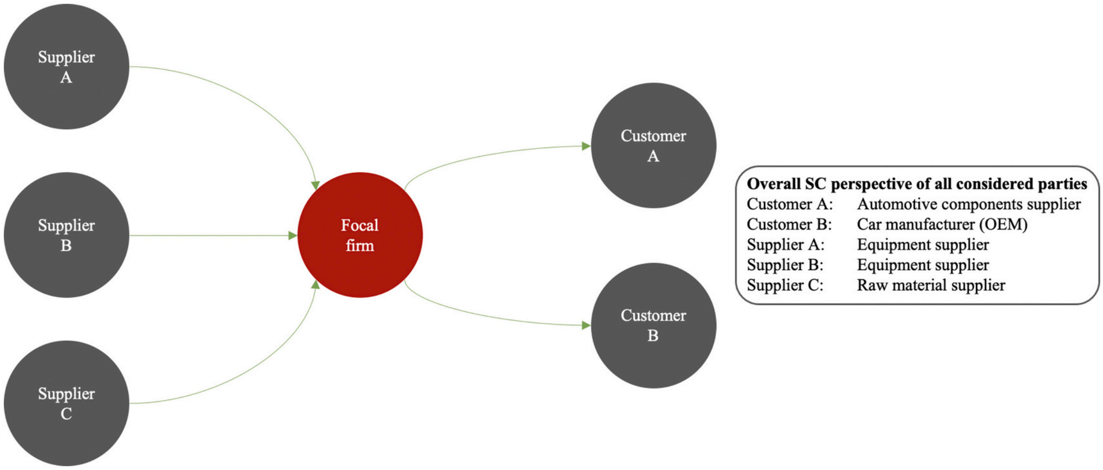

Fig. 1. The focal firm and its supply chain (SC) as captured in this study.

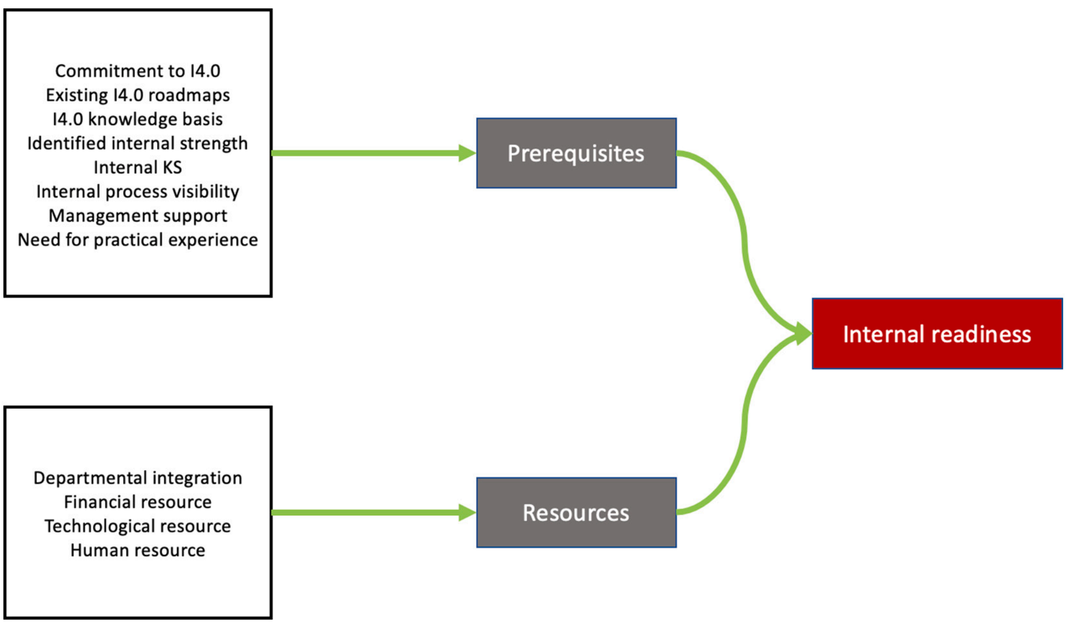

Fig. 2. Example of process of data coding and structure.

future, especially in high-wage countries, such as Germany. Compared to suppliers A and B, Supplier C is at a very early stage of I4.0 adoption. Although this firm has only been using isolated digital solutions and applying them internally, it considers I4.0 essential for adjusting existing processes to its customers' needs.

Consequently, the suppliers of the focal firm are eager to proactively engage in knowledge-sharing with their SC partners, particularly the focal firm, on integrating I4.0 technologies with current operational and analytical systems to enable real-time communication and facilitate the interconnectedness of objects and processes. Both suppliers' willingness to collaborate with the focal firm on I4.0 adoption stems from their recognition of the critical role of knowledge-sharing in advancing this process and the need to prepare for future competitiveness.

