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Privacy-Aware Supply Chain Ratings: Interdisciplinary Research On Collaborative Supply Chain Management

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Abstract

The establishment, expansion, and operation of reliable value-creation networks present an increasing challenge for manufacturing companies, given the growing volatility of the market environment in which they operate. For example, the development of new business areas, mass customization, or the disruption of supply chains frequently necessitates the establishment of partnerships with new suppliers, both short- and long-term. The utilization of supplier key performance indicators (KPIs) can facilitate the selection of new business partners, as they provide a quick and objective indication of their reliability. Nevertheless, access to potentially sensitive KPIs, such as a supplier's on-time delivery performance, is currently mainly limited to existing supplier relationships and not made available to other companies. This paper presents a coordinated approach for supplier rating systems, thereby enabling the privacy-aware exchange of supplier KPIs across organizations and exemplifies it using an application in the "Internet of Production". Specifically, we conduct interdisciplinary research by formulating the requirements from a business perspective (supply chain design, trust in data sharing, and business models) and evaluating promising solutions from a technical perspective (information security, data quality, data sovereignty, and collaboration). This approach enables the combination of state-of-the-art technology with the evolving requirements of stakeholders, thus creating new paths for exploiting inter-organizational supply chain rating.

Keywords

supply chain management; privacy awareness; data sharing; collaboration; Internet of Production

1. Introduction

In today's rapidly evolving business landscape, the effectiveness of decision-making plays a crucial role in cost reduction and overall organizational success [1]. The concept of supply chain management (SCM) builds on the idea that efficiency gains can be achieved through information sharing and collaborative planning between suppliers and customers [2]. As supply chains become increasingly integrated and dynamic, the need for digitized solutions to facilitate effective (data) communication has never been greater [3–5]. Recent studies indicate an increasing recognition of the relevance of information sharing among supply chain experts; however, many organizations still rely on outdated technologies for communication (e.g., fax, SMS, or email) or lack detailed frameworks for information exchange [6]. In contrast to the increasing awareness of the need to share data along supply chains, many companies are still reluctant to adopt this practice. In a 2022 survey, 58% of the 1,051 German industrial companies surveyed stated that they neither received nor shared (industrial) data [7]. These numbers indicate that, despite recent advancements in IT-based solutions [6], real-world applications still fail to adequately address the quality and value of data [8,9], as well as the need for trustworthy data exchange between business partners [10].

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The selection of suppliers selection is a fundamental function within supplier relationship management, as collaborating with the right suppliers can significantly enhance production quality and efficiency [1]. However, despite the critical importance of supplier ratings, reputation systems for companies to evaluate each other's performance remain largely unexplored in academic research and are scarcely implemented in practice. This gap is particularly concerning given that these systems are essential for prospective buyers seeking trustworthy sellers, especially in short-lived business relationships characterized by high uncertainty. [11]

In response to these challenges, our paper proposes a conceptual framework that integrates both technical and business perspectives with the aim of jointly creating a collaborative supplier rating system. By bridging otherwise isolated research efforts from both domains, we foster privacy-aware collaboration in supply chain ratings, which will ultimately evolve into improved supplier selection processes. Our approach not only enhances decision-making for SCM but also contributes to improved resilience within supply chains.

2. Overview of today's distinct research activities

Presently, there is a lot of ongoing research in various domains on enhancing the performance of value-creation networks through collaborative SCM [12,4]. While the importance of linking these research works is widely acknowledged, so far, they have remained largely isolated. In the following, we give an overview of the current research activities in the domains of business management and computer science.

2.1 Tackling business-associated challenges in collaborative supply chain management

To realize the potential of a cross-company supplier rating system, researchers in the business domain are developing requirements towards the scope and quality of the desired information exchange, as well as formulating the concerns and incentives of data sharing from a business model perspective [1,13,9].

