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Logistics Management

Contributions of the Section Logistics of the German Academic Association for Business Research, 2021, Dresden, Germany

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ISSN 2194-8917 ISSN 2194-8925 (electronic)
Lecture Notes in Logistics
ISBN 978-3-030-85842-1 ISBN 978-3-030-85843-8 (eBook)
https://doi.org/10.1007/978-3-030-85843-8

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Preface

This book contains selected papers presented at the 12th Logistics Management Conference (LM 2021) of the Scientific Commission for Logistics (WK-LOG) of the German Academic Association for Business Research (VHB). The LM conference series is continued every two years at different places in Germany. It aims at providing a forum for scientists and practitioners in business administration, IT, and industrial engineering to present and discuss new ideas and technical developments related to the management of logistic systems. LM 2021 was hosted by the Technische Universität Dresden. It took place from September 15–16, 2021, in a digital format. Previous LM conferences were held in Bremen (1999, 2013), Aachen (2001), Braunschweig (2003, 2015), Dresden (2005), Regensburg (2007), Hamburg (2009), Bamberg (2011), Stuttgart (2017), and Halle (Saale) (2019). The LM 2021 conference concerns itself with the current general dynamics and challenges in the field of logistics management. To give an insight into the field, LM 2021 has invited two keynote speakers to examine ongoing developments:

- Christian Bierwirth (Martin Luther University Halle-Wittenberg)
- Alexander Hohlfeld (Deutsche Bahn AG)

In addition to the keynote talks, around 34 presentations were given at LM 2021 out of which 15 are printed as full papers in this proceedings. These papers were selected through a careful review process. Each paper was reviewed by at least two reviewers and went through up to two rounds of revisions. The accepted full papers address a broad spectrum of facets of logistic systems with regard to digitalization, sustainability, and optimization. They divide this book into five parts, considering the digitalization of supply chains, supply management, supply chain operations, sustainable supply chain management, and supply chain risk management. We hope that it provides insights into the state of the art of logistics management and, thus, stimulates future research.

September 2021

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Acknowledgements

The editors express their gratitude to all of the authors and to everybody who has contributed to this volume. In particular, we thank Springer for the easy and uncomplicated collaboration in the editing and publishing process. Our special gratitude goes to DHL for awarding the best full paper contribution of LM 2021. Furthermore, we gratefully acknowledge the efforts of the program committee for reviewing the contributions submitted to the conference. The LM 2021 program committee consists of

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Contents

Supply Chain Digitalization

The Roles of Small and Medium-Sized Enterprises in Blockchain Adoption

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Abstract. Despite the growing maturity of Blockchain technology and an increasing deployment in Supply Chain and Logistics, many small and medium-sized enterprises (SMEs) struggle to use the technology for their benefit. Based on 27 expert interviews, we develop a typology of Blockchain adoption approaches for SMEs and discuss their implications. We find that SMEs can approach the technology as either an Observer, a Cooperator, or a Service Provider based on their technological expertise, the expected relevance of the technology for their organization, and their market power.

1 Introduction

Researchers and practitioners alike have high hopes of Blockchain technology improving Supply Chain and Logistics (SC&L) activities. Tracing goods, identifying counterfeit products, and coordinating with business partners are key activities for any modern business, but developing the necessary information infrastructure remains a challenge. Blockchain technology promises to fix this gap in trans-organizational communication through its distributed nature. Some large companies have already begun to deploy Blockchain technology for their operations, with what appears to be some success (Sternberg et al. 2020). While their small and medium-sized enterprise competitors have attempted to do the same, they do not have the same amount of know-how and financial resources. This is in stark contrast to those SMEs' need for information sharing infrastructure – their value-add relies on external relationships. Large corporations can more easily generate value-add in-house, and Blockchain may provide advantages for SMEs in this regard. However, there is little insight into potential adoption strategies for SMEs (Wong et al. 2020) and the organizational structure of Blockchain projects in general (Lumineau et al. 2020).

We approach this research gap with a qualitative, exploratory research design and Grounded Theory (GT). We conduct semi-structured interviews with 27 industry professionals and derive a typology of approaches. In particular, we gain insight into the criteria relevant for selecting an approach and the trade-offs associated with each approach. In doing so, we answer the following research questions:

U. Buscher et al. (Eds.): *Logistics Management*, LNLO, pp. 3–14, 2021.
https://doi.org/10.1007/978-3-030-85843-8_1

1. What approaches can SMEs take to adopt Blockchain in SC&L?
2. What considerations should drive the decision for a particular approach?

The rest of this paper is structured as follows. First, we describe the state of the art and existing research in the field. Then, we present our methodology, followed by the results of our study and a discussion of the implications. Finally, we consider limitations and conclude our findings.

2 Literature Review

At its core, a Blockchain is a distributed database. A full copy of this database is stored on multiple independent but synchronized computer systems. This enables every network participant to instantly access any information needed from their copy of the database (Nakamoto 2008; Swan 2015; Pilkington 2016). Previous research has identified use cases in food traceability (Caro et al. 2018), pharmaceutical products (Bocek et al. 2017), and the digital bill of lading (Dobrovnik et al. 2018), among others. The technology has also made inroads into practice. For example, retail behemoth Walmart uses Blockchain to track the origin of food (Corkery and Popper 2018), and shipping giant Maersk has matured initial experiments for freight documentation into a powerful platform that is now part of their regular operations (Carlsen 2021).

Research has also shown that Blockchain technology extends beyond the above-mentioned SC&L use cases. The technical characteristics of Blockchain have profound business implications for the deployment of Blockchain technology. A trusted operator of the shared technical system is no longer required; instead, participants can interact directly. The consequences of this change are far-reaching and poorly understood; recent research even claims that the organizational implications outweigh the technical ones (Lacity and Van Hoek 2021). Lumineau et al. (2020) highlight the importance of understanding the characteristics of participants (the “who”), their circumstances (the “where”), and their motivations (the “why”). Sternberg et al. (2020) focus on the importance of corporate cultures, the interdependencies between different participants, and the tensions between them. Furthermore, they emphasize the tension between competition and collaboration in information sharing. In their analysis of some early Blockchain projects, Beck et al. (2018) emphasize the importance of power relationships (“decision rights” and “accountability”) and the objectives driving the behavior of the actors (“incentives”).

Such power relationships play an important role in Blockchain adoption for SMEs (Corkery and Popper 2018), and research by Ilbitz and Durst (2019) is hence of particular relevance for those enterprises. The authors discuss the appropriateness of Blockchain and outline major challenges to SMEs, such as network effects, internalization, and financing. Furthermore, a study of Malaysian SMEs’ adoption of Blockchain has demonstrated that competitive pressure, market dynamics, and technology complexity are significant factors for SMEs (Wong et al. 2020). However, a study by Wang et al. (2019) revealed contradictory viewpoints in this regard: larger corporations can adopt the technology more easily due to their resources, but only smaller organizations have the agility needed to implement revolutionary technology. In addition, Clohessy and Acton (2019) find that larger companies are more likely to adopt Blockchain technology than small companies. They outline that top management support and organizational readiness are particularly relevant in Blockchain adoption. Existing research also highlights these areas of interest, but it does not provide in-depth insights, and most importantly, it emphasizes problems instead of paths towards a solution. Practitioners appear to face a similar problem and focus their efforts on the operational consequences of Blockchain rather than the strategic implications (Nandi et al. 2020), highlighting the need for research into this space. In fact, previous research has explicitly shown that choosing the right approach to Blockchain is crucial, particularly for SMEs (Ilbiz and Durst 2019). We contribute to this research area by providing insight into the different approaches towards Blockchain adoption, particularly their requirements and implications.

3 Methodology

We used an exploratory, qualitative GT approach to determine how SMEs position themselves in dealing with this emerging technology. We chose the GT approach because it "seeks not only to uncover relevant conditions but also to determine how the actors respond to changing conditions and to the consequences of their actions" (Corbin and Strauss 1990).

To answer our research questions, we interviewed experts from the SC&L field. Our sample included logistics companies, manufacturers, software vendors, and Blockchain service providers. All companies involved in the study were asked the same questions from a three-part, semi-structured interview guide. First, we asked them what experience the companies have with Blockchain technology and what potential they see. Then, we discussed opportunities and barriers with the respondents, after which we focused on regulations and incentives for companies on the topic of Blockchain.

We conducted 27 in-depth, semi-structured interviews from March 2020 to January 2021, each of which lasted between 32 and 111 min (mean: 58 min, median: 54 min). Due to the current pandemic, all interviews were carried out via web calls or phone, in either German (22/27) or English (5/27). We began with an initial sample of six interviews to test the interview guide and gain insight into the topic. Based on this knowledge, we slightly adapted the interview guide to include emerging themes and topics. We returned to the interviewees in four cases to clarify statements, discuss new topics, and discuss the current results.

This study employs theoretical sampling (Corbin and Strauss 1990). The interviewed companies represent a cross-section of industries with different levels of experience. Notably, we aim to identify adoption strategies in an industry that has not yet adopted the technology on a larger scale. We conducted interviews with interested industry participants and participants who have either already adopted the technology or attempted to adopt it. The limited knowledge of our interviewees is ultimately a limitation for our study. Furthermore, the considered SMEs are not only operational companies looking to deploy Blockchain technology for their SC&L activities but also technical companies currently providing computer software to aid operational companies in their logistics and/or supply chain work. We found that IT solutions providers working with SMEs have a strong understanding of the challenges facing these SMEs. Table 1 contains an overview of the sample, including the level of Blockchain experience.

Table 1. Sample of interview respondents

#	Company	Respondent Position	Employees	Experience
1	IT Solutions Provider	Founder & CEO	11–100	Very High
2	University	Researcher	>1,000	Very High
3	IT Solutions Provider	Engineer	101–1,000	High
4	Logistics Service Provider	CEO	11–100	Medium
5	IT Solutions Provider	Director of Development	101–1,000	High
6	Logistics Consulting Company	Founder & CEO	1–10	Very High
7	Blockchain Consulting Company	Founder & CEO	1–10	Very High
8	Blockchain Consulting Company	Consultant	1–10	Very High
9	Logistics Association	Project Leader	11–100	Medium
10	Waste Management	CEO	>1,000	Medium
11	IT Solutions Provider	Engineer	>1,000	Very High
12	IT Solutions Provider	Business Developer & Client Manager	11–100	Very High
13	Manufacturer	Head of Blockchain	>1,000	Very High
14	Blockchain Consulting Company	Consultant	11–100	Very High
15	Manufacturer	Head of IT	>1,000	Medium
16	Logistics Service Provider	Senior Developer	>1,000	High
17	IT Solutions Provider	Founder & CEO	1–10	Very High
18	IT Solutions Provider	Founder & CEO	11–100	Very High
19	IT Solutions Provider	Head Manager	11–100	Medium
20	Logistics Service Provider	Head Manager	11–100	Medium
21	IT Solutions Provider	Customer Success Manager	11–100	Very High
22	Logistics Authority	Head Manager	>1,000	Medium
23	IT Solutions Provider	Client Manager	11–100	Very High
24	Logistics Association	CEO	11–100	High
25	IT Solutions Provider	Client Manager	11–100	Very High
26	University	Researcher	>1,000	Very High
27	Manufacturer	Head of SCM	>1,000	Medium

We conducted data analysis in parallel with data collection using the iterative procedure developed by Corbin and Strauss (1990). Following the coding scheme of Charmaz

(2014), we analyzed the interviews with an open coding scheme in the initial coding phase. This resulted in 620 codes, each summarizing a fragment of the text. We reviewed the initial codes, generalized them, and merged frequently used codes into higher-level concepts during the subsequent focused coding. Finally, we used axial coding to create themes, marking larger common ideas related to the concepts (Charmaz 2014).

4 Findings

In our analysis, we were able to identify three ideal-typical roles that SMEs can assume to leverage Blockchain technology: Observers, who join existing solutions; Cooperators, who team up with other interested parties; and Service Providers, who offer Blockchain-based services to other companies. The typology is summarized in Fig. 1 and explained in more detail thereafter. In support of our typology, the participants' statements are incorporated into the text (Pratt 2009). Most importantly, the roles discussed here are not mutually exclusive – an SME may choose to adopt one role in one Blockchain project and another role in another project.

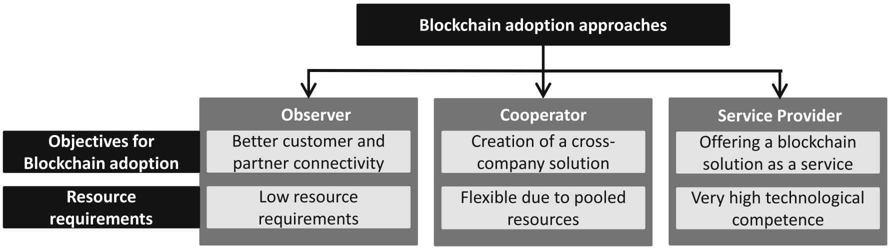

Fig. 1. Approaches to blockchain adoption for SMEs

4.1 Observers

Observers are operational companies that merely observe the development of Blockchain solutions and adopt finished systems. Once they discover a solution relevant to them, they deploy it as a turnkey solution. Other market participants provide "the entire onboarding process and connections to existing systems" for them (#12 IT Solutions Provider). In practice, these SMEs report being approached by "countless external providers, who naturally see the potential and propose something to [them]" (#10 Waste Management).

Two types of motivation can drive Observers. They can be motivated either intrinsically, by a desire to save costs or improve their product, or externally, by factors such as regulations or pressure from business partners. Organizations with substantial market power can force less powerful business partners into specific projects with an "if you don't do it, you are out" (#16 Logistics Service Provider) approach.

Due to their reliance on other developers, Observers do not require any technical competencies. They do not even need to "know what Blockchain really means" (#20 Logistics Service Provider). Their approach requires no market power and only limited internal resources; they simply "plug in somewhere" (#16 Logistics Service Provider).

4.2 Cooperators

Cooperators team up with other interested parties to jointly develop Blockchain solutions. One interviewee highlighted that companies “lose money together” in shared inefficient processes and that a “community spirit” is needed to resolve these issues (#6 Logistics Solutions Provider). Cooperators apply this community spirit and seek to actively shape developments in their industry. They design and create the solution together and shape it according to their ideas, and they can be both operational and technical companies.

Cooperators are motivated by their expectation of Blockchain adding value to their companies and their supply chains by saving costs or by improving their offerings (#4 Logistics Service Provider). Their goal can be to develop a productive system or evaluate the technology in general.

However, Blockchain may also provide some less-tangible benefits. For example, otherwise invisible SMEs may be able to gain “prestige” and “higher visibility” through technology development (#18 IT Solutions Provider). This can also work in reverse when a respected industry player pushes a project, “and through its pull, it brings part of the industry onto such a network” (#11 IT Solutions Provider). Well-known solutions can force others to follow or risk being left behind. The idea here is to use Blockchain adoption to signal innovativeness or other company characteristics and to use it directly due to its intrinsic properties.

Becoming a Cooperator has some preconditions. For instance, Cooperators’ active involvement requires them to deploy resources, and together with their co-cooperators, they create a shared pool of resources. The type and extent of contribution can vary across the different Cooperators; however, their shared project ultimately needs to receive sufficient resources. From the perspective of an individual Cooperator, access to reliable project partners is itself a resource. In smaller projects, all participants “have some sort of connection to everyone else” (#18 IT Solutions Provider), and more often than not, reliable partners looking to work on the same problem are competitors of the Cooperator. Hence, Cooperators must be willing to work with these competitors and “make certain data available” (#16 Logistics Service Provider), although many hesitate to do so.

4.3 Service Providers

Service providers are true believers in Blockchain solutions and build their business model around the technology. Service Providers provide various services going all the way to a “carefree package” for customers (#12 IT Solutions Provider). They essentially offer to connect their customers to the Blockchain in a Software-as-a-Service model, providing services based on the Blockchain or selling the Blockchain itself as an infrastructure for others to build on. They also serve as evangelists that spread information about the technology to as-yet uninvolved companies through their business development – technical companies usually take on this role.

Service Providers enable other companies to benefit from Blockchain technology but do not use the potential themselves. Therefore, they are driven by their customers’ motivations – when their customers seek to resolve regulatory problems, so do the Service Providers, for example. Considered in isolation, Service Providers themselves represent a new business model enabled by Blockchain technology.

As for prerequisites, Service Providers need a large technical competency because they offer a digital product. Conversely, they also require other companies that do not possess technical competencies themselves and outsource them to the Service Providers instead. In this regard, Service Providers need not hold substantial market power; their business model revolves around providing an attractive service at a competitive price. One Service Provider insinuated that it has “a special technology […] at a very good price” (#21 IT Solutions Provider). To develop these technologies, the Service Provider may need to invest its own resources.

5 Discussion

The first research question concerns the possible approaches to Blockchain technology adoption that SMEs can take. We tackled the second research question by discussing the factors involved in such a decision. The following sections discuss the implications of our findings. Crucially, however, our research only covers SMEs, although SMEs frequently interact with large corporations in the open market. Therefore, we also discuss the interaction between large corporations and the adoption approaches.

Interestingly, SMEs do not need to select only one approach. In one project, they may become an Observer to foster a better connection to a big company, whereas in another project, they may cooperate to ensure that solutions align with the company’s requirements. This can also provide them with options if either approach turns out to be inappropriate, as maintaining flexibility may be crucial when exploring new technology.