Regarding the focal firm's customers, the two firms included in this study are at a more advanced stage than the suppliers in their adoption of I4.0. Both Customer A and Customer B have already adopted advanced technologies internally and have started to interconnect their processes with SC partners. Both firms recognize that leveraging the full benefits of I4.0 requires applying a chain-wide perspective.

4.2. Knowledge-sharing in Industry 4.0 adoption

4.2.1. Phase 1 – internal readiness

The findings of this case show the internal readiness of firms for knowledge-sharing is prompted by three main factors: the need for *building internal knowledge*, *mobilizing relevant resources,* and *prioritizing relevant knowledge-sharing strategies*. To build internal knowledge, the focal firm perceived that it first needed to gain experience with investing in and managing I4.0 technologies. The firm built this initial knowledge by applying a learning-by-doing approach, exploring specific I4.0 approaches and identifying a prioritization of required different concepts before investing in I4.0 implementation on a broader scale. This provides the possibility to the focal firm to share experience knowledge with suppliers and customers on different prerequisites, such as gain visibility in both the production and the supporting areas, i.e., by digitalizing the existing historically established machinery.

Also, the focal firm's suppliers already share knowledge internally across different company sites to promote I4.0 adoption. As part of this initiative, employees working at different sites meet regularly to share best practices and learn from the experiences of their peers, resulting in greater openness to knowledge-sharing with the focal firm.

> "*We have so-called talent groups that exchange ideas across the entire organization on how to introduce Industry 4.0 and, what we can improve, and what is needed to share knowledge with our customers concerning intelligent networking, automated machines, and processes in the industry.*" (Sales Manager, Supplier C).

Customers A and B both emphasize the importance of first transforming and interconnecting internal processes with I4.0 technologies before connecting or engaging in exchanges with the focal firm:

> "*I think you always need a good basis. You have to work on Industry 4.0 technology yourself, have a certain level of experience. And then, in between, it's always good to take a look at [the focal firm] to realign yourself and get new impulses*." (Head of Supplier Development, Customer A).

Another important aspect of developing internal readiness is the mobilization of the technological and financial resources needed for I4.0 adoption. For this purpose, the focal firm's management earmarked a budget for I4.0 and established a department dedicated to I4.0 that now supports all the firm's other departments in the adoption and use of these technologies. Both Customer A and Customer B also emphasized that establishing I4.0 internally requires knowledgeable staff experienced in organizing and participating in knowledge-sharing. However, since Customer B presently enjoys a more prominent position in the market, it is in a better position than either Customer A or the upstream actors in the SC to recruit knowledgeable and highly qualified employees. This advantage creates a downstream asymmetry in the level of knowledge along the chain, since Customer B can internally develop the knowledge and competencies required for I4.0.

With regard to technological financial resources, the focal firm and Customer B alike concur that having departments solely dedicated to I4.0 adoption and the generation of internal I4.0 know-how and expertise is beneficial in spite of the high costs involved. For example, this investment means these new departments can be tasked with responsibility for all knowledge-sharing in these firms, resulting in fewer intermediaries and reducing the risk of any disruption in knowledge dissemination. As Customer B's Digitalization Manager explained, "*There are certainly areas where our firm is simply further ahead than many of our market competitors at the vertical level due to our size and financial resources*."

In addition to building relevant knowledge internally, firms also need to prioritize among various knowledge-sharing strategies for I4.0 adoption. For this purpose, the focal firm developed a roadmap specifying chronological steps to be undertaken to achieve its objectives. In doing so, the firm further determined how I4.0 adoption would support the company's overarching strategy and identified the points at which external knowledge on I4.0 adoption would most be needed. As one of the focal firm's Production System Manager explained, this pre-planning was seen as an essential step:

> "*We need a holistic view and approach of I4.0 before sharing knowledge with partners. First, >we need a vision, and then we can work out the individual improvements in a targeted manner and make them scalable.*"

4.2.2. Phase 2 – partner selection

The focal firm believes that careful partner selection seems to be crucial in order to benefit fully from knowledge-sharing and to reduce many of the risks associated with such sharing. Their selection is based on criteria that include consideration of the prospective SC partner's level of maturity vis-à-vis I4.0 adoption in comparison to the maturity of the firm contemplating the partnership. Because this process of adoption is a continuous undertaking, firms must be capable of forging *long-term* partnerships within the chain, focusing on a few carefully chosen suppliers or customers who face similar challenges in I4.0 adoption and with whom they have developed pre-existing relationships and mutual trust. The focal firm's production system manager described this process as follows: "*Limited, limited but selective. I would think selectively, so definitely not in such an inflationary way that we exchange knowledge with everyone who crosses our path*." In pursuing this highly selective strategy, the firm focuses primarily on dyadic knowledge-sharing partnerships at this stage. As one of the focal firm's sales managers explained: "*We don't have the ambition to include the entire SC immediately, but rather take a little step at a time and find out where the potential lies.*"