2.1.1 The need for supplier ratings in volatile supply chain networks

External influences on supply chains have increased significantly and affect existing value-creation networks. The occurrence of events such as the global spread of the SARS-CoV-2 virus, the blockade of the Suez Canal, and natural disasters like volcanic eruptions can be classified as high-impact, low-probability events that have had a deleterious impact on the flow of materials in value networks [1]. Furthermore, shifts in the market environment, such as the increasing trend toward mass customization, require that companies adapt their business models and the associated value-creation networks dynamically and flexibly [2]. For manufacturing companies to maintain their viability in the market, rapidly identifying alternative sources of supply for their existing portfolio is critical, just like subsequently establishing new value-creation networks to align with evolving customer requirements [3]. Both necessitate collaboration with previously unknown business partners. The performance of suppliers has a significant influence on a company's own ability to perform [4]. Therefore, supplier selection is crucial to ensure that production is supplied with the right goods in the right quality and at the right time, thereby ensuring a company's own customer satisfaction and competitiveness [4]. Key Performance Indicators (KPIs) offer the possibility of objectively comparing several suppliers and thus supporting rapid decision-making.

Specifically, KPIs related to delivery reliability are useful metrics for assessing the quality of suppliers. On the one hand, they are standardized (e.g., VDI guideline on logistic indicators [14]) and, on the other hand, they are collected by the majority of manufacturing companies, as they are recognized as relevant for certification purposes (e.g., ISO 9001 und IATF 16949 [15]). However, required data and evaluations are typically only accessible within the proprietary systems of the respective companies. From the perspective of supply chain network design, there is a need for reliable and objective information when selecting suppliers [16]. In the case of new suppliers with no prior business relationships, no KPIs are available in the company's own business application systems (e.g., enterprise resource planning [ERP] system), and also no subjective experience for deducing whether a supplier is a trustworthy partner or not can be utilized. The challenge for a collaborative supplier rating system is, therefore, to establish a means of accessing existing supplier evaluations from other companies while maintaining privacy awareness and creating trustworthiness in the data so that collaborative users can benefit from each other's experiences.

2.1.2 Cross-company data sharing: An organizational mind shift

From a business perspective, data on inventory levels or production data constitute internal knowledge and can thus be regarded as a company's resource, similar to machinery, human capital, or financial assets [17]. According to the resource-based view (RBV), companies naturally protect their resources to ensure they remain inimitable, thereby securing a sustainable competitive advantage [18,19]. In contrast, data sharing necessitates opening these resources to external parties, which demands a strong mind shift in organizations following the RBV in their strategy, as recent research has shown [20–23].

In these studies, companies have raised concerns about potential misuse by others when sharing data, such as data breaches, and indicate a lack of trustworthy partners with whom they would be willing to share sensitive information [22]. Other companies highlight the absence of frameworks and governance structures that would ensure they retain sovereignty over their data and their competitive advantages—while complying with European Union regulations (e.g., General Data Protection Regulation, Data Governance Act [24,25]). Moreover, managers perceive insufficient commitment from management, particularly in traditional manufacturing industries [20]. On the other hand, there is a notable lack of awareness regarding the benefits of sharing data [23]—an awareness that could counterbalance the concerns in companies and motivate them to work on overcoming open challenges. Companies also often lack the ability to define effective strategies to capture value from data sharing as part of their business model design. For instance, in the study by Büchel & Rusche [26], only 13% of data providers consistently receive compensation for their data, and just 3% of data recipients always purchase data in the form of a monetary exchange.

2.2 A glimpse at technical approaches for collaborative supply chain ratings

The most essential concerns of companies about data sharing are guarantees of security, privacy, and sovereignty; challenges that are tackled by various work in the domain of computer science. The following section also presents research addressing data and information quality in the business domain, as not only the secure exchange of data but also its interpretability and value are of essential interest to companies.