The approaches presented here quintessentially differ in the depth of involvement with the technology. Interested companies need to weigh not only the advantages and disadvantages but also the feasibility for their organization. An organization can only take on a certain role if the required competencies are available. Perhaps the most important criterion in this regard is the presence (or lack) of digital capabilities. A company already providing IT solutions to other companies is likely well equipped to become a Blockchain Service Provider or work on Blockchain solutions cooperatively. However, it would struggle to become an Observer – even if it chooses to connect its software product to an existing system, its role ultimately lies in connecting its (preexisting) customers to the Blockchain system. Conversely, an operational company can choose between acting as an Observer and a Cooperator. It may also decide to act as a Service Provider but likely lacks the experience and organizational setup to provide software services to other companies. Operational companies looking to deploy Blockchain technology and technical companies looking to make the Blockchain itself part of their business model have different options. Figure 2 provides an overview of the proposed decision opportunities.

As suggested in our literature review, some companies adopt Blockchain systems due to a requirement from a more powerful business partner (Hald and Kinra 2019; Ilbiz and Durst 2019). This forces them into the Observer role because that partner has already determined the characteristics of the system. Although they may still benefit from using the system, the system’s creator has ultimately extended its supply chain power into the digital realm, which can have negative consequences for SMEs in the long term.

On the plus side, Observers face a complete system to which they merely need to connect – the organization responsible for onboarding connects the Observer’s legacy infrastructure to the new system. From the more powerful partner's perspective, it is beneficial to offer a turnkey solution to lower the hurdle for adoption. Furthermore, we imagine the Observer as a company – or part of a larger company – that excels within its particular niche of the supply chain. Observers succeed precisely because they focus on their strengths rather than dabbling in their weaknesses, and they extend this same approach to Blockchain adoption.

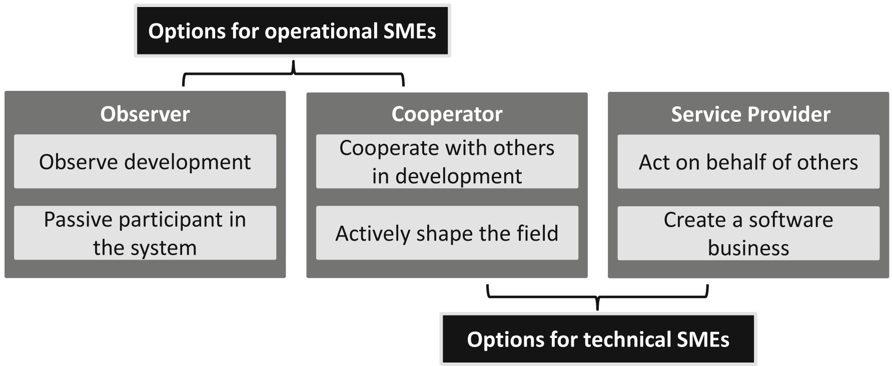

Fig. 2. Options for operational and technical SMEs

Companies that want to shape the industry may find themselves as members of a consortium rather than being Observers. Indeed, this goes back to the motivation for adopting Blockchain technology. Interviewees from all company types are motivated by ideas on solving large logistics or supply chain problems, such as the paper-based Bill of Lading, with Blockchain technology. This precludes being an Observer - observing is only an option when a project with the desired characteristics already exists and is open for new members. If no such project exists, then a new project needs to be developed.

However, one party cannot build such a system alone, because Blockchain serves to connect multiple partners. To build such a consortium, Cooperators must find partners looking to solve the same problems. This problem can result from a shared process, a similar product, or a regulation affecting multiple companies. Finding the right partners and distributing power across them is crucial for any new business venture, particularly for Blockchain projects, since the much sought-after network effects always require many participants (Ilbiz and Durst 2019; Wang et al. 2019; Koens et al. 2020).

Furthermore, some technical companies act as Service Providers, selling their solutions (or simply their efforts) directly. This allows them to focus on technological aspects, while their customers can focus on business aspects. For a technical company, the key difference between cooperation and service provision lies in the relationship with its partner. Service Providers offer a paid service, while Cooperators invest their own resources in shared projects in return for ownership and a seat at the table.

6 Implications

Choosing a particular role (or being forced into one) has implications for companies. It determines the learnings, the risk, the organizational complexity, and the design opportunities afforded by project participation. Figure 3 displays an overview of these implications.

	Observer	Cooperator	Service Provider
Project Learnings	Few learnings, only how to connect to a Blockchain	Many learnings on governance, technology and organizational structure	Many learnings on technology, limited on governance and acquisition
Risk of Project Failure	Low risk, because Observer will only be integrated	Medium risk, only the resources used are affected	Low risk on project level, but existential on a larger level
Organizational Complexity	Low complexity, has to set up a business relationship	High complexity, whereby it can also contradict the technology principle	Medium complexity, but a possible mismatch with technology
Design Opportunities	Low influence, cannot shape the existing system	High influence on the design of the Blockchain solution and the participants of a project	Medium influence on the design of the solution, but limited on the participants of a project

Fig. 3. Implications of choosing any particular approach

Since the different approaches cause companies to take on different responsibilities within a project, they will generate different learnings, and although the learnings may not be relevant within that particular project, they can be applied in later projects. Observers learn the least from a project, as they merely connect to the system once it is finished, while Cooperators learn about both the technical and the organizational sides of setting up the project. Crucially, the distribution of work among the different Cooperators may enable an inexperienced Cooperator to gradually deepen its involvement in the project as it learns more about the inner workings of the new technology. Meanwhile, Service Providers will learn mostly about the technical implementation, which is arguably the most important aspect for a technology company. Depending on the extent of their work, Cooperators and particularly Service Providers may go beyond learnings to build a capability for future projects.

The depth of involvement also dictates the risk that individual companies take in the project. An Observer takes on little risk, while a Cooperator risks a negative return on its resource investments. Service Providers also take on a smaller risk – they get paid for their services and usually receive payment even if the project does not succeed. However, their business model ultimately hinges on the success of Blockchain technology; if the technology fails, then they are forced to abandon their business model.

From an organizational perspective, Observers again face little complexity – they merely connect to the system once it is completed, which requires them to build some type of business relationship. In contrast, Cooperators face the full organizational complexity of Blockchain technology. Managers must coordinate all project partners' competing interests, distribute rights and responsibilities, and ensure that these considerations do not hamper technological development. This is of particular importance for managers because, unlike other technology developments, Blockchain adoption cannot be delegated to the IT department. Therefore, management attention is an important success factor for Blockchain projects.

These organizational problems worsen as project size increases due to the number of participants (Filippi and Loveluck 2016; Casino et al. 2019; Wang et al. 2019). However, Blockchain technology is said to require many participants to succeed and generate so-called network effects. Thus, Cooperators must create a scalable organizational setup for their system and determine how others can access their system. A Service Provider is also hired by Cooperators and enjoys a rather simple organizational situation (even though the Cooperators may draw on their experience in this regard as well).

In this vein, it is important to consider the design opportunities available when choosing any particular approach. When Observers adopt preexisting systems, their ability to influence the system structure is limited. Observers end up conforming to the newly set standard, which may or may not fit their needs; even if they cover their use case, they may have preferred to approach it differently to match their existing processes. Cooperators can influence the project in this regard. Service Providers also have some leeway, depending on the specific project.

By using this leeway, technical companies – as either Cooperators or Service Providers – may end up in a situation where they hold substantial technical power over the Blockchain system. Such influence defeats the purpose of using Blockchain. Technical companies need to limit their role, despite the obvious appeal of such a strong position.

The key question in terms of design opportunities is whether they are needed for a particular company in a particular project. A small industry participant has no interest in or resources for setting industry standards. Consequently, it has no need for design opportunities in a Blockchain project. An ambitious mid-sized company may need such opportunities. Managers should also consider the implications of running multiple projects at the same time or in succession. They may need to prioritize projects based on their importance for their business model and their probability of success. Moreover, a group of SMEs looking to shape the world around them may invest substantial resources in developing an operational Blockchain system, only to be forced into another system developed by a more powerful peer. If they lack meaningful power in the target market, they may end up as Observers regardless of their decisions.

7 Conclusion and Further Research

In conclusion, our research suggests that SMEs should consider the implications of following any particular path towards Blockchain adoption. From an academic perspective, we find that the situation for SMEs is complex, and further research is required. Previous conceptual work on the topic falls short when it comes to SMEs' decision-making. As for managerial insights, we find that managers should consider several factors before working with Blockchain technology. In particular, they should assess the extent of their resources, technical capabilities, and position in the supply chain.

Following the GT approach, we cannot claim the generalizability of our results. Future research could attempt similar studies in different settings to determine the validity of our findings there. Furthermore, in a field as young as Blockchain, the approaches are still prone to change. Therefore, in the future, we seek to investigate which company incentives lead to which approach, particularly regarding the supply chain position. In addition, examining the decision criteria employed by companies to decide on an approach to Blockchain would also be valuable.

Funding Disclosure The ChainLog IGF Project (20951 N) has been funded via the German Federation of Industrial Research Associations (AiF) by the Federal Ministry for Economic Affairs and Energy on the basis of a decision of the German Bundestag and on behalf of Bundesvereinigung Logistik (BVL) e.V. (German Logistics Association).

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Preconditions and Challenges in the Digital Transformation of Supply Chains: Findings from Academia and Practice

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Abstract. Digital technologies are omnipresent in today's world, and successful involvement in the digital transformation becomes increasingly important to companies from all industries. To stay competitive, companies are pressured to rethink their supply chains and adapt. However, the topic of digital supply chains is still in its infancy. The goal of this paper is to shed light on the preconditions and challenges regarding the transformation. The different areas of the digital transformation of supply chains, namely the strategic, organizational, process & method, and technological area are considered. Preconditions and challenges for companies in the digital transformation of their supply chain are extracted from literature with literature reviews and followingly discussed with practitioners to capture the magnitude of the transformation process. Furthermore, differences between academia and practice are revealed, and future research opportunities are identified.

1 Introduction

The digital transformation of supply chains is driven by the latest advancements in technology. Companies are being pressured to adopt emerging technologies to stay competitive and to satisfy changing customer requirements (Agrawal and Narain 2018; Bienhaus and Haddud 2018). Furthermore, companies start such transformation initiatives to capitalize on the gains of improving supply chain processes, increasing their resilience, and minimizing risks, while also improving operational excellence and revenues (Ivanov et al. 2019). Besides the evolutionary side, new business models emerge, partly having the potential to disrupt.

While digital transformation is expected to mitigate some challenges in today's supply chain management and bring many benefits and opportunities, it can also be seen as a complex and expensive undertaking (Agrawal and Narain 2018). Supply chains involve several functional areas on an intra-organizational level as well as interconnections between multiple actors on an inter-organizational level, thus requiring several preconditions to be successfully transformed. However, the adoption of digital technologies in supply chains is not very advanced, hinting towards obstacles and barriers

U. Buscher et al. (Eds.): *Logistics Management*, LNLO, pp. 15–32, 2021.
https://doi.org/10.1007/978-3-030-85843-8_2

associated with this process (Lammers et al. 2019). Supply chain disruptions are identified as one of the most severe risks and challenges in 2020 (Greg Dobie et al. 2020). The resulting loss of revenue can threaten the existence of both small and large enterprises.

The understanding of what a Digital Supply Chain (DSC) is (Büyüközkan and Göçer 2018) is still in its beginning, and the potentials are not fully explored. Previous research mainly focuses on single technological drivers or concepts like Industry 4.0, underlining the complexity and novelty of this topic. The process of digital transformation involves various challenges and must be well thought out. It can be daunting not having an overview and understanding of possible challenges and not knowing which ones to focus on. This can hinder the process of innovation and prevent companies from accessing the promising opportunities of new technologies.

Thus, in this paper, all areas of the digital transformation are considered: from strategic to organizational, process & method, and technological aspects. This paper aims to identify the preconditions and challenges for companies in the digital transformation of their supply chain. Literature but also practitioner's knowledge is taken into account to shed light on the following research questions discussed:

- Which preconditions and challenges regarding the digital transformation of supply chains can be identified in the literature regarding the different transformation areas?
- What are the insights from discussing the literature results with practitioners and their experience in expert interviews?

The remainder of this paper is structured as follows: In Sect. 2, the theoretical background is briefly outlined. In Sect. 3, the methodologies of literature reviews and semi-structured interviews are introduced. Afterward, the results of the conducted literature reviews are presented (Sect. 4) and reviewed with experts (Sect. 5). Finally, the findings are discussed in Sect. 6, and the paper concludes with a brief recap, limitations, and further research opportunities in Sect. 7.

2 Theoretical Background

To create a common understanding of terms and concepts referred to, the theoretical background of this paper is outlined in the following.

While digitization can be defined as "the action to convert analog information into digital information" (Verhoef et al. 2019: 3), digitalization is about changing tasks and processes in an organization, as its objective is a "reconfiguration of assets to develop new business models" (Verhoef et al. 2019: 3 f.). Digital transformation goes one step further. It can be seen as a process that is "concerned with the adoption and use of emerging technologies" (Morakanyane et al., 2017: 438). The emphasis is on major changes to an entire enterprise (Cichosz et al. 2020).

In this paper, Büyüközkan and Göçers' frequently cited definition of a DSC is used (Büyüközkan and Göçer 2018). They define the concept as an agile, customer-driven, productive way to develop different forms of returns for companies and to leverage efficient approaches with emerging technologies. Researchers emphasize that it is crucial to take advantage of new technologies in traditional supply chains to be successful in global markets (Agrawal et al. 2019). Frequently mentioned emerging technologies of a DSC in academia are, for example, big data analytics, internet of things, cloud computing, cyber-physical systems, or blockchain (Ivanov et al. 2019; Queiroz et al. 2019). However, besides the technological aspects, also other areas have to be taken into account to succeed in the digital transformation (Kane et al. 2015; Kohnke 2017).

Different authors have proposed structures and frameworks of DSC to obtain a deeper understanding of the concept (Büyüközkan and Göçer 2018; Farahani et al. 2017). Merging the frameworks and further digital transformation-related literature, we suggest a working definition of a DSC framework with four areas, namely Strategic Digitalization, Organizational Digitalization, Process & Method Digitalization, and Technological Digitalization. The areas are briefly presented and examined separately to create a structured overview. However, strong interrelations exist. The area of business digitalization has an external steering focus and covers aspects like strategy, governance, value offering, and more. The second area, organizational digitalization, focuses on the internal digitalization of the supply chain, covering aspects like employees, culture, and structure. The third area, process & methods, concerns itself with aspects such as the digital transformation of business and supply chain-related processes, as well as supply chain collaboration and networks. Lastly, the area of technological digitalization relates to the implementation of smart objects and autonomous systems, the integration of data, information-related processes, technological infrastructure, architecture, as well as IT security aspects. The two areas, strategic and organizational digitalization, are closely related, and therefore the identified preconditions stem from the same stream of literature. The same holds for the technological and process & method areas examined regarding the challenges (cf. Fig. 1). We acknowledge that it would be beneficial to include all four areas in the review with preconditions and challenges, which we propose for future research.

Digitalization Areas / Subject of Study	Strategic	Organizational	Process & Method	Technological
Preconditions	Considered in this study	Considered in this study	Future research	Future research
Challenges	Future research	Future research	Considered in this study	Considered in this study

Fig. 1. Transformation areas in digital supply chains and scope of study

3 Methodology

In this chapter, the methodologies are briefly described to ensure a transparent and clear structure of the research process. First, for information gathering, literature reviews are conducted to answer the first research question. Second, the results from the literature are discussed with and evaluated by experts from the industry. The methodology of semi-structured expert interviews is applied to answer the second research question.

3.1 Structured Literature Review

The applied procedure for the literature reviews is based on the recommendations of Vom Brocke et al. (2009). A conceptualization of the topic follows the definition of the scope of the search. This conceptualization corresponds to the four areas of the digital transformation presented in Sect. 2. The database Scopus is selected as the primary source, as it is one of the most extensive abstracts and citation databases of peer-reviewed literature regarding science and technology, and widely used. Further, Web of Science is used (in snowball search) as a complementary source due to its reputation and multidisciplinary nature. The literature reviews took place in November and December 2020. The applied search strings are separated and results are depicted in Table 1. Firstly, for the preconditions, a more general string is applied to identify relevant literature because literature pointing out only preconditions is absent. "TITLE-ABS-KEY (supply AND chain AND digital AND transformation)". Secondly, regarding the challenges, the following term is applied: "TITLE-ABS-KEY ("Supply Chain" AND ("Digital Transformation" OR "Digitization") AND ("Challenges OR "Challenging" OR "Obstacles" OR "Barriers"))".

The inclusion and exclusion criteria in the first review ("preconditions") focus on papers naming or discussing preconditions for a successful digital transformation of supply chains in the strategical and organizational area. The criteria of exclusion are mainly related to the content, many papers only focus on technological aspects. A number of case studies specifically describe the implementation of single technologies, failing to analyze the required preconditions. In the second review ("challenges"), the focus lies on barriers of digital transformation in supply chains related to the areas of processes & methods, and technology. Insights regarding digital supply chains, industry 4.0, as well as digitization and digitalization in supply chains are considered as relevant. A high number of papers is rejected because they focus on challenges regarding other areas (e.g., organizational digitalization, only considered in the preconditions part) or on obstacles of companies in general and not especially on the supply chain. Papers and identified preconditions/challenges are sorted following a concept-centric approach by Webster and Watson (2002). Therefore, if a precondition or challenge is identified, the corresponding authors are added. The data analysis is an iterative process during which the concepts are re-structured and re-grouped. In this paper, we only present the final allocation of preconditions and challenges. Collection of identified preconditions/challenges and analysis, are presented next.