Importantly, Suppliers A and B both desire to establish long-lasting knowledge-sharing partnerships to increase the depth of exchanged knowledge on adopting I4.0 technologies. With an upstream and downstream SC perspective on the partner selection, it becomes evident that the latter is considered by far more often. Suppliers A and B perceive the most significant potential for knowledge-sharing when partnering with the focal firm since, so far, most digital interconnections are integrated downstream of the SC. The focus of the focal firm and suppliers A and B in the partner selection process for KS concerns the size and scope of suppliers' production facilities and whether they are on equivalent levels of digitalization (I4.0 maturity level). Being confronted with similar challenges helps them understand the other party better and makes their experiences and knowledge more valuable and vice versa.

> *"Regarding >Industry 4.0 adoption, it is always the case that we should discuss and share our experiences with customers about the production facility and transaction data." (Team leader digital sales, Supplier A).*

However, Supplier C has thus far assigned only 'project status' to the undertaking of knowledge-sharing on I4.0, viewing such sharing as merely a matter of short-term 'knowledge boosts' only needed for the duration of certain projects. This is because Supplier C is at the very beginning of the process of I4.0 adoption and still conceives of this process in terms of isolated projects.

> *"The sharing knowledge on I4.0 adoption is also increasingly difficult if you try to include everyone in the chain. [...] Therefore, I think you can rather dive into one-to-one relationships and see if you can improve." (Sales manager Supplier C).*

For Customers A and B, the issue of selecting knowledge-sharing partners for the adoption of I4.0 involves a dilemma. On the one hand, the trend in the automotive industry is towards short-term relationships driven by powerful SC actors (often OEMs like customer B); on the other hand, adopting I4.0 technologies along a chain requires long-term relationships. This calls for a major rethinking in the industry towards long-term knowledge-sharing partnerships in which SC partners support each other to maintain their competitive positions.

When considering the level of I4.0 maturity of prospective knowledge-sharing partners, the focal firm and its SC suppliers and customers need to focus specifically on the respective size and scope of production of these firms, as well as their technological knowledge and knowledge-sharing strategies. According to both of the suppliers interviewed for this study, having similar corporate strategies for I4.0 adoption is also important as a sound indicator of 'a good fit'. Supplier A further indicated that the selection criteria should also include whether partners are at comparable levels of digitalization, especially regarding I4.0. The importance of finding compatible knowledge-sharing partners was also emphasized by the customers in the SC. In the words of Customer A's supplier development manager, for example:

> "*We buy from the most favourable suppliers, and it's a question of us working together to ensure that they are compatible. Because at the end of the day, it's not about supplier A or supplier B getting the order; it's about [customer firm] selecting the compatible supplier.*"

4.2.3. Phase 3 – exchange composition

Exchange composition refers to the content of knowledge and frequency of knowledge-sharing. This composition is important in determining the extent to which a firm can generate internal knowledge about I4.0 by expanding its existing resources through leveraging the knowledge of its SC partners. In this case to attain knowledge on specific I4.0 technologies, and associated elements, as well as an idea of the granularity of the I4.0 knowledge being shared. Besides, each participating firm must be aware of the extent to which distributed I4.0 knowledge provides insights into production knowledge and data, such as component details, costs, and cycle times. This means that before engaging in knowledge-sharing with SC partners, the focal firm considered it "*essential to agree upon the focus and guiding questions*" (Production system team leader, focal firm). Because the operation and production environments of the knowledge-sharing partners differ, there will also be differences in the areas of I4.0 applications, again indicating the importance of in-depth I4.0 knowledge-sharing. As confirmed by the focal firm's Head of Production System, differences of internal knowledge need not hinder the task of defining areas of common interest:

> "*What impresses me is that two different companies have so many overlapping topics of interest. You can also see that there are very similar approaches here. Some of them diverge a bit, but they still pursue the same goal and probably reach the same objective.*"

And while Supplier B noted that such inequalities were not a major concern in the short term, it emphasized the need to attain a balance over time to avoid a decline in reciprocity and motivation for continuing the knowledge-sharing partnership. For both suppliers, however, knowledge-sharing about I4.0 is primarily a means of obtaining new insights into customer needs and remaining competitive in the future, as reflected in the positive attitude to knowledge-sharing expressed by Supplier A's Digital sales manager:

> "*We are not afraid of our competitors copying from us; the idea is that we benefit from each other and that we can also learn from someone else, and therefore perform better, and I think that is really important in the SC.*"

Customers A and B both emphasized that the parties in a knowledge-sharing partnership must have a clear understanding of the benefits of such engagement for their own I4.0 adoption, and for their further collaboration with other firms in the chain to ensure such knowledge-sharing relationships yield optimum value. In considering which knowledge contents to share in partnerships, therefore, these firms first mapped out general fields of interest and then checked where the identified interests overlapped with those of their potential knowledge-sharing partners. Both customers stressed that the insights gained through knowledge-sharing should clearly relate to and address the companies' current needs. For Customer A, knowledge-sharing with the focal firm is about sharing *tacit* knowledge related to where I4.0 could be adopted quicker and lead to more efficiency due to data availability, intelligent communication, and decreased process cycle times.