2.2.1 Information security and data sovereignty: Challenges in volatile supply chain networks

Systems that enable cross-company data sharing have to first and foremost address issues of information security and data sovereignty [27–30] Especially in the context of volatile supply chain networks, the security and privacy dimension has two key aspects. First, companies have a significant incentive to preserve the privacy of their business relationships, particularly when rating suppliers, to maintain their competitive advantage. Hence, they are interested in achieving unlinkability of ratings and potentially even anonymity of contributing companies. Second, they want to reveal as little information about their business relationships and transactions as possible. Consequently, ensuring the confidentiality of both submitted information and recorded ratings is key. The latter desire nicely aligns with the concept of data minimization [7].

Even though various technical approaches for introducing security and privacy guarantees in (decentralized) information systems exist [30], their applicability to privacy-aware supply chain ratings remains mostly unexplored to date (just like the overall understanding of supply chain ratings [11]). As a result, we lack an understanding of the impact of such systems. In contrast, researchers from computer science extensively studied reputation systems [31,32]. However, reputation systems in other domains (e.g., e-commerce like Amazon or eBay, or online communities like Reddit or Stack Overflow) have significantly different requirements. In turn, for example, Gurtler and Goldberg [31] tried to standardize reputation systems. While these efforts ease the understanding of existing approaches, we argue that they are incompatible within a business-to-business context (as opposed to business-to-consumer settings, e.g., Amazon) [12]. Most recently, several blockchain-based reputation systems have been proposed [13–17]. However, without more sophisticated approaches, they can neither satisfy the former (keeping business relationships private) nor the latter (sharing as little information as possible) key aspects. Interestingly, the fact that blockchains provide anonymity of participants and confidentiality of information is a common misconception [18]. Hence, research must complement them with other technical building blocks. However, their default computational and storage overhead still question the feasibility of the research problem at hand.

Another key concern for companies is data sovereignty. In comparison to physical assets, once access is given, the challenge of controlling and enforcing the restrictions on the usage of data assets, such as the editing, copying, distributing, or publishing of data, is significantly harder [30]. While data sovereignty is a topic discussed mainly in terms of governance and legality, researchers in computer science are also developing technical solutions facilitating the concept of controlled ownership [31,32].

Regarding data infrastructure, decentralization is often considered a requirement or best practice for enabling data sovereignty [33,34]. The principle of renouncing centralized storage and instead having data remain with its owner reflects the existence of heterogeneous and distributed data sources and allows for an intuitive understanding of retaining control over data assets. This infrastructure design introduces challenges of developing analytics mechanisms that operate on decentralized systems [35,36].

The most prominent research initiative on cross-company data exchange is the International Data Space (IDS), whose centerpiece is the design of a connector architecture with standardized data exchange protocols [37]. The idea of IDS is driven by the concept of alliance-driven data ecosystems, enabling data exchange with trusted partners [38]. For this purpose, the reference architecture model incorporates identity verification mechanisms and designates intermediaries such as clearing houses between data providers and consumers, enabling the creation and validation of contracts and payments on a technical level [39]. While there are currently several ongoing pilot projects, the applicability (also in terms of appropriate security guarantees [40]) and scalability of IDS have yet to be fully evaluated.

2.2.2 Ensuring the value of information: Assessing and certifying data quality

As an asset, data will only be of interest if its value can be certified. From a technical perspective, measuring data quality may present one way of capturing the value of data. While companies widely recognize the potential of supporting their strategies with data-driven analyses, the quality of data is often seen as the bottleneck that determines whether the derived insights are valuable.

Data quality is commonly defined in terms of dimensions, several prominent of which are accuracy, completeness, timeliness, and consistency [37]. Multiple standardization and certification processes exist for those dimensions, e.g., ISO/IEC 25024 and ISO/IEC 25040. Regarding cross-company data exchange, conventional data quality management (DQM) frameworks often lack consideration of the requirements of external stakeholders and systems. To prevent hesitancy of stakeholders, DQM for data-sharing applications cannot be considered uncoupled from transparency and trustworthiness [38]. A further example is the degree of knowledge representation: the comprehensibility of a dataset for humans and machines may influence a dataset's perceived value from the perspective of an exchange partner [39].