3.2 Semi-Structured Interviews

To gain further insights into the preconditions and challenges and their perceived importance in industry, the results of the literature analysis are discussed in semi-structured interviews with industry experts. This type of interview is chosen as it promotes a sociable and informal atmosphere, in which the interviewee can be more forthright and rather respond in his or her own words (Longhurst 2003). The interviewees should be able to raise their own ideas, thoughts, and questions in an open conversation, while certain guiding questions and issues must still be addressed for the objective of the work.

Table 1. Details of conducted literature reviews

Literature review	Preconditions	Challenges
Number of results with search string (Scopus)	332	108
Remaining number of results after title, abstract and keyword analysis	21	27
Remaining number of results after full-text	12	9
Additionally considered papers (e.g. snowball)	31	11
Total number of papers included	43	20

Guiding questions are prepared beforehand, which are used for orientation for the interviewer. The interview guidelines developed by Myers and Newman (2007) are taken into consideration.

The structure of the interviews is briefly presented: First, general questions are asked about the interviewee, the company, and the importance of digital transformation. Second, the categories of preconditions/challenges identified in the literature are presented and explained by the interviewer without the number of occurrences in the literature. Next, the interviewees rank the preconditions/challenges regarding their perceived importance in practice. The interviewer inquires for detailed reasons and takes notes. Further questions conclude the interview. Subsequently, a protocol is created shortly after the interview.

The interviews are conducted as a virtual meeting due to contact restrictions given by the current pandemic. Furthermore, the interviews are conducted in German, the interviewees' native language, to foster an open and informal conversation. At the start of the meeting, the participant is asked for permission to record the meeting to create a transcript. Only the position and name of the company will be included to ensure anonymity but underline credibility. Each interview lasted about 60–90 min. The transcripts are sent to the interviewees to ensure appropriate representation. The first company chosen for the interview is an agricultural machinery manufacturer situated in Germany. Two supply chain managers attended the interview, providing extensive knowledge and project experiences in digital supply chains transformation projects. The second company is an outsourcing service provider with more than 15.000 employees, situated in Germany. The interviewee is head of a division in the digital solutions department.

4 Results of the Literature Review

The preconditions (Tables 2 and 3) and challenges (Tables 4 and 5) identified in the literature review are presented in the following. They can be ranked regarding their number of mentions in the literature and are presented in descending order.

4.1 Preconditions in the Area of Strategic Digitalization in DSC

One of the most elementary preconditions for the successful adoption of a DSC is the specific strategic orientation that guides a company as well as its associated business objectives (Sabri et al. 2018). The strategy of a company supports the translation of innovative ideas regarding the DSC into a framework for the project of transformation (Agrawal et al. 2020), besides playing an important role in deciding on goals and a vision for the whole organization (Narver and Slater 1990). A digital transformation initiative of a supply chain requires orientations such as customer-, technological-, competitor-, supplier- as well as innovation orientation (Agrawal et al. 2020; Wang et al. 2015). The focus of a customer-centric oriented strategy should especially be speed, flexibility, and transparency, among other related features (Agrawal et al. 2020; Büyüközkan and Göçer 2018; Xu 2014). Speed regards the reduced delivery time for, e.g., suppliers (Büyüközkan and Göçer 2018). Flexibility portrays the operational agility of a supply chain in adaption to changing circumstances by using collected and modeled information (Büyüközkan and Göçer 2018; Xu 2014). Regarding a transparent supply chain, actors perform according to the behavior and needs of other actors, enabled by anticipation, modeling of the network, or what-if scenarios (Büyüközkan and Göçer 2018).

Some authors report on the importance of suitable innovation strategies for the efficient development of digital transformation processes, as weak innovation strategies can be considered as a barrier (Lammers et al. 2019; Molinillo and Japutra 2017; Peansupap and Walker 2005; Sabri et al. 2018). Peansupap and Walker (2005) elaborate on issues of such a strategy that are critical for the adoption of information and communication technology, and especially emphasize management and employee issues. First, sufficient training and development should help users to understand the basics of applications they should use (Peansupap and Walker 2005). Second, from a psychological perspective, supervisor and organizational support is necessary to address the willingness of adopting new applications by role models. Lastly, reward systems motivating users in the adoption of applications in their work processes are of importance (Peansupap and Walker 2005). The above mentioned aspects depict the high significance of employee-focus.

The availability of industry-specific guidelines is another important aspect for a successful transformation of a supply chain and to have a clear vision of the implementation (Agrawal et al. 2020; Lammers et al. 2019; Preindl et al. 2020; Wu et al. 2016). Following guidelines can be challenging since most studies on DSC were conducted focussing on benefits. Frameworks and roadmaps on the adaption and implementation of a DSC in academia for specific industrial sectors are not yet available, even though they could provide helpful blueprints (Agrawal et al. 2020; Preindl et al. 2020). In such cases, joint efforts of business and IT are needed to formulate strategic plans to realize the transformation (Agrawal et al. 2020).

4.2 Preconditions in the Area of Organizational Digitalization in DSC

The organizational design of a company that is planning to transform its supply chain should be aligned according to Agrawal et al. (2020) for direct communication and sharing of data and information between different stakeholders. They argue that the DSC aims at enabling greater data transparency and synchronicity for the decision-making of stakeholders (Agrawal et al. 2020). Even though this can be considered as an important precondition within one organization, the same applies to inter-organizational collaboration within a supply chain, since accurate and timely sharing of such information

Table 2. Preconditions in the strategic digitalization area identified

Strategic precond.	Sources
Strategic orientation & business objectives	(Agrawal et al. 2020; Büyüközkan and Göçer 2018; Sabri et al. 2018; Wang et al. 2015; Xu 2014)
Innovation strategies	(Lammers et al. 2019; Molinillo and Japutra 2017; Peansupap and Walker 2005; Sabri et al. 2018)
Industry-specific guidelines	(Agrawal et al. 2020; Lammers et al. 2019; Preindl et al. 2020; Wu et al. 2016)

might enhance demand forecasting by suppliers or retailers in providing products and services on time (Rajaguru and Matanda 2019; Wu et al. 2016). Thus, Agrawal et al. (2020) identify the organizational structure for a digital transformation of a supply chain to be agile, integrated, innovative, and adaptive to allow a transparent flow of information serving the sharing of knowledge and learning, collaboration, and decision-making.

The development of a suitable organizational culture plays a significant role when addressing the changes needed for a digital transformation of a supply chain and highlights the human-related factors. One aspect is the innovation culture, which relates to the constant attention for improvement potential in products, strategies, and processes (Hjalmarsson et al. 2014). In case such an innovation culture is unsupportive, it is mentioned as an obstacle to introducing innovations (Hjalmarsson et al. 2014; Lammers et al. 2019). Additionally, this kind of culture requires an environment of open discussion, e.g., among employees, supporting new ideas and improvement suggestions. Other crucial aspects are time spent on planning (Lammers et al. 2019) or the readiness to take risks (Agrawal et al. 2020).

Another important precondition mentioned in the literature is knowledge management (Büyüközkan and Göçer 2018; Campos Martins and Simon 2018; Lammers et al. 2019). Employees need to possess a certain set of knowledge, skills, and attributes required to use digital applications in supply chains (Janssen et al. 2013). Companies require personnel to be able to implement the digital innovation beforehand, e.g., data scientists, who are often missing (Lammers et al. 2019).

Table 3. Preconditions in the organizational digitalization area identified

Organizational precond.	Sources
Organizational design	(Agrawal et al. 2020; Rajaguru and Matanda 2019; Wu et al. 2016)
Organizational culture	(Agrawal et al. 2020; Hjalmarsson et al. 2014; Kaner 2014; Lammers et al. 2019)
Knowledge management	(Büyüközkan and Göçer 2018; Campos Martins and Simon 2018; Janssen et al. 2013; Lammers et al. 2019)

4.3 Challenges in the Area of Process & Method Digitalization in DSC

The most prominent challenges in the area of processes & methods in the selected literature relate to a lack of standards, guidelines, and frameworks to support the digital transformation in supply chains. Having no guidance or best practices to refer to can complicate making the right decisions. Furthermore, not knowing what to transform first and where to start such an elaborate process is a barrier (Agrawal et al. 2020). It also makes the planning of such projects more complicated and prone to errors (Büyüközkan and Göçer 2018). This can cause mistakes and inefficiencies, which can consume many resources. Problems like this could be avoided when having industry-specific guidelines based on past experiences and studies to give directions and recommendations to facilitate the digital transformation. Further studies should therefore focus on creating standards, guidelines, and frameworks to overcome this challenge (Ghadge et al. 2020). At the same time, practitioners should also be aware of already available supporting measures and consider their benefits for their company (Zangiacomi et al. 2018).

Other obstacles are collaboration and coordination difficulties. Being an extensive and far-reaching process affecting many entities, the complexity of the coordination between the actors of the supply chain becomes more demanding. This is especially the case for cross-channel logistics (Ivanov et al. 2019). In addition, insufficient or too little collaboration between actors can lead to issues like inconsistencies or misalignments when implementing new technologies that have an influence on different systems and infrastructures. As a result, effective collaboration and coordination between those involved becomes imperative, and their capabilities should be leveraged for collective value creation (Lavikka et al. 2017).

Furthermore, the complexity of underlying processes, structures, and networks is also identified as a challenge. The digital transformation can require radical changes to the supply chain, its structures, and the processes of an organization (Ivanov et al. 2019). As this involves many business processes that can be extensive, involve many stakeholders, and might not always be well documented, their transformation can be hampered. This is further underlined by the multitude of actors in a supply chain and the underlying complex networks (Ghadge et al. 2020), as well as through the differences within an organization and its various projects (Anand and Krishna 2019). Due to this complexity, it becomes increasingly challenging to standardize different processes and synchronize the IT systems of those involved in the transformation (Cichosz et al. 2020). It emphasizes the need for efficient collaboration as well as structured guidelines to support the transformation.

The last challenge of process & methods relates to a lack of flexibility of processes, referring to the ability to adapt the processes to changes. When this is not the case, and the processes of an organization do not have the required agility, performing a digital transformation associated with a lot of change will be difficult (Büyüközkan and Göçer 2018). Business processes need to be adjustable and configurable to perform well (Agrawal et al. 2020).

4.4 Challenges in the Area of Technological Digitalization in DSC

Challenges relating to technology competence and the qualification of employees have a high occurrence in the selected literature. In general, the development of employee skills

Table 4. Challenges in the process & method digitalization area identified

Process & method chall.	Sources
Lack of standards, guidelines, and frameworks	(Agrawal and Narain 2018; Büyüközkan and Göçer 2018; Ghadge et al. 2020; Horváth and Szabó 2019; Lammers et al. 2019; Raj et al. 2020; Zangiacomi et al. 2019)
Collaboration and coordination difficulties	(Agrawal and Narain 2018; Büyüközkan and Göçer 2018; Ghadge et al. 2020; Ivanov et al. 2019; Lammers et al. 2019; Lavikka et al. 2017)
Complexity of underlying processes, structures, networks	(Agrawal and Narain 2018; Anand and Krishna 2019; Cichosz et al. 2020; Ghadge et al. 2020; Ivanov et al. 2019)
Lack of flexibility of processes	(Agrawal et al. 2020; Agrawal and Narain 2018; Büyüközkan and Göçer 2018)

is assigned to the organizational area of digital transformation. However, the employees' technical knowledge is crucial for providing a technical foundation and performing the transformation. Studies show that digital skills among employees are often scarce (Hoberg et al. 2017). A lack of necessary skills and qualifications is a major obstacle and can heavily stall the digital transformation (Agrawal et al. 2020). Enterprises should invest in staff training and acquire new personnel to address this vital challenge (Bienhaus and Haddud 2018). Nevertheless, this requires them to recognize the importance of developing the necessary technical competence, as well as to promote the sharing of knowledge and best practices among employees (Zangiacomi et al. 2018). In addition, it is challenging to determine how much staff and training in which specific areas is required (Schlaepfer and Koch 2015).

Obstacles addressing financial issues are frequently covered in the selected literature. The digital transformation requires large investments in new technologies, innovations, digital tools, and equipment (Lammers et al. 2019). Implementing and maintaining technologies is essential for the transformation but associated with high costs (Agrawal et al. 2020). Furthermore, it can be difficult to evaluate the financial merit of such investments (Raj et al. 2020). This can be seen as a barrier, but organizations should not disregard the long-term benefits. The selection of the right technologies and solutions in terms of their return on investments and the business needs of the respective enterprise is essential. For this purpose, a clear strategy for shaping investments should be developed (Zangiacomi et al. 2018).

IT security and data privacy issues are identified as one of the most critical challenges of technological digitalization in supply chains. As more devices become digitally connected and more information is shared between companies, cybersecurity risks will rise dramatically (Agrawal et al. 2020). Besides, as businesses become increasingly dependent on the various networked information systems, their smooth and proper functioning becomes more critical as well. Viruses and cyber-attacks can disrupt networked systems and cause downtime and enormous costs (Schlaepfer and Koch 2015). Incidents like unauthorized access or data breaches can lead to lawsuits and losing customers (Cichosz et al. 2020).

Another category of challenges relates to building a proper IT infrastructure. The digital transformation requires a solid technological foundation to build on, e.g., broadband infrastructure. Furthermore, new systems need to be integrated, and existing systems need to be adjusted. Studies show that many companies are lacking behind regarding this aspect (Schlaepfer and Koch 2015). Establishing a software architecture and platforms that can collect and utilize data to manage and operate the supply chain can be challenging (Büyüközkan and Göçer 2018). Large volumes of storage capacity are necessary, and problems such as a lack of uniform communication protocols or back-end integration systems can further obstruct this process (Horváth and Szabó 2019). This also relates to some of the other challenges. Large investments are needed for the realization of a solid IT infrastructure, and digital skills, proper collaboration, and supporting guidelines are important.

Information and data management is also associated with obstacles. Underlined by the multitude of different actors and projects in a supply chain, a variety of valuable information accumulates. Yet, much of this information is lost and not stored for future reuse (Anand and Krishna 2019). At the same time, large amounts of data are generated through multiple interconnected information systems. Managing these volumes of data can be demanding (Schlaepfer and Koch 2015). It is accumulated from different sources, while its accuracy and quality has to be ensured (Büyüközkan and Göçer 2018; Raj et al. 2020). To address these challenges and problems, organizations should establish information and knowledge management systems, as well as data warehouses and database management systems.

Barriers regarding the selection and adoption of the right technologies can be perceived as a hindrance as well. The digital transformation requires companies to implement new technologies (Bienhaus and Haddud 2018). However, recognizing, selecting, and adopting the best technology at the right time can be challenging (Cichosz et al. 2020). In addition, long-term ambiguities about legislative and regulatory requirements can further complicate matters (Hackius and Petersen 2020). Related to investment obstacles, selecting new technologies can also be difficult if their economic benefit cannot be accurately determined (Raj et al. 2020). Consequently, enterprises need to consider new technologies and identify which ones they should focus on based on their business needs (Zangiacomi et al. 2018).

The final challenge identified is related to the newness and immaturity of technologies. This concerns usability barriers due to selected technologies being novel and unsophisticated (Hackius and Petersen 2020). Resulting constraints in terms of security or interoperability can cause problems for the organization (Peraković et al. 2020). Such aspects should not be overlooked and taken into account when selecting and adopting new technologies.

5 Expert Interviews

In the following, two interviews are conducted to capture the expertise and opinion of the practitioners and depict them in a basic, measurable form. They are asked to allocate the

Table 5. Challenges in the technological digitalization area identified

Technological chall.	Sources
Technology competence and employee qualification	(Agrawal et al. 2020; Anand and Krishna 2019; Bienhaus and Haddud 2018; Büyüközkan and Göçer 2018; Cichosz et al. 2020; Dougados and Felgendreher 2016; Ghadge et al. 2020; Herceg et al. 2020; Horváth and Szabó 2019; Ivanov et al. 2019; Lammers et al. 2019; Pessot et al. 2021; Raj et al. 2020; Schlaepfer and Koch 2015; Sundaram et al. 2020; Zangiacomi et al. 2019)
Financial issues	(Agrawal et al. 2020; Anand and Krishna 2019; Cichosz et al. 2020; Ghadge et al. 2020; Herceg et al. 2020; Horváth and Szabó 2019; Ivanov et al. 2019; Lammers et al. 2019; Raj et al. 2020; Sundaram et al. 2020; Zangiacomi et al. 2018; Zangiacomi et al. 2019)
IT security and data privacy issues	(Agrawal et al. 2020; Bienhaus and Haddud 2018; Cichosz et al. 2020; Ghadge et al. 2020; Horváth and Szabó 2019; Ivanov et al. 2019; Lammers et al. 2019; Peraković et al. 2020; Raj et al. 2020; Schlaepfer and Koch 2015; Sundaram et al. 2020)
Establishing a proper IT infrastructure and foundation	(Büyüközkan and Göçer 2018; Ghadge et al. 2020; Horváth and Szabó 2019; Lammers et al. 2019; Raj et al. 2020; Schlaepfer and Koch 2015; Sundaram et al. 2020; Zangiacomi et al. 2019)
Difficulty and lack of information and data management	(Anand and Krishna 2019; Büyüközkan and Göçer 2018; Ghadge et al. 2020; Raj et al. 2020; Schlaepfer and Koch 2015; Sundaram et al. 2020)
Selecting and adopting the right technologies	(Bienhaus and Haddud 2018; Cichosz et al. 2020; Hackius and Petersen 2020; Raj et al. 2020; Zangiacomi et al. 2018; Zangiacomi et al. 2019)
Newness and immaturity of technologies	(Hackius and Petersen 2020; Peraković et al. 2020; Raj et al. 2020)

preconditions/challenges to two categories. Preconditions are divided into fundamental and supporting, and challenges into severe and moderate. Fundamental preconditions are argued to be indispensable to successfully transform the supply chain. Supporting conditions ease the transformation but can be counter-measured. This holds for challenges as well; severe challenges hinder the transformation process to a very high degree, while moderate challenges can be counter-acted more easily. This basic rating allows first insights into the topic. At the same time, the experts get the opportunity to explain their ratings, elucidating the perceived importance in a small-scale and explorative setting (cf. Figs. 2 and 3).