Lastly, an essential component for such a KS relationship is that both parties see the added value that the partnership brings to their company and understand the benefits for their own I4.0 implementation. Otherwise, they would not engage and participate to the same extent. Customers A and B acknowledge that they would lose interest and disengage if they do not perceive a benefit of KS. *"If there's too much of a gap, I think someone will lose interest at some point." (Control and digitalization manager, Customer B)*. Table 3 summarizes the study's findings regarding knowledge-sharing in I4.0, including the various phases, criteria, and actors' perspectives.

5. Discussion

Manufacturing firms worldwide are under increasing pressure to adopt and expand their implementation of I4.0 technologies, not only in-house but also throughout SCs. Previous research into this process of adoption has predominately focused on the importance and diversity of emerging I4.0 technologies and their associated affordances and challenges. By contrast, this article has drawn on a qualitative study of a focal manufacturing firm from the German automotive industry, as well as several of its SC actors, to expand the scope of investigation to the importance of dyadic knowledge-sharing partnerships among SC actors when adopting I4.0.

Table 3
Summary of the findings.

Phase	Criteria	Focal firm	Customers	Suppliers
Internal readiness	Build internal knowledge	• Gain experiences with specific I4.0 approaches	• Establish a reliable internal I4.0 structure to test solution	• Suppliers A and C: build knowledge by bi-annual or annual meetings • Supplier B: hire skilful experts
	Mobilizing technological and financial resources	• Set up a budget for lean and I4.0 matters • Establish department to ensure the transformation of the company towards I4.0	• Establish technical department for I4.0 adoption • Large investment into grows the department	• Suppliers A and B: build the technical team for I4.0 and use the financial resources to hire knowledgeable resources • Add the task of I4.0 to the scope of existing employees
	Strategy	• Set up a clear roadmap from current standpoint • Discover the existing processes and then search for solutions in chronological steps	• Draw clear roadmap and identify an extraordinary solution to the management team	• Supplier B: map out a strategy which focuses mainly on IT management • Suppliers A and C: discovering I4.0 to not fall behind
Partner selection	Strategic partner	• Dyadic relationships to specific topics • Long-term relationship • Mutual trust and face similar problem areas	• Focus on pre-existing strategic relationships considering the dependency • Long term relationship towards I4.0 adoption and aware of new trend of short-term perspective	• Suppliers A and B focus on strategic relationship with exiting partners based on highest added value expected. • Supplier C considers KS for I4.0 with a project character in the sense of a short-term knowledge
	Maturity level of partners	• Focus on partner with high level of production size and advance KS strategy	• Focus on advanced technological partner • Share knowledge if partner fulfil the lack of knowledge	• Equal levels of digitalization in order to have comparable problem areas
Exchange composition	Tacit knowledge-sharing	• In terms of underlying reasons for potential implementations, measures, and know-how to mitigate implementation challenges	• Share knowledge such as experiences about approaches that already proved to increase the company's efficiency or competitiveness	• Suppliers A and B share knowledge on predefined, distinct structure, covering specific needs and related problems
	Map out of interest	• KS based on overlapping interests/ needs • Discuss the topic, realize similarities, and gain even more insights and mutual benefits	• First map out general fields of interest • Second check those topics overlap with the interests of the partners	• Suppliers A and B: predefined, distinct structure, covering specific needs and related problems in regard to KS

To address the two research questions guiding this study, the findings outlined above were integrated within a conceptual framework (see Fig. 3). In exploring the first research question guiding this study four approaches are identified to explain how knowledge-sharing can facilitate I4.0 adoption: (i) knowledge-sharing through principles; (ii) upstream flow of knowledge; (iii) strategic positioning; and (iv) application-relatedness. Regarding the second research question the findings of this study indicate that the factors which influence knowledge-sharing can be categorized as company-related attributes (i.e., internal capabilities and I4.0 maturity level) and relational attributes (i.e., organizational fit, power asymmetry, and relationship quality).