For a meaningful data quality assessment, a thorough understanding of the domain context is needed. The interpretation of data quality differs depending on the application environment. Requirements of involved stakeholders, systems, tasks, and goals must be understood to formulate and prioritize data quality criteria, and processes need to be developed to conduct and certify a holistic DQM [40].

Overall, we derive the pressing need for integrated technical designs tailored to the outlined business requirements when realizing a global approach for collaborative, privacy-aware supply chain ratings.

3. A coordinated approach for privacy-aware, collaborative supply chain ratings

Considering both state-of-the-art approaches and our prior research, we identified the crucial need of overcoming today's situation of uncoordinated research activities in this important research direction. We thus developed a coordinated approach that is essential for joining the business dimension with the technical dimension, which on their own already contribute a level of complexity. Figure 1 illustrates our contribution.

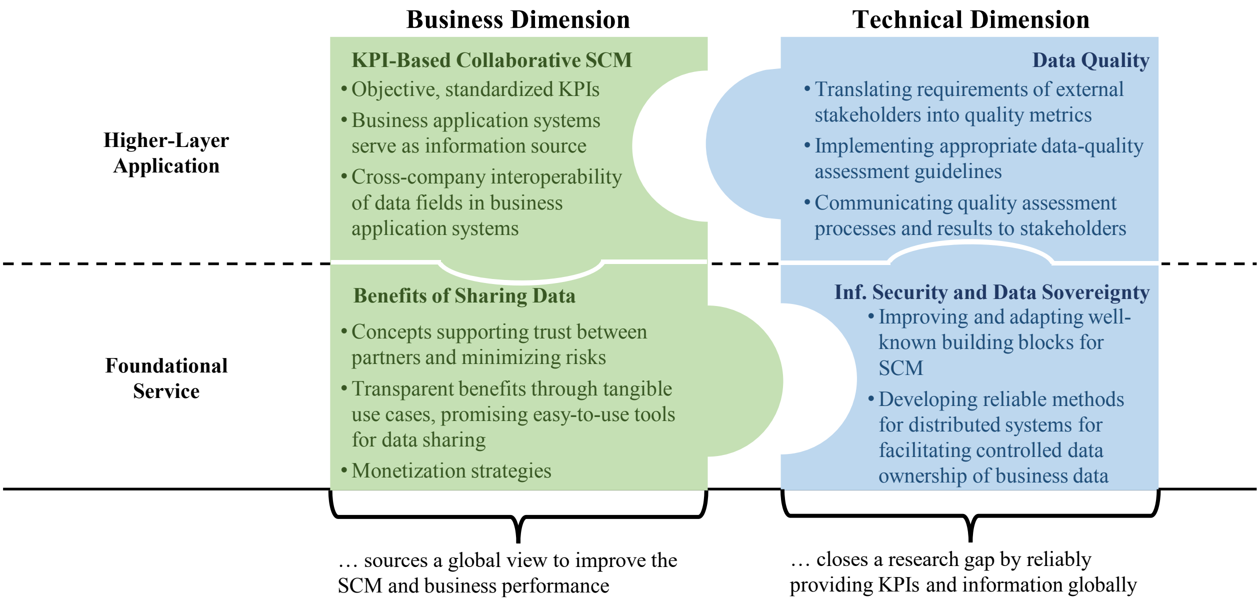

Figure 1: Realizing privacy-aware, collaborative supply chain ratings in practice can succeed by joining business- and technical-focused research into a coordinated activity without neglecting the individual contributions to their field. Fortunately, both dimensions offer suitable links that ease this endeavor

3.1 Linking currently isolated research activities

Overall, we noticed two important strains of research. On the one hand, we have activities that directly yield improvements for supply chain ratings, potentially with direct implications for businesses. On the other hand, we have foundational aspects that are not strictly tied to the overall goal but serve as enablers for higher-layer applications such as the supply chain ratings, i.e., they have rather implicit effects for involved companies. Figure 1 also visualizes this division for both dimensions.