5.1 Expert Interviews on the Preconditions

The interviewees were asked to sort the preconditions aggregated from the literature into two categories. Not all literature distinguishes preconditions into categories and thus implies all preconditions to be fundamentally necessary. The interviewees classified the organizational design, industry-specific guidelines as well as the knowledge management as supporting conditions (see Fig. 2). They reasoned that the organizational design is quite important concerning inter-organizational communication and reported on projects like a web-based Electronic Data Interchange. However, they did not elaborate on intra-organizational design. They also recognized the benefits of their industry-specific guidelines to enable digital transformation. Still, they stated that those often cannot be used for the companies' operations and supply chain, as they are very specific and often not comparable with other manufacturers, e.g., guidelines coming from the VDA (German association of the automotive industry). Knowledge management was also categorized as a supporting precondition, often the innovation initiatives are started within the company, but human resources, especially from IT, are lacking. This problem can be countermeasured, and in such a case consultancies are engaged to provide those resources. The strategic orientation & business objectives are categorized as fundamental. The digital transformation strategy is placed very high at the company, and the interviewees referred to the annual report showing that both of their projects are driven and approved by the general initiatives on digital transformation. Innovation strategies are also a fundamental precondition since many instances of lacking change management made projects quite challenging. The same applies to the organizational culture, which was identified as a barrier and showstopper for initiating digital transformation projects. The interviewees emphasized for all of those three preconditions that those might be fundamental not only for supply chain-specific digital transformations but for all similar initiatives in different functions and areas.

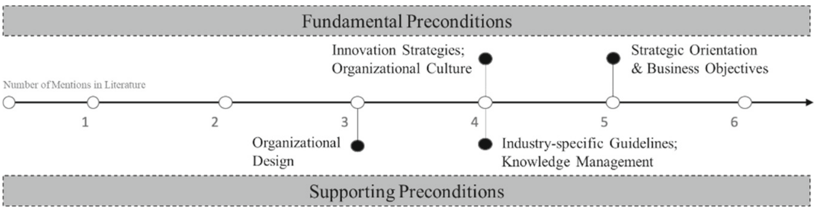

Fig. 2. Preconditions in literature and practitioner's assessment

5.2 Expert Interviews on the Challenges

Regarding the process & method challenges, five challenges are identified to be severe, while the remaining six challenges are perceived as moderate (Fig. 3). According to the interviewee, the complexity of underlying processes, structures, and networks is one of the most difficult challenges because processes are often not thoroughly understood and transformed without genuinely improving them. This indicates that the context of processes needs to be considered and understood to result in increased efficiency. A lack of flexibility of processes is also assessed as severe, while it is implied that the problem rather lies in people resisting change than in processes being inflexible. This strongly hints towards the connection to the organizational area of digitalization. Collaboration and coordination difficulties were ranked on the moderate level, as well as the lack of standards, guidelines, and frameworks. As an additional challenge, the difficulty of making change during ongoing operations is pointed out. This can hamper the digital transformation and associated efficiency gains, as old processes are often preserved in order to avoid risks such as business interruptions. Moreover, the problem of having multiple actors and interfaces in the supply chain and realizing the value of digitizing individual parts only when the entire process is digital is stressed by the interviewee. When asked for plans or strategies to approach the process & method challenges, the importance of proper change management and planning is brought forward. To recognize the inevitability of the digital transformation and to be open to change is key.

Moving to the technological challenges, financial issues are assessed as most challenging by the interviewee. The cause relates to the late amortization of added value of digitalization, the difficulty of estimating economic benefits of investments in advance and making the right assumptions. Also, this obstacle highly influences the other challenges. Technology competence and employee qualification are also evaluated as severe because of the overwhelming nature of new technologies when lacking the expertise to deal with them. The respective training is time-consuming and expensive, relating to financial issues again. The high pace of IT and the related continuous adoption to innovations were underlined as a crucial problem. IT security and data privacy issues are ranked as severe. The fast speed of new developments in IT leads to new legal requirements. The compliance of these can be laborious and hinder the optimization of processes. The establishment of a proper IT infrastructure is highly dependent on the previous challenges and is categorized as moderate, as well as the difficulty and lack of data management. It is pointed out that the company tries to introduce more AI-based technologies and that there is often a shortage of the proper mindset and strategy when it comes to data. Selecting and adopting the right technologies is considered moderate as well, besides the newness and immaturity of technologies. According to the expert, the company has always been able to solve obstacles associated with the immaturity of technologies as they have experienced software developers at their disposal.

6 Discussion of Results

In the literature, the occurrence of the different preconditions in the strategic as well as organizational area is relatively balanced. None of the identified sources in the literature include all preconditions. Most papers only refer to one of the preconditions identified

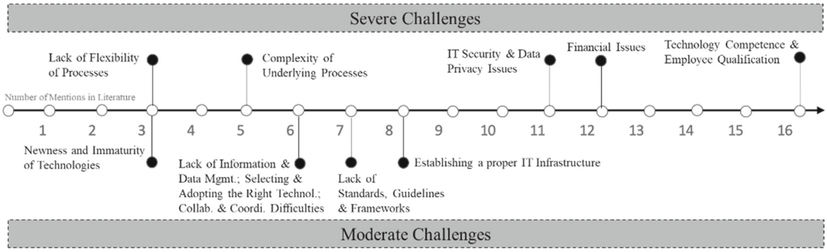

Fig. 3. Challenges in literature and practitioner's assessment

(Campos Martins and Simon 2018; Hjalmarsson et al. 2014; Janssen et al. 2013; Kaner 2014; Molinillo and Japutra 2017; Peansupap and Walker 2005; Preindl et al. 2020; Rajaguru and Matanda 2019; Wang et al. 2015; Xu 2014). For example, Janssen et al. (2013) conduct Delphi studies and define digital competence areas that are reflected in the knowledge management precondition. However, two sources include at least four of the six identified preconditions in their work, while only Agrawal et al. make an effort to rank them and analyze interrelations (Agrawal et al. 2020; Lammers et al. 2019). The expert interviews expand the seemingly relatively balanced importance of the preconditions and divide them into fundamental (three) and supporting (three) preconditions. This reveals an essential difference between academia and practice. The strategic orientation and business objectives as well as innovation strategies and organizational culture are ranked highest by the practitioners, which is in line with some transformation-related literature (Kane et al. 2015; Kohnke 2017). Yet, other authors argue that industry-specific guidelines are most important (Agrawal et al. 2020). By the experts in this study, this was only seen as supporting. To master the transformation, companies must include supply chain-related issues on the agenda and connect them to the overall strategy, even though strategies vary (Preindl et al. 2020).

Moving on to the challenges, the findings deviate regarding the two areas. In the process & methodological area, only one source includes all identified challenges but misses to thoroughly elaborate on the methodological aspects of the research conducted (Agrawal and Narain 2018). Other authors focused on barriers regarding Industry 4.0 and take into consideration other aspects, e.g., the influence of company size (Horváth and Szabó 2019). Discussion about the challenges of the process & methodological area with the practitioner shows that the assessment deviates from the findings in the literature. On the one hand, the lack of standards, guidelines, and frameworks is identified most frequently in the literature (c.f. Table 4). Authors like Raj et al. (2020) underline the high importance of standards. This challenge is followed by collaboration and coordination difficulties (c.f. Table 4). It is addressed by different authors focussing on digital technologies in supply chains and the ripple effect (Ivanov et al. 2019). On the other hand, the expert sorts both previously mentioned challenges in the moderate section. In contrast to the literature, he perceives the complexity of underlying processes, structures, and networks as most challenging. He describes one issue as follows: "*A common problem is that processes are not fully understood and then just digitized without improving them. If you simply digitize an inefficient process, you end up with an inefficient process that is digital*". In the technological area, it is striking that the evaluation of the practitioner seems almost equal to the importance in the literature (c.f. Table 5). Only the financial issues are rated as slightly more critical by the interviewee. However, some authors specifically point out the high importance of investments (Zangiacomi et al. 2019).

Comparing the different areas, the interviewee states that the process & method area can be seen as more challenging than the technological area altogether. The reason is that technological constraints can be overcome as long as sufficient monetary and time resources are available, which is not always the case with the other area. Furthermore, the interviewee noted that the main challenge of digital transformation rather lies in people than technology, which is a claim supported frequently in literature (Kane et al. 2015; Kohnke 2017). This hints towards the importance of the organizational area, evaluated in the first interview, and strengthens the call that all areas of the digital transformation should be considered simultaneously.

Regarding the implications for academia, this study gives first insights into preconditions and challenges connected to the digital transformation of supply chains. We hope to start an academic discussion, highlighting further research in the conclusion. For practitioners, the identified preconditions and challenges are first reference points to consider when planning transformation projects.

7 Conclusion

Regarding the first research question, preconditions and challenges of the digital transformation are identified in the literature. Three to seven preconditions/challenges are determined (c.f. Tables 2, 3, 4 and 5). The preconditions all have similar numbers of occurrences in literature. In contrast, some challenges stand out, being more noticeably present in literature. Regarding the second research question, the results from the literature are discussed with experts from industry. The experts sort the preconditions and challenges regarding the perceived importance in practice. Deviations but also similarities are uncovered and discussed.

However, some limitations of this work need to be taken into account leading to future research. First, the structure of DSC into four areas is preliminary and the current analysis is limited to the preconditions in two areas and the challenges in the remaining two. This could be extended including all four areas with preconditions and challenges, leading to interesting connections between them, e.g., when examining the challenges, many sources consider organizational and human-related factors, not in the scope of this paper. Second, regarding the literature review methodology, including more sources is beneficial. Currently, the results from the literature only represent an approximation of the actual relevance of the preconditions/challenges. Third, the insights from practice are liable to the subjectivity of the interviewees. The small number of interviews leads to a certain bias, and context-based argumentation can be brought forward, e.g., that guidelines and frameworks of similar industries often cannot be used to enable transformations. It would be necessary to discuss this with more experts from different companies. The focus of this study is small-scale and exploratory, and only two categories are introduced to rank the preconditions/challenges. Further research could apply more elaborated measuring criteria, with a greater number of participants, to assess the perceived impact of the different preconditions/challenges more accurately. Prioritizing the various options can lead to a roadmap, highlighting what should be tackled first.

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Digitalization's Effects on Transport Planning and Specifically the Transport Coordinator's Role

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Abstract. Road freight transport has become a vital part of today's life, and its importance will only rise in the future due to developments such as increasing e-commerce orders. Transport planning has become more complex and has to deal with many difficulties such as demand volatility, high customer expectations, or the consideration of legal regulations. The fast-changing environment makes dynamic and highly reactive planning, typically done by the transport coordinator, necessary. Incorporating technology is a promising way to deal with the complexity and dynamic environment of transport planning. Indeed, more data and computing power is available than ever before, and developments coined under "digitalization" are transforming transport planning. Before understanding the benefits digitalization can have, examining its influences on the industry, the roles participating in transport planning, and their relationship is necessary. Hence, this paper establishes an overview of roles associated with transport planning, identifies digitalization's effects on transport planning and specifically the transport coordinator, and then provides an updated overview of roles considering these effects. The results show that new relations and roles are important for transport planning. The role of the transport coordinator itself is transformed mainly due to the emergence of platform-based business models.

1 Introduction

The importance of freight transport, i.e., the movement of goods from a starting area to a destination area, is ever increasing. In 2017, more than 1.9 billion tonne-kilometers were reached only within the EU. More than 70% can be attributed to road freight transport, making it the most used transport mode for inland transport (eurostat 2018). While the transport volume, in general, is continuously growing due to, e.g., globalization and increasing e-commerce orders, especially the share of less-than-truckload road transport, i.e., the transportation of goods, which do not fill a complete truck, is rising (Ridouane et al. 2020). Moreover, road transport is and most likely will be favored over other transport means due to the demand for fast and flexible delivery as well as direct access to customers. Compared to other transport modes, road transport exhibits some characteristic features that influence all activities of the industry. Routing is more flexible due to a ramified road infrastructure, less than truckload deliveries are very common, a wide range of products are suitable for road transport and lead as well as delivery times are

U. Buscher et al. (Eds.): *Logistics Management*, LNLO, pp. 33–48, 2021.
https://doi.org/10.1007/978-3-030-85843-8_3

typically shorter than for other transport modes (Günther and Seiler 2009; Ivanov et al. 2017). The whole road freight transport industry faces numerous challenges. Prevailing business conditions like demand volatility, high customer expectations with regard to delivery speed, and shorter product life cycles require changes in transport planning and management. Additionally, the industry has to deal with numerous legal regulations regarding environmental aspects, working hours, or data protection, as well as internal challenges such as rising transport costs, driver shortage, or cumbersome business processes (Günther and Seiler 2009; Holcomb et al. 2014; Ji-Hyland and Allen 2020; Liachovičius and Skrickij 2020).

All of the mentioned challenges and influences need to be considered in particular when planning road freight transports. Usually, planning is done by a central role, the transport coordinator, responsible for creating transport plans and coordinating transports. A transport plan sets the ground for a successful transport execution, and the transport coordinator needs to pay attention to given circumstances such as regulations, infrastructure, or available resources. Moreover, planning has to be done under high time pressure (Seiler 2012). Due to more aggressive service promises and a highly competitive environment, there is an increasing freight demand, including high day-to-day freight volume fluctuations, which puts pressure on the transport coordinator's operational planning (Ridouane et al. 2020). Every day, a huge number of transport orders have to be processed, routes to be planned, and drivers to be assigned to trucks as well as trucks to routes. In addition, external influences, such as the current traffic situation or weather, and uncertainty, such as sudden changes in the traffic situation due to accidents, can change the setting and lead to the need to update a transport plan in real-time. Hence, there is a need for transport coordinators to improve their operational and real-time planning capabilities to consider all influences (Ridouane et al. 2020; Sigakova et al. 2015; Stank and Goldsby 2000).

One promising possibility to do so is the use of new and emerging technology. Incorporating technology has always been used to improve planning processes regarding visibility, speed, and dependability (Belvedere and Grando 2017). However, recently, new technological innovations are developed and made available to the industry faster. Technological innovations change how business is done or create entirely new business models. Their use is subsumed under the term "digitalization", which seems to be a valuable opportunity for transport coordinators. The *27th Annual Study of Logistics and Transportation Trends* shows that the vast majority of respondents agreed with the statement: "Being a digital business is important to the success of my company" (Schaefer et al. 2018). There is an increasing availability of computing power and data, e.g., via GPS or sensor data, in the road freight transport industry. Therefore, transport coordinators could make use of these resources and apply new technologies such as artificial intelligence to create efficient transport plans considering all relevant influences and, in general, improve their operational and real-time transport planning (Barua et al. 2020; Ridouane et al. 2020; Schaefer et al. 2018).

Overall, the digitalization of road freight transport changes processes and allows for new business models. Therefore, it also influences the transport coordinator's interactions during transport planning. To reap the promised benefits of using new technologies, it first must get clear where and how the transport coordinator can apply them. There is currently a lack of understanding of emerging technology's influences on the industry, in general, and on the central role of the transport coordinator and its task of transport planning specifically (Barua et al. 2020; Belvedere and Grando 2017; Liachovičius and Skrickij 2020; Pernestål et al. 2021).

This paper wants to provide a first step towards addressing this lack of understanding. It examines the influences digitalization has on the transport coordinator's role and its relationship to other industry roles, specifically when creating transport plans that are the basis for the actual transport execution. The following three research questions (RQ) are addressed:

1. What are typical roles in the road freight transport industry relevant for operational and real-time transport planning, and what is their relation to the transport coordinator?
2. Which effects does digitalization have on operational and real-time road freight transport planning?
3. How do digitalization's effects on operational and real-time road freight transport planning change the transport coordinator role and its relationships to other roles?

The following section synthesizes existing literature to answer RQ1 and creates a framework picturing roles in road freight transport and their relation to the transport coordinator. Then, the methodology to answer RQ2 and 3 – based on the results of RQ1 – is described. The results are presented in the following two sections: First, it is examined how digitalization influences transport planning and the transport coordinator. Second, the picture of roles and their relationships is updated accordingly. The paper closes with a conclusion summarizing the main results, highlighting limitations and future research options.

2 Roles in Road Freight Transport

Freight transport aims to "bridge the distances between spatially separated places of supply and demand" (Tavasszy and Jong 2014). Goods can be transported using various means grouped into road, rail, air, inland waterways, and sea. Indeed, the choice of a suitable transport mode or problems of inter-modal transport are the most researched decision problems within transport management (Günther and Seiler 2009; Tavasszy and Jong 2014). Different roles are relevant for transporting freight via roads. The differentiation between a company and its role is essential. On the one side, a company can act as more than one role, and on the other side, one role can be fulfilled by more than one company. Consequently, there is an n:n-relationship between companies and roles.