5.1. Knowledge-sharing approaches

5.1.1. Knowledge-sharing through principles

Put briefly, sharing tacit knowledge facilitates I4.0 adoption because it reduces the risk of encountering challenges along the SC. The focal firm and customer A shared, for instance, which know-how, beliefs, attitudes, and experiences they considered during their I4.0 adoptions, commonly defined as tacit knowledge (cf. Li, 2020; Polanyi, 1966). According to Pihlajamaa et al. (2019), such sharing should consider and include core principles since achieving a good fit tends to increase actors' satisfaction with knowledge-sharing (Wagner and Bukó, 2005). In addition, closer congruence between partners in principles facilitates the separation of technological knowledge and operational production data, reducing the risk of undermining firms' core competences, and thus, promoting the openness needed to share tacit I4.0 knowledge (Suh et al., 2019). However, principles are not easy to implement in practice, which may result in incompatibilities between different approaches to I4.0 adopted along the chain (Birkel and Hartmann, 2019). Nevertheless, research indicates that developing common standards can prevent divergence during digital transformation and I4.0 adoption across an SC (Birkel and Hartmann, 2019; Horváth and Szabó, 2019). The findings of the present case study confirm this conclusion insofar as the focal firm's customers are the only SC actors with a similarly high level of I4.0 maturity and correspondingly high levels of tacit knowledge. This approach to knowledge-sharing based on shared principles thus appears to be ideally suited for the downstream side of the chain, from where it can then be disseminated upstream.

5.1.2. Upstream flow of knowledge

Implementing knowledge-sharing within dyadic relationships can enhance the likelihood of yielding the desired outcomes of sharing partnerships. For example, the dyadic relationships formed by the focal firm served to facilitate the joint transmission of knowledge upstream. The downstream SC actors in this case study possess a knowledge surplus and a higher internal readiness, contrary to a knowledge deficit and lower I4.0 maturity level on the upstream side of the SC. Therefore, knowledge originates on the downstream side which is transferred upstream until it reaches the opposite end of the SC. This is in line with Moradlou et al. (2020), who found that suppliers often lag and can thus not comply with the innovativeness of their partners. This argument is also supported by the strategies adopted by the focal firm's customers when selecting knowledge-sharing partners according to their internal readiness, among other factors, since both parties must benefit from the exchange (Suh et al., 2019). However, this approach might risk excluding less developed SC partners, which may in turn cause disruptions in the knowledge-sharing process along the SC. Sharing knowledge about I4.0 with less developed SC partners could serve to offset this risk, since the resulting improvements in digital linkages would also benefit the more developed firm in the partnership. Overall, the upstream flow of knowledge approach facilitates the adoption of I4.0 as it distributes successively adapted knowledge along the SC to less knowledgeable SC partners. This is in line with the present case, as supplier A struggles with the complexity and the many design possibilities of I4.0, and therefore lacks imagination and creativity for which I4.0 can be used in its firm. Knowledge-sharing with subsequent progressive partners can help them gain impulses and thought-provoking ideas that will drive their I4.0 implementation within the SC forward.

5.1.3. Strategic positioning

To guarantee knowledge-sharing with valuable and in-depth exchanges about I4.0, firms should selectively choose a few KS partners with whom they have common strategies. Based on the findings of this study, knowledge-sharing for I4.0 adoption might be most effective when confined to a limited number of carefully selected and highly compatible partners ready to commit to long-term knowledge exchange (cf. also Zangiacomi et al., 2020). In fact, the adoption of I4.0 is not an one-off project but requires a long-term horizon, which needs continuous attention and development internally and across the SC. This