In the following, we first detail how the business and technical dimensions can be coordinated to improve the respective research strains (Figure 1, bottom and top, respectively). Subsequently, we further outline the interplay between the two strains for each dimension individually (Figure 1, right and left, respectively). This way, we present how our coordinated approach comes into existence.

Linking the foundational service: Appropriate technical building blocks and solutions for information security and data sovereignty allow for the development of corresponding business models and tools, which directly contribute to increasing the benefits of sharing data. Likewise, the need for advanced technical approaches and precise expectations regarding their features, as communicated by business experts, provides computer science with a clear roadmap of how to evolve their approaches.

Linking the higher-layer application: A similar situation is apparent when focusing on research that directly affects supply chain ratings in practice. Specifically, technical means for ensuring and communicating the quality of data, and thus, the value of information that covers supply chain networks have direct positive consequences for KPI-based collaborative SCM since the decision-making builds on an objective and reliable data foundation. In the other direction, specific KPIs, as well as required data that has not yet been processed, allow for precise requirements to be communicated to the technical dimension. This way, research can focus its improvements on these data points. Altogether, both dimensions are key for bringing new higher-layer SCM applications to light.

Interplay in the technical dimension: The links in this dimension are straightforward to introduce. Only foundational building blocks that provide a sufficient level of information security, paired with distributed analytics concepts, can contribute to improving data quality and associated (technical) guarantees. In this context, data quality is a crucial goal that also drives innovation on the building-block level.

Interplay in the business dimension: In this dimension, the supplier selection, which is part of the KPI-based collaborative SCM, is a concrete use case that outlines why companies should share their data. Otherwise, they will (most likely) not receive any valuable data themselves, as research on the benefits of sharing data reveals. In the other direction, new developments and tools related to business models and data sharing (from a business perspective) can also motivate changes in (collaborative) SCM.

In conclusion, we observe that closing the technical research gap of providing information security, data sovereignty, and data quality in global settings (e.g., value-creation networks) contributes to having important information available to make more informed decisions in SCM. Here, developments toward KPI-based, collaborative settings will only succeed if awareness of the benefits of (globally) shared information, as well as the demonstration of appropriate business models, are already successful.

Next up, we will detail the specific contribution each research activity makes in this regard.

3.2 Individual contributions to the coordinated approach for advanced supply chain ratings

The presented coordinated approach can only succeed if the individual research activities address their individual research challenges. Accordingly, we outline how we are currently tackling this undertaking.

KPI-based collaborative SCM: A KPI-based collaborative SCM approach enables companies to establish and shape relationships based on objective key figures. Standards and guidelines such as the Supply Chain Operations Reference Model of the association for Supply Chain Management or the VDI guidelines offer companies a broad spectrum of possible KPIs for SCM [41,14,42,43]. In the initial step of establishing a new business relationship, a challenge is to determine which KPIs are necessary for the supplier rating as part of the supplier selection process. In the next step, KPIs can also be used in an existing collaboration, e.g., as part of supplier evaluation and development. Here, too, determining which KPIs are beneficial in the context of collaborative SCM and can be shared objectively under the presented technical solutions for data quality and security is important.