Various authors have discussed those roles, their responsibilities and found different names and definitions for them. However, there are evident similarities, and Table 1 shows how different labels can be aligned.

As stated in the introduction, this paper focuses on the central role *Transport coordinator* and its task of transport planning. This process is based on transport orders that provide relevant information about the transport to be conducted. They are typically received from *consignors* or *consignees*, i.e., whenever something needs to be shipped

Table 1. Overview of roles' and their names in scientific literature

	Consignor	Consignee	Transport operator	Transport coordinator	Facility & infrastructure provider	Authorities
Bäumler and Kotzab (2016)	Shipper	Receiver	Transport company, driver	Traffic control center	Systems provider	Public authorities
Crainic et al. (2018)	Shipper	Customer	Carrier	Freight logistic provider	Facility & Infrastructure Manager	Institutional Authorities
Holmgren et al. (2012)	Producer, transport buyer	Customer, transport buyer	[actor on physical level]	Transport chain coordinator, transport planner	-	-
Ramstedt and Woxenius (2006)	Consignor	Consignee	Transport operator	Transport coordinator	Terminal operator, supporting actors	-
Schroeder et al. (2012)	Sender	Recipient	Carrier	Transport service provider	-	-
Seiler (2012)	Sender	Receiver	Carrier	Shipper	-	-
Wang et al. (2007)	Shipper	Customer	Carrier	Shipper or carrier (organizational unit)	Technology & financial service provider	-

from a consignor to a consignee, both can send the order to the coordinator (Crainic 2000; Seiler 2012). The transport coordinator then creates a transport plan, also referred to as an operational or load plan, that includes all relevant information about the transport such as loads, routes, departure and arrival times, or possibly (de-)consolidation points (Crainic 2000; Ramstedt and Woxenius 2006). The transport plan has to oblige to existing regulations posed by *Authorities* and included routes and time schedules have to consider infrastructure such as roads or terminals provided and managed by *Facility & Infrastructure Providers* (Bäumler and Kotzab 2016; Crainic et al. 2018; Ramstedt and Woxenius 2006). The coordinator can then decide to operate the transport itself (acting as coordinator and operator as often done by third-party logistics providers) or to hire a transport operator (as in the case of a freight forwarder contracting a carrier to conduct the transport) (Ramstedt and Woxenius 2006; Seiler 2012).

Figure 1 provides a simplified overview of the roles and their central relations. For ease of representation, the figure only displays the transport coordinator's relationships during transport planning. Relationships between roles other than the coordinator are not depicted in Fig. 1.

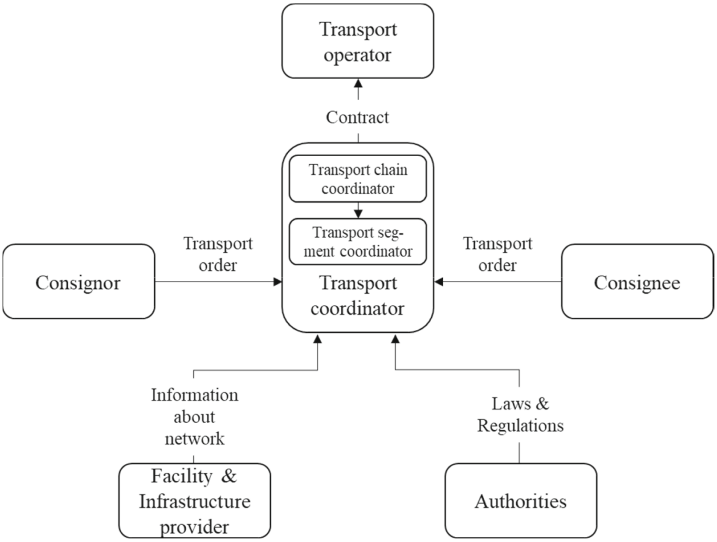

Fig. 1. Overview of roles and relationships in road freight transport from the transport coordinator's point of view

It is essential to notice that a transport coordinator typically does not process a single transport order into a single transport plan. Instead, multiple transports are planned simultaneously, using terminals for (de-) consolidation and contracting various transport operators to carry out transport segments (Crainic 2000; Ramstedt and Woxenius 2006; Schroeder et al. 2012). This makes a hierarchical division of the transport coordinator role necessary, as also proposed by Holmgren et al. (2012) and Ramstedt (2008). Companies can hire a *transport chain coordinator* and assign responsibility for their whole transport chain to them. The *transport chain coordinator* can then separate the transport chain into segments (e.g., based on regions or countries) and hire other *transport segment coordinators*. This leads to the establishment of a hierarchical relationship within the transport coordinator role. A possible scenario is, for example, that a fourth party logistics provider takes care of a global manufacturer's whole distribution network and contracts a third-party logistics provider to coordinate transports within a specific country (cf. for example, Hsiao et al. (2010) for more information on fourth and third-party logistics providers and their covered services). It has to be noticed that it is possible to have both a transport chain and segment coordinator or only one of them. The existence of roles always depends on the viewpoint of definition and the considered scenario.

Due to the increased volume to be transported and the rising customer expectations – as described in the introduction – requirements for the transport coordinator have changed during the last years. These changes re-shape the transport coordinator's role, the relationship to other roles and may also lead to the emergence of entirely new roles. Hence, this paper aims at uncovering those changes and provide an updated overview of roles and relationships.

3 Methodology

RQ1 could already be answered in the former section by synthesizing existing literature and deriving typical roles and their relationship to the transport planner resp. coordinator. Methodology-wise, it has to be mentioned that in addition to the sources presented in Table 1 to establish the roles' overview, further publications have been used to evaluate the developed scheme. Both scientific papers and reports published by practitioners confirmed the derived roles, and hence it was safe to assume that the set of roles presented in Table 1 and Fig. 1 is complete.

To answer RQ2 and 3, i.e., to identify digitalization's effects on operational transport planning and their consequences on the transport coordinator's role, a multi-vocal literature review (MLR) has been conducted as proposed by Garousi et al. (2019). In general, literature reviews are a suitable tool to identify existing knowledge on a topic (Thomé et al. 2016). Hence, it is chosen to provide a structured overview of how digitalization affects transport planning and how far these effects are addressed in the literature. The main feature distinguishing an MLR from a structured literature review is the additional consideration of grey literature. Hence, an MLR provides a structured way to gain insights both from scientific and practice-oriented literature. Especially concerning technological trends, some consultancies and more prominent companies are well-known for conducting studies or publishing reports. These publications are a valuable source for gathering a broader picture of digitalization's effects on road freight transport (Garousi et al. 2019). While other research methods such as expert interviews or case studies might deliver more in-depth information, an MLR is suitable as a first step to examine the topic at hand and synthesize what is already known and discussed in the literature. Garousi et al. (2019) propose five phases to conduct an MLR: (1) Search process, (2) Source selection, (3) Study quality assessment, (4) Data extraction, and (5) Data synthesis.

(1) Search process: The search process was divided into (1a) searching for scientific literature, i.e., white literature, and (1b) searching for grey literature. Scopus was used as one of the largest scientific databases during phase 1a to search for "digital* AND road AND transport* AND (freight OR product* OR goods OR item OR commodit*)" in the title, abstract, and keywords. Only results published in 2017 or later were considered to ensure a very recent picture of the influence of digitalization. The search resulted in 117 hits. A similar search was then conducted in the standard Google search engine to conduct phase 1b and look for grey literature. Here, a different search term "*digitalization AND road freight transport AND filetype:pdf*" was used for two reasons: (1) restricting the filetype to PDF excluded blog entries or similar, leading to hits that were mainly white papers, studies, and reports relevant to the topic (cf. Garousi et al. (2019) for a discussion on different reliability levels of grey literature) and (2) the search term used in Scopus did mainly yield links to scientific sources. Industry uses slightly different terms to describe the same phenomena, and hence the search term was adapted accordingly. The search resulted in roughly 138.000 hits. As it is impossible to review all hits due to time and resource constraints, Garousi et al. (2019) propose different criteria to decide when to stop the search. Our search combined the criterion of theoretical saturation with the bounded effort one. We looked at the top results until at least 20 did not provide additional insights. This has led to an examination of the first 130 results, and the search was stopped at that point. While the stopping criteria still do not entirely eliminate subjectivity, theoretical saturation is a good way to identify relevant information while keeping the effort manageable. Since search results are sorted according to relevancy, it is unlikely that there will be a hit with completely new information sorted after 20 irrelevant ones.

(2) Source selection and (3) study quality assessment: During the second and third phase, the abstract of all hits for white and the first pages of all hits for grey literature were examined to decide whether they are relevant for this paper's objectives. For white literature, 22 out of 117 hits were regarded as relevant after reviewing their abstract. After a full-text review, six additional sources were excluded, leading to a set of 16 papers for further examination. Excluded sources either focused on other transport modes, did not discuss digitalization in relation to transport planning, or examined public transport. The same exclusion criteria as before have been applied to the investigated hits of the Google search. In addition, pure advertisements or product presentations, presentation slides, and scientific sources were excluded. A first rough scan led to 13 relevant results. This number was reduced to 8 pieces of grey literature after a more in-depth look into the content and quality of each publication. So overall, the set for investigation consists of 24 publications, 16 from white and eight from grey literature, which contain relevant content and exhibit high quality. Table 2 provides an overview of the so-far-described phases.

Table 2. Overview of the search process, source selection, and quality assessment

	White literature	Grey literature
Search engine	Scopus	Google
Search term	Digital* AND road AND transport* AND (freight OR product* OR goods OR item OR commodity*)	Digitalization AND road freight transport AND filetype:pdf
Search results	117 publications	Reviewed first 130 of about 138.000 hits due to theoretical saturation
Exclusion criteria	Focus on other transport modes; examination of public transport; no discussion of digitalization concerning transport planning	
		Scientific source; advertisement or product presentation; presentation slides
Abstract review	22 remaining publications	13 remaining publications
Full-text review	16 remaining publications	8 remaining publications
Final set	24 publications	

(4) Data extraction and (5) data synthesis: Each source is reviewed during the data extraction phase, and all information relevant to answering the RQs is extracted. We have read all publications in detail and extracted which effects of digitalization they analyzed and how they describe the impacts on road freight transport planning. The gathered insights were then put into categories to provide a data synthesis. As there is no suitable overview existing so far, the categories have been defined inductively according to Mayring (2000) based on the information extracted from the papers. Hence, the categories were built and adapted during data extraction. At the end of the category definition, each category encompasses a specific effect of digitalization and contains all relevant information provided by the identified publications. Instead of separating digital developments according to their content (e.g., autonomous driving), the categories group them according to their influence on the transport coordinator role (e.g., new data sources). Based on the categories' content, RQ3 is answered. It is examined and discussed how the impacts influence and change the transport coordinator's role and relationships to other roles.

4 Digitalization's Effects on Transport Planning

The identified scientific and grey literature was analyzed regarding their description of digitalization's effects on transport planning. Especially the number of scientific sources was lower than expected. Additionally, it became apparent that research papers typically discuss a particular issue and barely view digitalization's effects from a broader standpoint. Pernestål et al. (2021) have noticed the same and constitute an exception in that they discuss various possible effects of digitalization. Following their idea, this paper aims at considering various aspects of digitalization instead of focusing in-depth on a specific one. These effects include "for example the use of digitized data, connected vehicles, and automated driving" (Pernestål et al. 2021). Grey literature tends to go along with this view and discusses digitalization's effects from a broader perspective. The focus is often put on the emergence of new business models and how they change the industry (e.g., Baron et al. (2017) or Schönberg et al. (2020)). Despite the different levels of detail in scientific and grey literature, digitalization's effects on road freight transport planning could be extracted from all identified papers and then be summarized in categories according to their influence on transport planning. Each category is shortly described concerning which effects of digitalization they encompass and how this affects the roles in transport planning and their relation to the transport coordinator. The following section then subsumes these effects in an updated framework depicting the changing roles and relations.

4.1 New and More Data Sources

All sources agree on the fact that aspects such as increased and cheaper storage capacities as well as emerging technologies such as connected cars or increased tracking and tracing lead to the availability of more data (e.g., Federal Ministery of Transport and Digital Infrastructure (2019), Ghosh et al. (2018) or Heistermann et al. (2017)). For transport planning, this means that more and new data sources can and need to be considered when designing a transport plan. Data can either be collected internally or acquired from external data providers. Examples are movement data, weather data, or detailed information about the road network and its status (Federal Ministery of Transport and Digital Infrastructure 2019; Ghosh et al. 2018; Schröder and Cabral 2019). Other sources even base planning on a completely digital model of the road network (Komiya et al. 2019; Korhonen et al. 2017).

In summary, using more data for transport planning can be beneficial, and it can either be collected and stored internally or acquired from external sources. Consequently, the new role of "Data provider" becomes relevant for transport planning.

4.2 New Laws and Regulations

On the one hand, digitalization allows for innovations that need to be regulated before implementation. The most famous examples with regards to road freight transport are truck platooning (Seidenova et al. 2020), autonomous driving (Engholm et al. 2020), or electric vehicles (IRU 2018; Nicolaides et al. 2019). While the technology might be (almost) ready for implementation, various legal aspects, such as liability issues, need to be clarified. On the other hand, digitalization offers new possibilities to set and monitor new regulations. Examples that literature thinks about are kilometer-based taxes (Pernestål et al. 2021) or the smart tachograph to avoid breaching driving hour regulations (Baldini et al. 2018).

Once new regulations have been established, a transport coordinator's relation to authorities is affected. New regulations need to be considered just as maximum driving hours or similar today.

4.3 New and Digital Infrastructure

Two significant influences affect the infrastructure. First, the development and increased use of electric vehicles require establishing a new charging infrastructure (Nicolaides et al. 2019). When incorporating electric freight vehicles, a transport coordinator also needs to schedule charging times and places. Information about these can be acquired from according infrastructure providers. Second, digital infrastructure and its providers become more relevant to freight transport planning, resulting in adding them as a new role. Increased data exchange is only possible via gigabit networks (Federal Ministery of Transport and Digital Infrastructure 2019). Cloud providers offer the infrastructure to analyze the data and use high processing power for complex and powerful algorithms (Baron et al. 2017).

Transport coordinators will rely on this new and digital infrastructure to process more data, analyze it faster and more in-depth to create more efficient transport plans.

4.4 New Software or Service Providers

Apart from new actors providing data or digital infrastructure, new software or service providers will also play an essential role in transport planning. Providers will offer new and advanced fleet or transport management systems to enhance transport planning (Riedl et al. 2018; Schönberg et al. 2020). Many providers are expected to provide their software as a service (SaaS) (Graser et al. 2017). Such services could encompass advanced analytics capabilities (Schönberg et al. 2020) or blockchain-based solutions such as smart contracts (Federal Ministery of Transport and Digital Infrastructure 2019).

Transport coordinators can use the offered services to outsource specific transport planning tasks such as calculating optimal routes or performance measurement. Additionally, the provided software and services can increase the efficiency and transparency of transport planning.

4.5 Platform-Based Business Models

One of the most discussed effects of digitalization is the emergence of platform-based business models, which especially grey literature addresses. Simply said, platforms provide a basis for transport buyers and sellers to interact digitally and engage in business (Jain et al. 2020). Currently, platforms focus on the non-contracted business segment, i.e., are a digital version of the spot market. However, the related business models are expected to threaten and fundamentally change the business models of classical freight forwarders or logistics service providers (LSP) (Baron et al. 2017; Graser et al. 2017). There are different names for and manifestations of such business models: freight transport exchanges (Jain et al. 2020), digital freight forwarders (Jain et al. 2020), digital freight exchanges (Baron et al. 2017), freight exchange platform (Schönberg et al. 2020) or digital connectors (Hentschel et al. 2019). While slight differences among those are discussed, mainly revolving around whether a provider owns assets or regarding the offered services and functionalities, a clear distinction cannot be made so far (Jain et al. 2020). Hence, all platform-based business models are joined in this category.

Typically, transport coordinators act as buyers on platforms and use them to contract transport operators, who offer their free capacities (Jain et al. 2020). However, platforms may also offer matchmaking algorithms or other additional services that allow direct interaction, tendering, and contracting between transport buyer and seller. In such a case, a platform can also – at least partly – take over the role of a transport coordinator. However, so far, industry-specific characteristics impede the broader expansion of platform models and the obsolescence of traditional freight forwarders and LSPs (Hentschel et al. 2019). Nonetheless, the literature highlights the importance of platform-based business models. Primarily grey literature discusses successful examples of new market entrants, and established companies have also started to offer their own platform solutions (e.g., Schönberg et al. 2020).

In summary, two main effects on transport planning result from platform-based business models: (1) Transport coordinators can use platforms to interact with mainly transport operators, and (2) platforms and their offered functionalities can be used as a substitute for a transport coordinator.

5 Digitalization's Influence on the Transport Coordinator

Based on digitalization's effects on transport planning, which are described and categorized in the section before, it becomes clear that the overview of roles and their relationship to the transport coordinator must be updated. There are new roles like the data provider and changed relationships, such as providing more or different information about the network (e.g., electric freight vehicle utilization). Moreover, when looking at the transport coordinator's role, platform-based business models need to be considered. Hence, Fig. 2 provides an update to the first figure and depicts the new roles and relationships of road freight transport, including all the afore-discussed digitalization effects. There are some roles and relationships that are not directly affected by digitalization and remain the same. While, e.g., the interaction between a transport coordinator and a consignee might become digital or use different IT systems, the goal of this relationship stays the same: sending transport orders. Hence, such relationships can be considered unchanged and are depicted as light grey in Fig. 2.