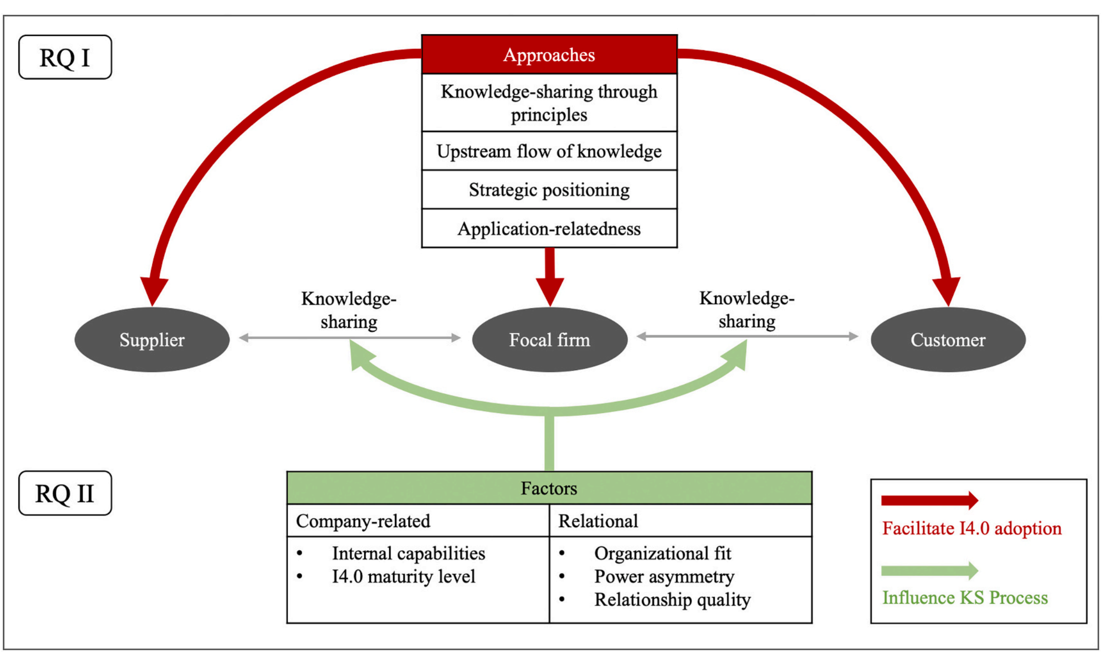

Fig. 3. Integrative framework for knowledge-sharing in I4.0 adoption.

finding is consistent with the argument advanced by Lorenz et al. (2020) that maintaining a small number of qualitative relationships instead of collaborating with as many partners as possible might be more effective, not least in reducing the resources needed to maintain such relationships (Li, 2020). Since well-established relationships require fewer investments to maintain, they also tend to be more productive (Spekman and Davis, 2016; Yang et al., 2016). The findings of this case thus suggest that SC parties can facilitate knowledge-sharing by leveraging existing relationships with partners who are already in daily contact through the different units. Since they regularly exchange operations-related data, e.g., on inventories or forecasts, trust is established (M. Lin et al., 2021), from which they can benefit in their KS partnership. This approach facilitates the adoption of I4.0 in two respects. First, it enables KS partners to understand each other's needs more comprehensively, thus enabling them to exchange knowledge in a more targeted manner. Second, it leads to a higher level of commitment, enhancing the reciprocal knowledge flow. Consequently, this supports the approach as mentioned above of 'knowledge-sharing through principles' as tacit knowledge is shared best within stable and intensive interactions (Alavi and Leidner, 2001; Li et al., 2017) and when a highly trustworthy atmosphere is ensured (Qiu and Haugland, 2019).

5.1.4. Application-relatedness

Shared knowledge must always be focused on and adapted to the overlapping needs of both knowledge-sharing partners to prevent straying and sharing unnecessary knowledge. The findings of this study underline the importance of sharing common goals and similar expectations of knowledge-sharing to ensure this process benefits all SC parties involved. Here, it is beneficial if the participants first identify their own knowledge needs based on their stage of I4.0 adoption before searching for partners in the chain that could help them meet these needs through knowledge-sharing (Bibby and Dehe, 2018). Importantly, Vázquez-Casielles and Iglesias (2013) have cautioned that sharing too much information may have the same effect as not sharing enough information, which suggest that SC partners should make efforts to define precisely which I4.0 information will be exchanged with their partners. This is consistent with a study by Lorenz et al. (2020), which findings suggest that firms should build strong ties with a few external knowledge partners rather than "surface relations" with many partners at once. This approach to knowledge-sharing further ensures that topics are correctly understood by the other party, reducing the ambiguities that can arise from the sheer breadth and scope of I4.0 and the complexity of its adoption. Carefully defining the parameters of knowledge-sharing in this way thus facilitates the adoption of I4.0 insofar as it ensures that all knowledge shared specifically meets the knowledge-gaps of the partners. As such, this approach appears to be best suited for knowledge-sharing partners that already have a similarly high level of I4.0 maturity, since partners with low current levels of existing knowledge may lead to future divergences of interests.

5.2. Company-related and relational factors

The study reveals that two types of factors influence knowledge-sharing for more efficient I4.0 adoption (see Fig. 3 above): company-related factors and relational factors. Company-related factors include two internal preconditions of each knowledge-sharing partner, i.e. their internal capabilities for adopting I4.0 and level of maturity in this respect. Relational factors, such as organizational fit, power asymmetry, and relationship quality, have a significant impact on relationships between the knowledge-sharing partners and hence on the knowledge-sharing process overall.