When selecting appropriate KPIs, any approach must ensure that they can be unambiguously calculated, based, for example, on guidelines such as VDI 4400 (Logistic indicators for procurement, production, and distribution) [14,42,43]. In addition to mathematical calculation, describing exactly which data fields from business application systems are required for this purpose is challenging. In the example of on-time delivery, VDI 4440 Part 1 describes mathematically in detail how the KPI is to be calculated. However, the “agreed delivery date” that is used for the calculation is interpreted differently in business practice. For some companies, this data is the first delivery date confirmed by the supplier and, thus, a data field that is filled once and then fixed. Other companies have a more dynamic understanding, and the date can change several times until the goods arrive, with the respective data field overwritten several times. Furthermore, the naming of the data fields in the specific operational business application system differs depending on the ERP provider (e.g., “statistical delivery date”, “stochastic delivery date”, or “first confirmed delivery date”) or a company's individual system configuration.

To enable an integration of the framework into business practice, domain-specific agreements must, therefore, precisely define which data fields of the operational application systems provide the data for calculating a reputation score and, in turn, serve as input for the distributed analytics algorithms.

Data quality: Interested data consumers further expect technical approaches that ensure the data’s value and certify its quality[44]. In the context of supplier selection, the experiences that other companies have had with a specific supplier present a valuable asset, provided that the data amount to a degree of objectivity and trustworthiness. For instance, in evaluating a supplier's on-time delivery performance, relying on subjective measures like five-star ratings or self-reported figures would be insufficient. Instead, the on-time delivery KPI should be derived from objective figures such as actual transactional data. To guarantee this reliability, a mechanism (e.g., trusted sensing [45]) is needed to ensure that the KPI is calculated from verified, real-world business transactions, safeguarding its accuracy and usefulness.

Analytics methods that operate on decentralized systems, while addressing the matter of data sovereignty, present an approach that also has the potential to improve data quality in several dimensions: Information may be enhanced by basing the calculated information on real company databases (accuracy), and algorithms may be designed to return meta-information, such as the timeframe of the data (timeliness) and the number of data points used in the calculation (sample size). Documenting these features would not only enrich data quality but also help ensure that the shared information is more comprehensive and reliable. Distributed analytics frameworks, while having yet to be fully evaluated in supply chain contexts, thus present a promising approach toward supporting a holistic DQM.

Benefits of sharing data: We already pointed out that companies often experience tension between the risks associated with data sharing and the uncertain benefits [46]. This dilemma frequently results in companies either not sharing (industrial) data at all or relying on highly manual processes [47]. In some cases, even data-driven companies must put their ambitious business model innovation projects on hold because they lack access to data from external partners [22].

To enable advanced collaboration, there is, on the one hand, a pressing need for frameworks that mitigate risks, such as data misuse, and clearly define access and usage rights for the shared data [29,46]. On the other hand, the benefits of data sharing must be made more transparent [48,49]. Through tangible use cases, like supplier selection, companies can identify advantages of data sharing for their operations. When they recognize that they can generate greater value - such as enhanced production efficiency or increased customer satisfaction through shorter lead times - than they could achieve without sharing any data across companies, they may be more incentivized to overcome their tendency to protect (sensitive) business data.

Finally, research expresses a demand for easy-to-use tools for data sharing, as not all companies possess the capabilities to establish complex data connections or databases along their supply chain independently [20].

Information security and data sovereignty: While several building blocks for information security have been proposed in the past, they have either not been applied in supply chain context [46] or they fail to cover all relevant dimensions [30]. Accordingly, ongoing research on building blocks creates the foundation for improved application in the context of value-creation networks. Relatedly, the sharing of entire logs and datasets, containing sensitive business transactions, also raises concerns over data sovereignty. Technical approaches for this concern often involve distributed analytics methods, where algorithms are brought to the data rather than sending the data to the algorithm [50]. One framework that exemplifies this approach is the Personal Health Train [51]. Experiments have already been conducted in different domains with PADME, an implementation of the framework [52,53]. In PADME, the algorithm is packaged in a Docker container and sent to “stations” (data sources). The code in this container can be viewed by station owners and granted or denied access to its system. For instance, the container may have access to the ERP system of a station, and an on-time delivery score could be computed based on the transactional data, with transparency that the code would return only the calculated score - leaving the underlying data where it is.