Two of the effects, namely *New laws & regulations* and *new infrastructure*, are only indirectly visible in the overview of Fig. 2. They do not lead to the addition of new roles or relationships, but they change the already existing connection between *Facility & Infrastructure provider* and *Transport coordinator* as well as *Authorities* and *Transport coordinator*. As elaborated before, the emergence of e-vehicles or truck platooning leads to a new infrastructure that needs to be considered when planning transports. Hence, the information about the existing network stemming from *facility and infrastructure providers* changes accordingly and incorporates new infrastructure information. Similarly, authorities will provide information about new *laws & regulations* that are passed regarding digital technologies, innovations, and alike.

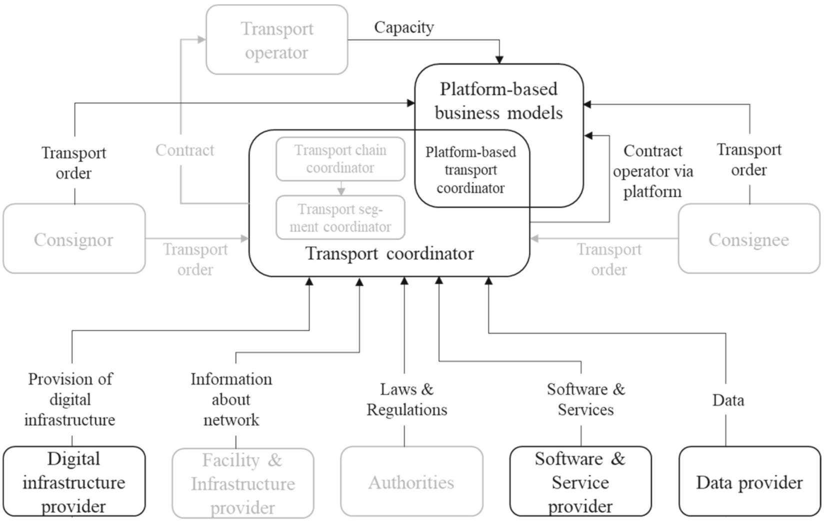

Fig. 2. Updated overview of roles and relationships in road freight transport from the transport coordinator's point of view (unchanged roles and relationships are depicted in light grey)

Apart from changing existing roles' relationships, digitalization also leads to the need to consider additional roles: *digital infrastructure provider*, *software & service provider,* and *data provider*. While transport coordinators have used software and data before, digitalization has led to a new way of using them and creates new value associated with data and resulting insights. Data is now generated and stored internally and bought from external sources, leading to the additional data provider role. This role can be occupied both by external data providers and internal departments or similar.

Transport planning and the necessary data analysis now often require higher processing power, and while assets such as new servers can be bought, digital infrastructure such as cloud solutions or web services will often be rented and used. The new role of a *digital infrastructure provider* supplies such infrastructure. Finally, some planning process steps and data analytics tasks can be outsourced to a dedicated *software & service provider*. Such providers might offer specific software or algorithms that help prepare and process data or even take care of whole planning or analysis steps and provide this service to transport coordinators. In general, all three new roles can be affiliated to the increasing availability, significance, and value of data, which strongly influences the transport planning process. It has become necessary to incorporate more data to gain better results. Often transport coordinators lack the capabilities to do this, as their primary business requires different ones, so outsourcing tasks to external services is a reasonable and beneficial solution. Consequently, the way a transport coordinator does its typical tasks is changed and now incorporates these new roles.

The major change regarding the transport coordinator's role is the emergence of platform-based business models. As described above, platform-based business models can be used by transport coordinators to search for transport operators with free capacity (*contract TO via platform*). At the same time, consignors or consignees might offer parts of their transport orders on such a platform instead of sending them to a transport coordinator (new arrows *Transport order* from consignor and consignee). However, the highest impact of platform-based business models is that they can also act as transport coordinators, leading to a new and hybrid role *platform-based transport coordinator*. Indeed, this new form of transport coordination is a threat to existing classical coordinators such as freight forwarders or third-party logistic providers. To not let platform-based models overtake the hybrid role, established transport coordinators have started to offer their own platforms and platform-based solutions (Baron et al. 2017; Graser et al. 2017).

Whatever the future developments will be, it has become apparent that a transport coordinator's role has changed during the last years due to increasing digitalization and the application possibilities of emerging technologies. These developments cannot be neglected and should be considered when planning a transport coordinator's future. The identified effects of digitalization and the derived overview of emerging changes to the picture of the road freight industry (as depicted in Fig. 2) can help understand recent developments and their effects on transport planning. This understanding is pivotal to incorporate new and innovative technologies into transport planning successfully. Therefore, the presented results provide ground for future studies concerning where and how to integrate digitalization into transport planning.

6 Conclusion

This paper aims to examine digitalization effects on road freight transport planning and specifically on the transport coordinator. As a ground for this analysis, literature has been reviewed to clarify which actors typically play a role in road freight transport planning and how they are related to the transport coordinator. Next, scientific and grey literature was analyzed to derive the main effects of digitalization on road freight transport planning: (1) new & more data sources, (2) new laws & regulation, (3) new & digital infrastructure, (4) new software & service provider, and (5) platform-based business models. The five identified effects were then transferred to the overview of roles. Roles and their relationship to the transport coordinator have been adapted accordingly. The relations to *facility & infrastructure providers* and *authorities* change due to the consideration of new infrastructure and new regulations. Moreover, three new roles – *data provider*, *software & service provider*, and *digital infrastructure provider* – were added due to their new relevancy for transport planning. The most significant adaptation is the addition of platform-based business models. They not only add a new form of relation for consignors, consignees, and transport operators, but they also provide ground for a new form of transport coordinators: the *platform-based transport coordinator*.

All digitalization effects and changes to roles and relationships have been discussed based on relevant scientific and grey literature. Consequently, both the viewpoints of research and practice are reflected in the results. However, the results should be validated and extended with expert interviews or similar. This way, it can be evaluated whether the literature reflects road freight transport's situation or whether further adaptations are needed. Future research should take care of this evaluation. Moreover, an extension of the examination towards the procedural level is an interesting idea. The effects of digitalization change not only roles and relationships but also the processes of transport planning. A more detailed analysis of the transport planning process and the process steps affected by digitalization can lead to a better understanding of how "digital transport planning" looks like and could be implemented. This deeper understanding could also be extended to other transport modes. While this paper focuses on road freight transport, some insights might be generalizable to other transport modes but would need to be adapted to their respective peculiarities.

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Supply Management

Smart Contract: A Literature-Based Analysis and Development of a Taxonomy Framework

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Abstract. So far, the term 'smart contract' is mainly reflected in research addressing technology, IT applications or peculiar businesses like stock exchange or bitcoin. However, a smart contract is an issue of purchasing and supply management (PSM) due to its potential to connect suppliers with customers through state-of-the-art digital means. Thus, we identify the need to define the concept of smart contracts within the PSM domain. Therefore, the main research aim is to clarify the construct of a smart contract. The core finding is that a deconstruction of existing definitions reveals peculiarities in the perspectives and domains but gives insufficient validity to PSM analysis. Thus, the result of this research is a definition proposal for smart contract. The implications of this analysis could pave the way for a wider discussion of how smart contracts affect PSM outside the typical blockchain and bitcoin arenas.

1 Introduction

A Google scholar search for 'smart contract' restricted to the timeframe of 1990 to 2000 brings only 33 hits, and the number is still low today, with 145 hits in the timespan of 2000 to 2010. However, in the last decade, the smart contract has been discussed extensively, with 17,600 hits from 2010 to today. The figures indicate that something happened to increase the use of the adjective 'smart' in popularity and research interest when talking about 'contract'.

Most obviously, the new distributed ledger technology blockchain has been developed as an enabler of the smart contract (PwC 2017; Carson et al. 2018). Overall, practice has awakened high expectations: 'Smart contract bears the potential to replace the traditional contract form' (PwC 2017). However, research has also formulated high expectations (e.g., that smart contracts might solve established contract challenges like the hold-up problem (Meier and Sannajust 2020). Smart contracts are expected to have substantial benefits, such as providing transparency and efficiency and decreasing costs, because of their ability to execute independently and automatically (Osmanoglu et al. 2020). According to Szabo (1994), smart contracts are able to avoid intermediaries as much as possible and, therefore, reduce the risk of opportunistic behaviour. Generally, it is assumed that operational relationships based on smart contracts and blockchain

This paper is funded by dtec.bw – Digitalization and Technology Research Center of the Bundeswehr which we gratefully acknowledge [project DigiPeC].

U. Buscher et al. (Eds.): *Logistics Management*, LNLO, pp. 51–66, 2021.
https://doi.org/10.1007/978-3-030-85843-8_4

technology will improve performance outcomes (Saberi et al. 2019). Furthermore, it is expected that smart contracts will be a solution mechanism for sustainability management (Salmerón-Manzano and Manzano-Agugliaro 2019) and have the potential to manage economic and ecological aspects of sustainability effectively (Saberi et al. 2019). Briefly, a smart contract is perceived as a solution mechanism for some of the most urgent problems of our times.

Stepping back from the enthusiasm, there are inconsistencies in the reasoning behind smart contracts. First, the concept of a smart contract is not clearly separated from an electronic contract, a topic that has been discussed for some decades (Salmerón-Manzano and Manzano-Agugliaro 2019). To increase confusion, other concepts can be mentioned as well (e.g., computer-aided contract, e-contract or intelligent contract). Second, there is no consistency in the definition of smart contracts, and we perceive the heterogeneity in understanding as a barrier to further research. For example, some authors directly relate smart contracts to blockchain technology only: 'Computer programs that verify contracts digitally, enforce those contracts, and run on a blockchain network are called smart contracts' (Christidis and Devetsikiotis 2016). Others link smart contracts more broadly to technology: 'Smart contracts are a computerized transaction protocol that executes the terms of a contract' (Szabo 1997), or 'Smart contracts are self-executing digital transactions that use decentralized cryptographic mechanisms' (Gatteschi et al. 2018). Furthermore, there are differences in the content as well as in the technological understanding of smart contracts. Although there are substantial differences between whether a contract is verified, enforced, agreed upon or self-executed, this is not fully reflected in the available definitions for smart contracts. There is also a difference in if a smart contract acts automatically (i.e., according to predefined rules) or autonomously with an own learning, evaluation and decision-making logic (i.e., algorithms, artificial intelligence). Therefore, there is still room for research on the conceptual basics of smart contracts, even if earlier review works on the topic already exist (e.g., the bibliometric analysis of Salmerón-Manzano and Manzano-Agugliaro 2019).

For the purchasing and supply management (PSM) discipline, research seems to be urgently needed, because surprisingly few contributions address the topic. After reviewing the *Journal of Purchasing and Supply Management*, *Journal of Supply Chain Management*, *Journal of Business Logistics*, *Business Research*, and *Journal of Operations Management,* not a single hit was found with 'smart contract' in the article title. However, there are contributions that address the topic; Schmidt and Wagner (2019) frame the blockchain/smart contract topic and connect it with a transaction cost theory perspective. Other studies examine the internet-of-things and name a number of 'smart' applications (e.g., smart city, smart store, smart agriculture), but it is not fully clear how the smart contract is related to new digitalized technologies and applications (Legenvre et al. 2020). There are some voices that identify smart contracts as a highly relevant topic for PSM (Debono 2019; Kleemann and Glas 2020; Nicoletti 2018), but overall, it seems as if the current (technological) debate on blockchain and smart contracts is not linked with or still underrepresented in PSM academic discourse. Therefore, this research addresses the construct of smart contracts and aims to clarify its understanding. In other words, the research question is as follows:

RQ: Which characteristics define a smart contract for purchasing and supply management (PSM) research and which are the main characteristics that differentiate it from other procurement contracting types?

To answer that question, a structured literature review has been conducted. As a result, an operationalized definition of digitalization in contracting, especially smart contracting, and associated constituent characteristics have been derived.

The remainder of this paper is as follows. The second section reviews how technology supports contracts. Then, the methodology is described in the third section. Afterwards, the findings are presented in the fourth section. The identification of a missing operationalization of smart contracts guided this research to propose a model of smart contract levels, which will be presented in the fifth section. Finally, Sect. 6 concludes and points to some limitations.

2 Review of the Discussion on Digitalization of Contracts

'Contract' is a basic legal term (Raskin 2017). Overall, a contract is a legal agreement between two or more parties where each is committed to fulfilling certain conditions (e.g., delivering a product, paying a price). Depending on the legal system, there are several different types of contracts defined (e.g., purchase, loan, lease, service, copyright, license, insurance, etc.). The format of the contract is typically relevant but not decisive. A verbal contract is binding, but due to several reasons, most importantly evidence function, a written agreement is the typical and traditional format of a contract.

Alternatively, the contract is also a construct in management science. Contract theory examines how a contract emerges and what effects it causes (e.g., moral hazard, hold-up or other agency challenges). Notable researchers include Kenneth Arrow, Oliver Hart and Bengt R. Holmström, who examined contracts, their (optimal) design and contract party behaviour. Contracts are intensively discussed in management research. For example, Williamson (2002) talks about a 'science of contract' when he discusses if and to what extent a contract is (in-)complete. Linked to that research is the typical (trade-off) question of how to make a contract flexible but incomplete or rigid but comprehensive.

While rigid and comprehensive contracts are good for optimization in non-complex, non-dynamic models, such contracts typically become less effective when complexity increases or the contract lasts over a longer time period with dynamic contingencies. This trade-off has guided business research to a number of managerial approaches to optimize the application of a contract, including a so-called performance-based contract, as a mechanism to formulate a flexible, incomplete contract that is still rigid in terms of binding performance indicators (e.g., Essig et al. 2016; Glas and Kleemann 2017).

Aside from the managerial approach to optimizing the use of a contract, there is also a technology-oriented approach to support contract management in buyer-supplier relationships (Eßig and Amann 2013). It is not possible to fully review the literature on the technical support of a contract, but we want to highlight that we found research on computer-aided contracts as early as the late 1970s (e.g., Thomson 1978). Later, literature on e-contracts rose in popularity with the e-commerce hype in the 1990s and 2000s and dealt with contract conclusion and enforcement in an online environment (e.g., Becher and Zarsky 2007; Chiu et al. 2002). Early research on smart contracts was being published by the end of the 1990s.

In Szabo's (1997) famous article, it is stated that the basic idea behind a smart contract is to make use of hard- and software to enforce contractual clauses in a way that goes far beyond the existing paper-based paradigm of a contract. Szabo (1997) also notes that simply adapting a contract to an electronic environment (with EDI/e-contract) is insufficient and that smart contracts can only achieve a dynamic contract management in contrast to inanimate traditional ancestors.

This aligns with the general discussion about digitalization and the implications of technology (Elsäßer et al. 2019). Holmström et al. (2019) distinguish between digitization and digitalization. Digitization means the replacement of (in this case) a contract by its digital analogue, whilst digitalization indicates a fundamentally different way to orchestrate, execute and build contracts and contract management. This development can be seen as a three phase process, according to Berman and Bell (2011) and Mooney et al. (1996).

Phase 1 is the 'digital products' phase, which uses the informational power of IT; contracts in this case are the sum of the information they include, which can be easily collected, stored and processed. Phase 2 is the 'digital distribution' phase, in which the automational possibilities of IT (like automated execution, easy dissemination, etc.) are used for contract management to improve the cost and benefits of contract management (e.g., improved decision quality). Phase 3 is the'digital transformation' phase, which enables new business models based on smart contracting possibilities; thus, the full transformational power of an IT-like service or product enhancement will be unleashed.

This reasoning would imply four necessary steps in digital technology usage to support contracts: (1) physical contracts without technology use; (2) digitized contracts as digital products, which translate paper-based contracts into digital formats; (3) digitized distributable contracts which make use of interconnected technologies (the web, etc.); and (4) digitalized transformational contracts which enable new business models in the buyer-supplier relationship, including through its ability to establish a new market based on a new (technological) logic of contracting. This logic spans the framework for our analysis (Fig. 1).

3 Methodology

3.1 Execution of the Literature Review

Fisher and Aguinis (2017) describe theory elaboration as a process of conceptualizing and executing empirical research to develop new theoretical insights. To ensure a theory elaboration, a systematic literature review is necessary for the consolidation of existing knowledge. Therefore, a systematic literature review has been conducted based on the methodological guidelines of Durach et al. (2017). Both best practice and unique attributes of doing supply chain management research are ensured by this paradigm for systematic literature review (Durach et al. 2017).