5.2.1. Company-related factors

5.2.1.1. Internal capabilities. Internal capabilities, here, refer to the respective resources of each knowledge-sharing partner in an SC and what they are willing to contribute to the partnership for adopting I4.0 (cf. Spekman and Davis, 2016). This case study has revealed how firms can increase their internal readiness by establishing an I4.0 department specifically tasked with enhancing internal competencies, by identifying knowledge-sharing needs and pursuing innovative ideas for I4.0 adoption (Wang and Hu, 2020). This finding accords with the conclusion reached by Tortorella et al. (2020) that an internal organizational learning environment is conducive for increasing a firms' ability to utilize and integrate new knowledge into business processes. The present study further indicates that positive experiences with internal knowledge-sharing reduce resistance to subsequent knowledge-sharing with SC partners for I4.0 adoption. This accords with the findings of Mehdikhani and Valmohammadi (2019), who found that employees need to be encouraged and incentivized to share knowledge in the first place. In sum, higher levels of internal capabilities seem to positively influence the knowledge-sharing process and lead to a higher level of I4.0 adoption.

5.2.1.2. I4.0 adoption maturity level. The level of a firm's I4.0 maturity significantly influences the knowledge-sharing process. The I4.0 maturity level refers to firms at a higher maturity level that have more I4.0 experience and consequently possess (1) a higher level of knowledge, which they can share with their KS partners, and (2) have a better understanding of their needs, ultimately making the KS process more effective. This finding builds on and expands a previous finding by Lorenz et al. (2020) that a higher level of internal knowledge positively influences the effectiveness of a firm's external search for knowledge on I4.0 adoption. This, in turn, implies the need for the continuous development of internal processes to promote I4.0 adoption and maturity, thereby making the company more attractive for knowledge-sharing to its external SC partners. However, it is worth noting that companies with a higher level of I4.0 maturity, such as Customer B in the case study, may be reluctant to participate in knowledge exchange that goes beyond exchanging data through I4.0 technologies because they want to protect their innovations and superior market position (cf. Cheng, 2011). By contrast, upstream SC actors with lower levels of I4.0 maturity might view I4.0 as a tool for process optimization, making them more open to knowledge-sharing around I4.0 adoptions. In sum, levels of I4.0 maturity and related goals are important determinants of whether a firm might be able and willing to share its experience with SC partners, which in turn influences the effectiveness of knowledge-sharing across the chain.

5.2.2. Relational factors

5.2.2.1. Organizational fit. The findings of this case study indicate that organizational 'fit' between SC partners is essential for successful knowledge-sharing. As highlighted in the literature review, Spekman and Davis (2016) have demonstrated that having similar levels of knowledge leads to a better understanding between SC partners in advancing I4.0 adoption, while studies by Liu et al. (2012) and Singh and Power (2014) have emphasized that the interests of actors in knowledge-sharing partnerships must be balanced to ensure that all partners benefit to similar degrees from the exchange in order to avoid divergence in the long term. These findings further align with the conclusion drawn by Vázquez-Casielles and Iglesias (2013) that short-term knowledge-sharing imbalances can be temporarily overlooked by SC partners insofar as congruence in their long-term orientation rebalances these initial issues in the knowledge-sharing relationship. In sum, the better the organizational fit and match between the knowledge needs of the SC partners, the more these partners can benefit from knowledge-sharing, ultimately leading to greater commitment and thus increasing the efficiency of the chain as a whole.

5.2.2.2. Power asymmetry. Power asymmetry among actors in SCs can lead to one-sided exchanges and opportunistic behaviour that hinders knowledge-sharing (Cheng, 2011; Vázquez-Casielles and Iglesias, 2013). This is exemplified in the current case study by the focal firm's decision to exclude one of its customers from knowledge-sharing. As noted by Cai et al. (2013), power asymmetry can also be used to persuade actors into a knowledge-sharing partnership, though such coercion risks undermining the quality of exchange, since one party does not share knowledge about I4.0 voluntarily. Nevertheless, even if a more powerful party initiates the exchange, its partner can still take advantage of this process by using the knowledge obtained for improving its own internal capacities. Again, this indicates that short-term power imbalances may not necessarily be a disadvantage in knowledge-sharing relationships if each party takes responsibility for deriving benefits from this process.

5.2.2.3. Relationship quality. The knowledge-sharing process is inevitably affected by the quality of the relationship between partners inasmuch as levels of mutual trust determine the amount of information each party is willing to share. As previous research has found, *long-term* relationships tend to promote and enhance knowledge-sharing (e.g. Chesbrough, 2003; De Vries et al., 2014; Spekman and Davis, 2016). This is because such relationships foster and reflect a high level of trust, which is essential for sharing tacit knowledge (Li, 2020; Qiu and Haugland, 2019). For these reasons, firms tend to rely on close interpersonal dyadic relationships between key individuals (Cai et al., 2013; Müller et al., 2020; Rungsithong and Meyer, 2020). As demonstrated in this study, such relationships can serve as knowledge-sharing accelerators. In sum, high-quality partnerships can positively influence the knowledge-sharing process, especially if supported by pre-existing interpersonal relationships.