Overall, with the proposed framework, we have established that individual research activities can jointly address the bigger-picture challenges. In the next section, we outline the primary benefits of having such a coordinated approach for privacy-aware, collaborative supply chain ratings globally in place.

4. Primary benefits for an Internet of Production

The goal of the “Internet of Production” [54–56] is to enable data sharing and integration across all stages of the manufacturing process to enhance decision-making, efficiency, and adaptability. In the context of modern supply chain networks, which are the basis for industrial production, a stronger integration of business requirements and technological solutions is necessary to meet challenges in dynamic markets. The framework developed brings together business requirements and technological possibilities. This interdisciplinary approach offers companies the opportunity to access objective, system-based KPIs from other companies. Corresponding data can be used to evaluate existing supplier relationships (supplier ratings), enabling companies to rapidly identify new and trustworthy business partners. This information is particularly valuable in situations where existing supply chains are disrupted, and alternative sources of supply are required quickly. In this sense, the framework strengthens the resilience of companies as it improves their ability to adapt to unexpected changes in the supply chain.

In addition, the framework addresses key challenges in business practice, such as the increasing demand for mass customization. This development leads to dynamic and often short-lasting business relationships in which fast and flexible access to suitable suppliers is essential. Accordingly, the framework can support this need by providing companies with a reliable basis for evaluating and selecting new partners. A global and widely used approach to supply chain ratings, as pursued with the proposed framework, could further help to include additional factors in the evaluation of supply chain partners beyond the traditional economic criteria. The framework presented provides the opportunity to evaluate and compare aspects such as flexibility or ecological factors. Data from operational application systems can be used as well as individual expert assessments.

At this point, the practical implementation of this framework in large supply chain networks remains a key challenge. In particular, trust and the willingness to share data are essential prerequisites. Companies must develop trust in the confidentiality and added value of shared information for the framework to be fully practical. However, this work is a first step toward reliably supporting collaborative SCM using technical approaches for data quality and information security.

5. Outlook and conclusion

A holistic approach for enabling privacy-aware, collaborative supply chain ratings and thus tapping into various possible benefits, e.g., metric-driven supply chain predictions, has been missing so far. While individual business-related and technological advances are readily available, they have not been combined so far. However, to realize an Internet of Production, such individual innovations must be brought together. Our research therefore contributes to its implementation by outlining a research framework that exploits synergies and symbioses between otherwise currently isolated research endeavors. Specifically, improved data quality and objective metrics allow for more reliable decision-making, while corresponding data sharing will be motivated by tangible benefits and data sovereignty guarantees backed by technical advances in information security. Hence, bringing such a coordinated approach to real-world use will introduce significant benefits to SCM in value-creation networks.

Continuing with such joint, interdisciplinary research further work on the following topics promises additional benefits:

Sourcing objective information. In addition to relying on business application systems when deriving supply chain ratings, the use of additional truly objective data could be very beneficial to improve trust in them [57]. The deployment of trusted sensors [45] across value-creation networks would introduce technical guarantees. Respective implications for SCM and decision-making are yet to be explored.

Cross-company supply chain analytics. Once an infrastructure for distributed analytics is implemented, the derivation of KPIs is not limited to rather straightforward dimensions like on-time delivery. Algorithms to extract more groundbreaking KPIs may be implemented, and advanced methods such as incremental learning may be explored, for example, to design network-spanning recommendation systems.

Framework for collaboration in the context of circular economy. Implementing a circular economy (in contrast to the prevailing linear economic model) necessitates the collaboration and data exchange of previously uninvolved companies. The presented framework and methodology of interdisciplinary research provide a suitable foundation for addressing the associated challenges, such as cross-company data exchange of product and process data. Future research can (and should) explore the integration of the framework into the logic of the digital product passport or any of its extensions.

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