After the definition of the research question (see Sect. 1 of this article), the determination of the selection criteria for the article search was necessary. The selection criteria were used to identify relevant papers that clearly address the construct 'smart

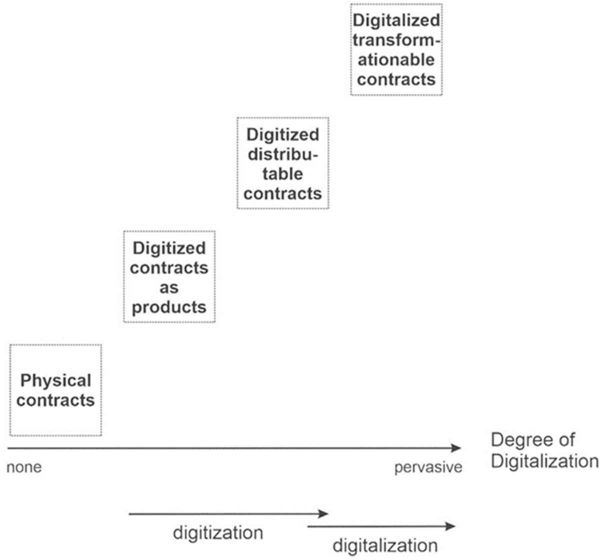

Fig. 1. Digital contracting framework (based on the frameworks of Berman and Bell 2011; Holmström et al. 2019; Mooney et al. 1996)

contract'. For the identification, the database Scopus and the discipline Business Administration/Management with the subdisciplines Procurement, Logistics, Supply Chain Management, Organization and Production were used. The subdisciplines of Technology and Business Informatics were tolerated with the condition that there was a direct connectivity to Business Administration/Management. To ensure quality, the selection of journals was referred to the corresponding ranking VHB Jourqual 3 (Verband der Hochschullehrer für Betriebswirtschaft e.V. 2021). In this respect, papers from journals listed in the VHB Jourqual ranking were considered. Furthermore, the selection process included a focus on current papers, specifically those published in the last five years. The language had to be English or German. After generating the adequate article list with only available articles, every duplication was removed. Finally, the established limitation criterion provided a convenient foundation for the execution of the article selection process.

3.2 Coding and Analysis Execution

This subchapter informs about the coding structure and the analysis execution. Firstly, the literature will be analysed through reading and annotating to collect relevant information about smart contracts. Secondly, the collected information will be used to classify the literature content. The classification is necessary to generate an overview of the entire information spectrum and associate the information with the authors. The classifications represent the general codes:

- Definition of smart contract
- Characteristics of smart contracts
- Functionality of smart contracts
- Relevance/necessity of smart contracts

The next step included the design of a link code structure. An excerpt with the essential coding implications for this paper is shown in the Table 1. The defined code structure is based on the content of the considered literature. Therefore, the codes were elaborated on during the systematic literature review to identify and analyse the data with a focus on characteristics and usage, the development level and the fundamental description/definition of smart contracts.

The first stage of the link code structure depicts the various coding blocks. Every block represents elements which can be used to characterize smart contracts. For example, the block 'Characteristics and Usage' is measured with the code 1.1, 'Transactions/Operations/Actions' in a business process. The second block is for the definition of the development level of smart contracts. In this block, the development level describes the intelligence level of a smart contract. It differentiates between digital, automatic and autonomous smart contracts. The last section entails characteristics for the 'Description/Definition' of a smart contract. The code descriptions can be interpreted as 'a smart contract is a computer/software/chain code', 'a smart contract represents agreements' or 'a smart contract can be defined as a computer/software program'.

Table 1. Excerpt of the coding implications

Block	Code no	Code description
Characteristics and usage	1.1	Transactions/Operations/Actions
Development level	2.1	Digital
	2.2	Automatic
	2.3	Autonomous
Description/definition	3.1	(Computer/Software/Chain) Code
	3.2	(IT) Protocol
	3.3	(Represent) Agreements
	3.4	(Computer/Software) Programs

Finally, the content analysis has been used to select and differentiate between relevant definitions. Consequently, each definition citation must be marked by the link code implications. This method is necessary for the evaluation of the definitions.

4 Findings

4.1 Quantitative Results

Table 2 shows that, after the application of filter criteria, 26 publications are considered relevant for further evaluation. Additional articles were found by using back-referencing and a snowballing search method. Through these methods, 10 additional sources were added.

Table 2. Application context of smart contracts articles

Keyword 'smart contract'	Matches	Discipline	VHB ranking	Availability	Final sources
Hits	1,342	156	39	26	36

4.2 Qualitative Results

The identified papers are quite heterogenous and show the plurality of approaches to addressing the topic. Some authors describe technical aspects like algorithm creation (e.g., Yeh et al. 2020; Nelaturu et al. 2020; Gourisetti et al. 2020; Epiphaniou et al. 2020; Lee and Ra 2020; Panja et al. 2020; Guerar et al. 2020; Manupati et al. 2020). Other authors address changes in supply chain structures. For the purpose of our research, four articles are of particular relevance: Saberi et al. (2019), Kumar et al. (2020), Lohmer et al. (2020) and Osmanoglu et al. (2020). For the clarification of the smart contract notion, the systematic literature review included the analysis of the available definitions in the papers. Not every source used an own definition, and some sources describe smart contracts but do not contain an explicit definition. Table 3 shows five selected definitions.

According to the argumentation of several authors (e.g., Meier and Sannajust 2020; Jabbar and Dani 2020; Casino et al. 2020), Szabo can be seen as the creator of smart contracts. The references to his definition have a sophisticated relevance. Meanwhile, Gourisetti et al. (2020) refer to the importance of the definition from SearchCompliance (2021) because of the crucial terminus and the reference to traditional contracts. Generally, the authors describe a smart contract as a self-executing code, protocol or program that generates an action, like a transaction, when predefined terms are met. While some authors combine the term 'execution' with 'automation', others use the term 'autonomy' to describe the independence level of the operations. However, the definitions join the understanding that smart contracts are a tool for the digital processing of contractual terms.

As listed in Table 4, the systematic literature review contains an overview of how smart contracts understood and used. The table presents the codes per source. A description of the code is listed in Table 1 (Sect. 3). If one of the codes applies to the source, the box will be filled with the symbol 'X'.

For instance, the first column of code classification records the code number 1.1 'Transactions/Operations/Actions'. This code arises ten times throughout list. That means that ten authors connect the usage of smart contracts with 'Transactions/Operations/Actions'. The definition of smart contracts as a '(Computer/Software/Chain) Code' (Code 3.1) is utilized by ten authors, while three authors define smart contracts as an '(IT) Protocol' (Code 3.2), and eight authors define them as a '(Computer/Software) Program' (Code 3.4). The definition that smart contracts

Table 3. Selected definitions of smart contracts

Author	Definition
Szabo (1994)	'A smart contract is a computerized transaction protocol that executes the terms of a contract. The general objectives of smart contract design are to satisfy common contractual conditions (such as payment terms, liens, confidentiality, and even enforcement), minimize exceptions both malicious and accidental, and minimize the need for trusted intermediaries.'
Osmanoglu et al. (2020)	'A smart contract is a piece of codes consisting of predefined terms agreed by the counter parties of the contract. When these terms are met, the smart contract autonomously executes itself and produces an output to the network.'
Kumar et al. (2020)	'[…] smart contracts implies a self-executing code on the blockchain that automatically implements the terms of an agreement among parties or other business logic. It is for the most part an unbreakable agreement with predefined rules.'
Saberi et al. (2019)	'[…] the smart contract, as a critical feature of blockchain technology allows the performance of credible transactions without third parties' involvement.'
SearchCompliance (2021)	'A smart contract, also known as a cryptocontract, is a computer program that directly controls the transfer of digital currencies or assets between parties under certain conditions. A smart contract not only defines the rules and penalties related to an agreement in the same way that a traditional contract does, but it can also automatically enforce those obligations.'

'(Represent) Agreements' (Code 3.3) emerges three times. The authors used three various terms in their definitions to describe the 'Development Level' of a smart contract. The term 'Digital' (Code 2.1) appears four times, 'Automatic' (Code 2.2) nine times and 'Autonomous' (Code 2.3) two times. Several articles were not considered for the coding, because they lacked an explicit definition. From the remaining 33 definitions, ten definitions arose from the back-referencing/snowballing method.

The literature analysis reveals that authors often combine the definition of smart contracts with terminus blockchain technology. According to the selected definitions in Table 4, researchers like Saberi et al. (2019) and Kumar et al. (2020) mention blockchain in their definitions. In this paper, we aim to separate the notion of the smart contract from blockchain technology, because it seems that a broader understanding of enabling technology may help to further specify the construct of the smart contract. Reviewing the analysed literature, almost all references define one central aspect: whether the contract is an intermediary in itself, acting as a kind of institution, or not. This aligns with institutional economics, where contracts fulfil this role. Talking about 'smart', most references refer to some kind of autonomy or flexibility in these contracts.

Table 4. Coding allocation of smart contract definitions

No	Author	No definition	No own definition	Codes							
				1.1	2.1	2.2	2.3	3.1	3.2	3.3	3.4
1	Angieri et al. (2020)			X							X
2	Androulaki et al. (2018)										X
3	Antonopoulos and Wood (2018)				X				X		
4	Buterin (2014)			X		X					
5	Casino et al. (2020)		X								
6	Choo et al. (2020)	X									
7	Chang et al. (2019)							X			
8	Coyne and McMickle (2017)			X		X		X			X
9	Christidis and Devetsikiotis (2016)										
10	Drummer and Neumann (2020)										X
11	Dolgui et al. (2019)					X			X		X
12	Epiphaniou et al. (2020)		X								
13	Gourisetti et al. (2020)		X								
14	Guerar et al. (2020)	X									
15	Howells (2019)						X	X			
16	Hughes et al. (2019)			X	X			X		X	
17	Jabbar and Dani (2020)		X								
18	Kher et al. (2020)			X		X		X			
19	Kumar et al. (2020)					X		X		X	
20	Kim and Laskowski (2017)			X							
21	Lee and Ra (2020)							X			X

(*continued*)

Table 4. (*continued*)

No	Author	No definition	No own definition	Codes							
				1.1	2.1	2.2	2.3	3.1	3.2	3.3	3.4
22	Lockl et al. (2020)		X								
23	Lohmer et al. (2020)		X								
24	Leng et al. (2019)		X								
25	Manupati et al. (2020)			X		X					
26	Meier and Sannajust (2020)		X								
27	Nelaturu et al. (2020)				X			X		X	
28	Osmanoglu et al. (2020)						X	X			
29	Panja et al. (2020)	X									
30	Pereira et al. (2019)		X								
31	SearchCompliance (2021)			X		X					X
32	Saberi et al. (2019)			X							
33	Schmitz and Leoni (2019)		X								
34	Szabo (1994)			X					X		
35	Weber et al. (2016)				X	X					
36	Yeh et al. (2020)					X		X			X
	Frequency	3	10	10	4	9	2	10	3	3	8

5 Discussion and Proposition of a Smart Contract Understanding

The discussion refers back to the guiding RQ, which addresses the characteristics of smart contracts. It can be shown that previous understanding is based on, or at least heavily inspired by, a dated definition from Szabo (1994). It is an understanding that notes the 'computerized' format of a smart contract, something that aligns with the digitization of previously non-digitalized content. This is the starting point of the smart contract. More recent contributions highlight peculiar technologies (blockchain; crypto-technology), but there seems to be no conceptually new quality to the concept of a smart contract. Technologies continue to develop, and even Szabo (1994) did not limit the concept of a smart contract to a particular software or application, instead referring to a general technological support for contracts. In this respect, smart contracts can generally be used in combination with different technologies. According to Szabo (1994), some ancient technologies can also be considered as crude smart contracts, for example, point-of-sale terminals and cards, electronic data interchange and allocation of public network bandwidth. Other authors, such as Kumar et al. (2020), mention alternatives for the fulfilment of business contracts between parties by the usage of service-oriented architectures (SOA). However, SOA cannot enforce the business contract automatically like smart contracts can. In the case of SOA, a web service is provisioned and controlled by a party, which is why it is not 'unbreakable'.

One characteristic that may be a new quality for contracts is the 'smart' notion of the construct. However, many authors do not explicitly explain what 'smart' means exactly, and even Szabo (1994) stays vague on this point. Similarly, other authors (e.g., Angieri et al. 2020) do not clearly express their understanding of what smart functionalities are. In their understanding, a smart contract is a software program (stored in a blockchain) that executes the terms of a contract. On the one hand, this understanding meets the traditional interpretation of a contract as a documentation routine basis for contract terms. On the other hand, it focuses the execution (phase) of this contract. Furthermore, other authors explicitly highlight the smart quality of the construct. In that sense, a smart contract is able to automatically execute transactions according to pre-specified rules (Buterin 2014). Other authors go a step further and see the role of a smart contract (software) in the verification of more complex topic (such as the generation of decision-making queries, re-scheduling, etc. Dolgui et al. (2019). This is the point where we distinguish automatic from autonomous functionalities of a smart contract. This difference lies in whether a contract is able to execute known pre-defined rules or if it is possible to assess risk situations, learn through statistical procedures or artificial intelligence and improve or change decision-making rules. The most extensive functionality is called autonomous and is linked to the discussion of the simple and complex terms a smart contract must deal with (Howells 2019).

In summary, we see an understanding of smart contracts that starts with the technological support of a contract but is also driven by the task/decision functionalities a contract can take over. Referring back to the digital contracting framework (Sect. 2), this means that we must distinguish graduations of smart contracts. With the transformation of physical contracts into digitized ones, we can already discuss smart contract type 3. Adding an automatic software routine, we gain the ability to act in a digital business environment that increases the market impact (smart contract type 2). In the narrowest sense, the smart functionality is key to enabling new digitally transformed business that can also have disruptive and, thus, pervasive economic impact. We illustrate this finding in Fig. 2 by adding a new, third dimension to our framework of analysis to develop it into a conceptual framework helping to define different smart contracting types.

As a result, we conceptualize the smart contract as follows:

> A smart contract is a digitally enabled transaction technology that acts as the intermediary contract link in supply relations and which can make use of automatic or autonomous planning and decision-making.

Thus, in the widest sense, contracts are smart as soon as they are in the digitized format, which eases communication and transparency as well as performance measurement and management (smart contract type 3). After all, type 3 of the smart contracts

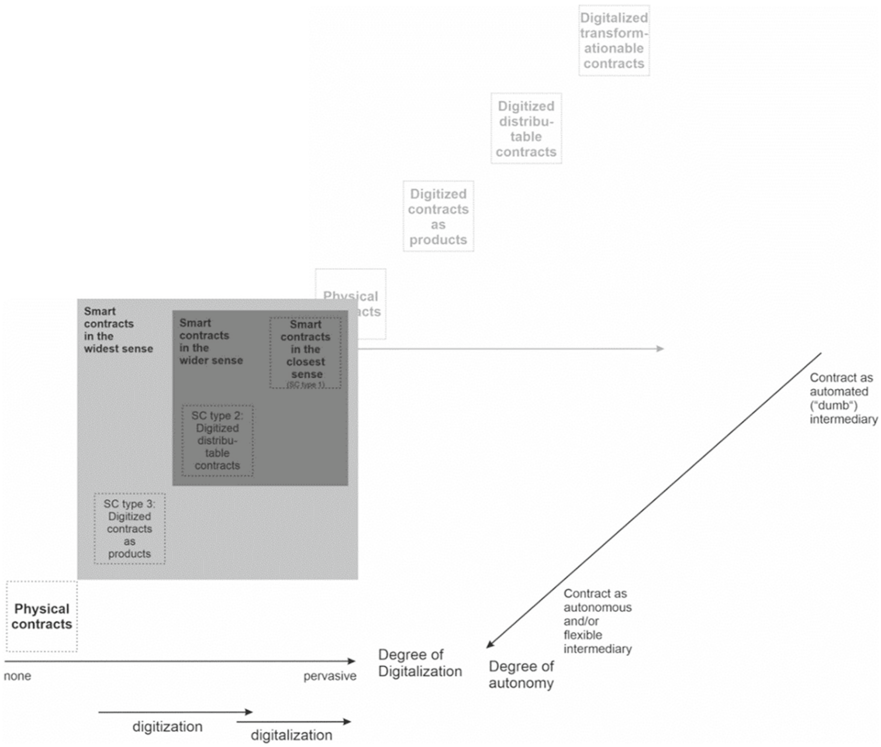

Fig. 2. Smart contract understanding

can be seen as 'simple digitized contracts'. This kind of contract does not yet exhibit intelligence, but because of the creation of transparency, they are able to fulfil the role as an intermediary contract link. That is why type 3 can be seen as an initial stage of smart contracts. In a wider sense, contracts make use of distributable IT technology to be called 'smart'. This includes all kinds of interorganizational systems, mainly web technologies with pre-defined rules and automatic execution (smart contract type 2). Smart contracts in the closest sense need a kind of executional intelligence (e.g., AI based) to be marked as 'smart' (smart contract type 1).

In this respect, smart contracts can be implemented in a variety of areas of PSM topics. Following the examined literature, example applications are in supply chain transparency/coordination, financial services, healthcare, the energy industry, device cybersecurity, identity management, food and agriculture (Manupati et al. 2020; Kumar et al. 2020; Gourisetti et al. 2020; Osmanoglu et al. 2020).

6 Conclusions and Limitations

Overall, this paper is a first approach to opening the topic of smart contracts, because most PSM literature on the topic discusses technology (e.g., blockchain). Alternatively, the general research interest in the topic is almost establishing a hype. As briefly presented above, 'contract' is a basic term for PSM research. Therefore, it is justified to review and consolidate smart contract understanding. Purchasing and supply management as a kind of 'bridge builder' (Ellram et al. 2020) between supply market possibilities and internal requirements has a major interest in further developing the agreements as a kind of groundwork for this 'bridge'. Following the understanding of different degrees of technology support (i.e., none, digitization, digitalization), we were able to identify similar shades of grey in the construct of smart contracts. The graduation follows the degree of technology and the degree of contract intelligence. Digitized contracts can also be referred to smart contracts, but in a narrower sense, we see smart as automatic or even autonomous contract management (initiation, creation, execution, application, enforcement, etc.) as a relevant characteristic of a smart contract. Thus, a smart contract also has an innovative functionality as an automatic/autonomous intermediary element in supply relations.