5.3. Theoretical implications

The main theoretical contribution of this study lies in the light it sheds on the vital role played by knowledge-sharing between SC partners in facilitating the adoption of I4.0 technologies. Based on a case study of a leading manufacturing firm and its SC partners in Germany, the findings of this study draw on and extend Zangiacomi et al.'s (2020) insights into the role of knowledge-sharing from their multiple case study of I4.0 adoption among manufacturing firms.

Whereas extant research has primarily explored the adoption of I4.0 technologies from the perspective of single firms without including the viewpoints of their direct customers and suppliers along SCs (Sharma et al., 2021), this study has applied a chain-wide perspective to this process that confirms and emphasizes the importance of *external* knowledge in I4.0 adoption and how knowledge-sharing can benefit chains as a whole. By contrast with the scope of studies focused on external sources of knowledge in general, including valuable research by Lorenz et al. (2020) and Zangiacomi et al. (2020), this study has specifically highlighted the importance of SC partners as a source of knowledge for I4.0 adoption. And while previous work has explored instances of one-sided knowledge-sharing in which only one-party benefits, e.g. by gaining the knowledge it lacks from the other party without reciprocating, this study has examined a case of dyadic knowledge-sharing among customers and suppliers upstream and downstream of a focal firm in which all actors benefit alike from sharing and accessing each other's knowledge.

The current literature on knowledge-sharing has paid little attention to how shared knowledge can be passed on to further parties, for example, knowledge-sharing partners, which is a matter of considerable importance when aiming to adopt I4.0 throughout an SC. By applying a chain-wide perspective, this study identifies and elucidates several different approaches to knowledge-sharing across several SC partners. And while previous literature on I4.0 adoption has primarily focused on barriers to such adoption (e.g. Horváth and Szabó, 2019), little attention has been paid to different adoption approaches (Hofmann and Rüsch, 2017). Expanding Zangiacomi et al.'s (2020) argument that knowledge-sharing can facilitate I4.0 adoption, this study has considered such knowledge-sharing as more than a punctual exchange between two companies to show how knowledge-sharing can occur in dyadic exchanges along a chain.

Finally, this study contributes to the literature by offering a counter perspective to the common view that adopting I4.0 by itself promotes knowledge-sharing through increased SC integration and interconnectedness. Conversely, this study has shown that it is rather the case that knowledge-sharing facilitates I4.0 adoption by mitigating major challenges arising in the process of adopting these technologies in an SC.

5.4. Managerial implications

The results of this study are especially relevant for SC managers in manufacturing firms either planning to adopt I4.0 technologies or still being in the initial stages of this process. By evidencing how knowledge-sharing with upstream and downstream actors in an SC can facilitate I4.0 adoption, this study has highlighted a number of significant benefits to be gained through learning from the experiences of other SC partners, including as a means of informing the development of a tailored adoption strategy and prioritization of tasks for this process.

As another practical implication for managers, this study has further outlined how *dyadic* knowledge-sharing approaches can strengthen long-term relationships between SC actors and enhance their collaboration in adopting I4.0 technologies. This benefit is amplified in the context of I4.0, moreover, since the higher level of SC interconnectedness afforded by these technologies not only facilitates a higher level of competitiveness for the SC but can also counterbalance the current trend in the automotive industry that favours short-term relationships. These and other findings of this study underline the importance of carefully defining criteria for the selection of potential knowledge-sharing partners in SCs for I4.0 adoption. One key implication of these findings, for example, is that firms seeking to use knowledge-sharing to support I4.0 adoption might best focus on developing knowledge-sharing relationships with those direct SC counterparts with whom strategic relationships already exist and who share their attitudes regarding I4.0 implementation. At the same time, this study shows that firms need to develop adequate internal capabilities to be sufficiently ready to engage effectively in knowledge-sharing partnerships. As a final additional insight of relevance for managers, this study finds that knowledge-sharing may represent a cheaper alternative to hiring external consultants or other solutions for making progress in I4.0 adoption, showing how the benefits of effective knowledge-sharing among firms in SCs can help compensate for a firm's current lack of internal resources and knowledge in this adoption process.

5.5. Limitations and future research directions

Although the German automotive industry is highly relevant as an empirical setting for the research purposes of this study on account of its leading competitive position and technological sophistication, valuable additional insights could be attained through future in-depth research into knowledge-sharing across chain-members in different contexts in this industry. A longitudinal research design, for example, could prove especially fruitful for capturing the challenges and solutions of knowledge-sharing on the adoption of I4.0 adoption over time. Given that the findings of this study are based on the instance of only a single chain, moreover, it would be useful to explore the validity of the statistical generalizability of these findings, e.g. by drawing on a large-scale quantitative study.

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Data availability

Data will be made available on request..

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