Of course, this research has some limitations. First, the examined stock of literature is still a narrow base. We expect that PSM research will explicitly address the topic more deeply in the future with a higher number of research approaches that provide a better picture of how smart contracts are applied and understood. Second, current smart contracts are called 'flexible' and 'automatic' but often follow a tight programming logic. Maybe an autonomous smart contract is still possible and requires more empirical evidence.

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The Impact of Intelligent Process Automation on Purchasing and Supply Management – Initial Insights from a Multiple Case Study

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Abstract. The Covid-19 pandemic drives the need for Intelligent Process Automation (IPA). However, the technology's adoption for purchasing and supply management (PSM) is still in the initial stage and has hardly been explored. Therefore, this empirical multiple case study builds on 19 organizations, including private and public procurement departments, consultancies, and IPA providers, to examine the impact of IPA on the PSM function. The findings provide comprehensive insights and reveal suitable operational and strategic application areas as well as several benefits related to IT systems and data, operational efficiency, process quality, and employee satisfaction. The study also identifies various technological, organizational, and environmental challenges that need to be overcome for further IPA adoption. Therefore, future research directions and managerial implications are outlined.

1 Introduction

The impact of the Covid-19 pandemic accelerates organizational change and the need for digital transformation and process automation (Coombs 2020). Due to its interface and networking function, the procurement department plays a vital role in Industry 4.0-related projects to enhance corporate performance and competitiveness (Bals et al. 2019). Buzz words like *Procurement 4.0* (Bienhaus and Haddud 2018; Nicoletti 2020) outline the change of purchasing and supply management (PSM) towards a more strategically integrated business function.[1] Nevertheless, the crucial digital transformation of PSM often lags behind other business functions (Allal-Chérif et al. 2021; Hartley and Sawaya 2019). Although repetitive and low-value-adding processes based on structured data are increasingly being automated through e-procurement systems and the emerging Robotic Process Automation (RPA) technology, manual activities still dominate the purchasers'

[1] This paper uses the terms *purchasing*, *procurement*, and *PSM* interchangeably and refers to them as operational and strategic activities of private and public organizations "to ensure that the goods and services they need from their suppliers are available at the right time, in the right place, of the right quality, and at acceptable cost" (van Raaij 2016, p. 13).

U. Buscher et al. (Eds.): *Logistics Management*, LNLO, pp. 67–89, 2021.
https://doi.org/10.1007/978-3-030-85843-8_5

work routines. Most procurement tasks involve unstructured data, which challenges RPA and e-procurement systems (Nicoletti 2020; Schoenherr 2019).[2]

To overcome the shortcomings of RPA and enhance its capabilities and application areas, software providers increasingly integrate RPA with artificial intelligence (AI) (Mohanty and Vyas 2018; Syed et al. 2020). Following a recent leading AI conference's nomenclature, this paper refers to that advanced form as *Intelligent Process Automation (IPA)* (Chakraborti et al. 2020; Taulli 2020; Zhang 2019). IPA's market volume was valued at 10 billion USD in 2020 and is expected to grow with a compound annual growth rate of more than ten percent due to the impact of Industry 4.0 and the Covid-19 pandemic (Coombs 2020; Markets and Markets 2020). Along this line, procurement departments in the private sector consider intelligent technologies, like IPA, as core elements to make full use of their (unstructured) data and automate operational and strategic processes (Bienhaus and Haddud 2018; Jacobi and Groher 2019; Nicoletti 2020). IPA also receives growing interest from the public sector (Dias et al. 2019; Markets and Markets 2020). Despite the emerging practical dissemination, scientific research on IPA is still scarce (Ng et al. 2021; Syed et al. 2020; Viehhauser 2020), specifically in the context of PSM (Srai and Lorentz 2019). Existing publications (e.g., Allal-Chérif et al. 2021; Nicoletti 2020; Teli and Prasad 2018) are either generic or RPA-centered. They are also limited in their *scope* (i.e., focusing on benefits while neglecting challenges) and *information base* (e.g., interview studies involving private companies while neglecting public organizations). Therefore, PSM scholars and practitioners from private and public organizations are in great need of comprehensive and guiding research that examines the adoption of intelligent technologies and their potentials and challenges (Srai and Lorentz 2019; Van Hoek et al. 2020; Viale and Zouari 2020). To address this demand and the limitations of existing publications on IPA, this paper contributes to the following research questions (RQ):

RQ1: Which procurement processes are suitable for IPA?
RQ2: What are the potential benefits and challenges of IPA adoption?
RQ3: How does IPA influence the future development of PSM?

The paper follows a qualitative multiple case study approach to provide initial, yet comprehensive, empirical insights on IPA's impact on the PSM function. Nineteen semi-structured interviews with experts from private and public procurement organizations, consultancies, and software vendors were conducted. The study's contributions for researchers and practitioners are threefold: Firstly, a classification framework is developed to provide a common understanding of IPA. Secondly, potential application areas, benefits, challenges, and developments for procurement are presented. Lastly, the study points out future research directions and managerial implications to facilitate the further adoption of IPA in PSM. In that sense, the next chapter provides the relevant background. In Sect. 3, the applied qualitative research methodology is described, while the results

[2] RPA is an umbrella term merging robotics and business process automation. Software licenses, so called "bots", mimic human behavior and automate "swivel chair work", i.e., repetitive, rule-based, and tedious business processes based on structured data. RPA is non-intelligent (Hofmann et al. 2020; Syed et al. 2020).

on the RQs are presented in Sect. 4 and discussed in Sect. 5. The paper concludes with a summary and outlook.

2 Intelligent Process Automation

Hitherto, academia and practice lack a clear consensus on IPA terminology and components. Therefore, the following section provides a common understanding of IPA by explaining its essential components and characteristics. The proposed framework is also helpful to grasp the presented results in Sect. 4. Besides, an overview of process automation in PSM is given in Sect. 2.2.

2.1 IPA Classification Framework

IPA bots are considered a form of "*weak AI*" as intelligence is applied only to specific areas. Bots are designed and trained for particular tasks, e.g., to convert data. In contrast to "*strong AI*", IPA bots cannot autonomously solve problems beyond their programmed parameters (Viehhauser 2020).[3] The term IPA is also referred to as *Cognitive Automation* (e.g., Hofmann et al. 2020; Jacobi and Groher 2019; Taulli 2020; Willcocks 2020) or *Intelligent Automation* (e.g., Coombs 2020; Ng et al. 2021). However, it is reasonable to define IPA systems as the extension of basic, non-intelligent RPA with AI technologies. Therefore, IPA is part of Cognitive Automation, which in turn belongs to the broader concept of *Cognitive Computing* (Viehhauser 2020; Zhang 2019) (see Fig. 1).

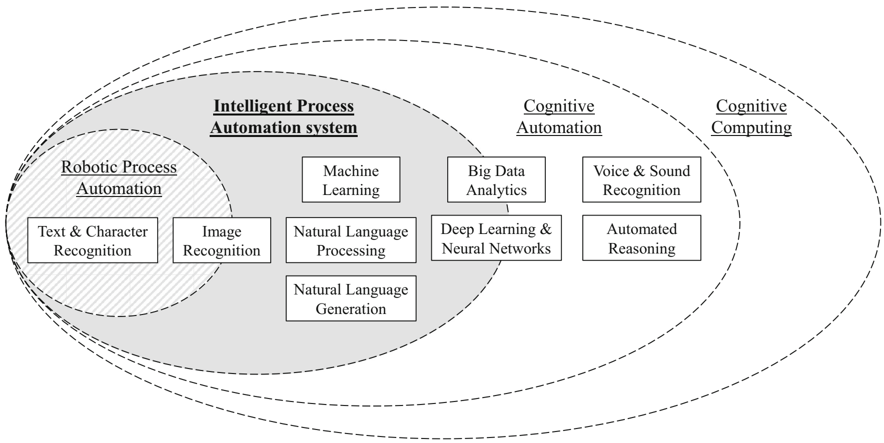

Fig. 1. IPA classification framework

Cognitive Computing is a subset of AI inspired by the human mind. It enables human-like interactions with users, interpretations and analyses of the contextual meanings, and

[3] Usually, the term *AI* is applied "when a machine mimics 'cognitive' and other functions that humans associate with human minds, for example, learning, problem solving, visioning, prediction and association" (Willcocks 2020).

autonomous decision-making based on deductions (Gupta et al. 2018). Cognitive Computing platforms comprise various advanced AI technologies, such as Machine Learning, Natural Language Processing, Natural Language Generation, Big Data Analytics, Deep Learning and Neural Networks, voice recognition, and automated reasoning (Nicoletti 2020; Viehhauser 2020). IPA systems extend RPA with several of those technologies to collect data and process information. Data is collected through text, character, and image recognition. While the first two are considered standard features of basic RPA, image recognition requires more sophisticated approaches, like *Optical Character Recognition* and *Computer Vision* (Mohanty and Vyas 2018; Viehhauser 2020). The former allows for converting unstructured to structured data, e.g., by extracting text from images, scans, or handwritten documents (Taulli 2020). Computer Vision draws on similarity analysis and visual conformance to identify, recognize, and categorize digital elements on user interfaces. Thus, the dependence on accessible underlying data is eliminated, enhancing the flexibility and application areas of bots (Viehhauser 2020).

For information processing, IPA relies on *Machine Learning*, *Natural Language Processing*, and *Natural Language Generation* (Mohanty and Vyas 2018; Zhang 2019). Machine Learning is an algorithm-based subset of AI for data pattern analyses (Hartley and Sawaya 2019). It is not explicitly programmed but learns and improves automatically to enable targeted predictions, recommendations, error handling, and responses to changing conditions (Mohanty and Vyas 2018; Taulli 2020). With IPA, Machine Learning typically refers to "*supervised learning*" as bots are trained with a large set of specific (historical) data to react to predefined output variables (Viehhauser 2020). Natural Language Processing enables the analysis and standardization of the unstructured oral or written input of conversations through contextual or sentiment analyses (Mohanty and Vyas 2018; Viehhauser 2020). Natural Language Generation is used to generate text or speech from that analyzed and structured information. IPA chatbots draw on both technologies to learn and communicate with customers and employees (Chakraborti et al. 2020; Gotthardt et al. 2020). Thus, they are applied for conversational processes based on unstructured data and human interaction (Ng et al. 2021). In contrast to RPA, IPA chatbots (referred to as "*virtual agents*") are applied for both the back-office (i.e., employee services and supportive tasks) and the front-office (i.e., customer-facing businesses and interaction) (Allal-Chérif et al. 2021; Chakraborti et al. 2020; Mohanty and Vyas 2018).

While IPA and Cognitive Automation are both subsets of Cognitive Computing, Cognitive Automation goes beyond IPA as it iterates "its own automation approaches and algorithms for more expansive or more thorough analysis" (Suri et al. 2019). Thereby, Cognitive Automation uses more sophisticated Deep Learning and Big Data Analytics approaches based on cognitive domain knowledge (Taulli 2020; Zhang 2019). Although RPA and IPA are evolving towards Cognitive Automation (Hofmann et al. 2020), advanced cognitive capabilities, like voice or sound recognition and automated reasoning, are not incorporated yet (Viehhauser 2020).

In sum, IPA systems can be defined as platforms that integrate RPA with ERP systems and AI technologies through various interfaces to automate business processes that entail unstructured data and decision-making. Thereby, self-learning capabilities minimize the need for human interaction and training (Chakraborti et al. 2020: 219; Viehhauser

2020; Zhang 2019). In contrast, *cognitive* or *intelligent RPA* means that AI is directly incorporated into RPA itself and not added by external software via the platform approach (e.g., Syed et al. 2020; Teli and Prasad 2018; Viehhauser 2020).

2.2 Process Automation in Purchasing and Supply Management

Even though ERP and e-procurement systems are the backbones for procurement automation, they are often disparate and insufficient for real-time data exploitation, interoperability, and flexible decision-making (Hartley and Sawaya 2019; Schoenherr 2019). Therefore, organizations increasingly apply RPA as a bridge solution to automate manual, tedious, and rule-based processes while updating the essential IT systems within comprehensive projects (Jacobi and Groher 2019; Nicoletti 2020). Although scientific research on RPA for PSM is still nascent, initial studies show its positive impact, i.e., time and cost savings, employee reliefs, efficiency gains, error reduction, and increased quality of buyer-supplier relationships. RPA is applied in back-office processes to create purchase orders, support supplier communication, and collect and maintain data (Hartley and Sawaya 2019; Nicoletti 2020; Viale and Zouari 2020). However, RPA requires standardized workflows, exact programming, and structured data in a predefined format (Syed et al. 2020). Processing and converting the vast amount of unstructured data within procurement departments involves more sophisticated AI-based technologies (Allal-Chérif et al. 2021; Bienhaus and Haddud 2018). Therefore, IPA systems are an integral part of Procurement 4.0 (Nicoletti 2020; Schoenherr 2019).[4]

However, many organizations struggle with the required digital readiness (Bienhaus and Haddud 2018; Van Hoek et al. 2020). Thus, the adoption of advanced technologies in PSM is still nascent, particularly in small and medium-sized enterprises (SME) (Hartley and Sawaya 2019; Viale and Zouari 2020) and the public sector (Arlbjørn and Freytag 2012; Dias et al. 2019). Similarly, relevant scientific contributions for IPA adoption in procurement are limited. For example, Teli and Prasad (2018) emphasize the potentials of RPA and IPA (which they termed as *Robotic Cognitive Automation*). The publication examines several suitable application areas in supplier relationship and risk management, contract management, and master data management. However, the differentiation between RPA and IPA is not apparent. Since their interview study involved consultants only, the authors call for further empirical research covering different organizational levels and sectors. Hartley and Sawaya (2019) as well as Viale and Zouari (2020) focus on RPA benefits for procurement. They emphasize the necessity to implement more sophisticated approaches and investigate respective challenges for the PSM function. The urgent need to examine the impact of new automation technologies for procurement, including related application areas, benefits, and challenges, is also emphasized by other authors (Allal-Chérif et al. 2021; Jacobi and Groher 2019; Nicoletti 2020).

[4] With Procurement 4.0, intelligent technologies process structured and unstructured data, execute natural human interactions, and draw deductions. They also automate strategic and recurrent planning processes like sourcing, supplier segmentation, negotiation, and contract management (Allal-Chérif et al 2021; Srai and Lorentz 2019).

3 Research Methodology

The qualitative multiple case study conducted to respond to that urgent research need contributes to the scarce body of scientific literature on IPA and generates initial yet rich insights on its impact on the PSM function. The qualitative multiple case study approach seems feasible as case study research is appropriate for in-depth investigations and analyses of contemporary phenomena within their real-world context to provide comprehensive insights and empirical descriptions for theory building (Eisenhardt and Graebner 2007; Yin 2018). Besides, case study research has already been applied for RPA and IPA (e.g., Hartley and Sawaya 2019; Viale and Zouari 2020; Viehhauser 2020). The research process followed the steps proposed by Stuart et al. (2002), i.e., defining research questions, developing the study design, selecting appropriate cases, collecting and analyzing the data.

3.1 Study Design and Case Selection

The study design draws on a blended inductive-deductive approach to develop new theory while also examining existing knowledge. The case selection is based on theoretical sampling to ensure *external validity* (Eisenhardt and Graebner 2007; Stuart et al. 2002). It was initiated by a broad search for private and public procurement organizations and facilitated by personal contacts to the "*Association for Supply Chain Management, Procurement, and Logistics*", which comprises nearly 10,000 members in Central Europe and fosters the digital transformation of PSM. Suitable organizations for the multiple case study had to differ in their business fields and sizes and have planned, initial, or mature RPA and IPA applications.

In sum, 19 organizations were examined (see Table 1), involving six private and six public procurement departments. One polar case (Priv.F) was included among the private organizations to enrich the study's picture (Eisenhardt and Graebner 2007). Priv.F refrained from RPA implementation and recently rejected an IPA project. Besides, four digital procurement consultancies with extensive experience in RPA/IPA projects in both sectors were involved to yield more comprehensive data. Thereby, two consultancies (Cons.A, C) also provide self-developed RPA/IPA software. Additionally, three established RPA/IPA providers were included in the study, with Prov.A and Prov.B being global market leaders (Markets and Markets 2020). The respective sample sizes are consistent with the literature's proposals for qualitative case study research (Eisenhardt and Graebner 2007; Yin 2018). The participants are mainly headquartered in Germany and operate globally or throughout Europe.

3.2 Data Collection and Analysis

All participants received the research project's description and privacy statement beforehand to grant anonymity and build trust (Stuart et al. 2002). The respective informants were either directly contacted by the author or selected by the organization based on their job position, knowledge level, and willingness to participate in the study. Then, 19 semi-structured interviews were conducted, each consisting of up to three participating informants (i.e., 27 informants in total). Whenever possible, multiple informants per interview were preferred to diminish potential bias and enhance *construct validity*, as they often represented different viewpoints, hierarchical levels, and functional areas (Eisenhardt and Graebner 2007; Stuart et al. 2002). The semi-structured approach with open-ended questions (Yin 2018) allowed for flexibility and adjustments regarding the *organization* (type, level of RPA/IPA experience) and *informants* (knowledge, job position). All interviews took place in 2020 via telephone or face-to-face meetings and lasted 51 min on average. The informants had an average work experience of 19 years, with a minimum of four years and a maximum of 31 years.

Based on the research questions, two interview guidelines were developed and divided into four blocks: (1) opening questions about the organization and informant's experience; (2) understanding of terms and concepts (i.e., RPA, IPA, and PSM); (3) the impact of RPA and IPA on PSM, including application areas, benefits, challenges, and future developments; and (4) closing remarks. The first guideline was used for private and public organizations as well as consultancies (see Table 2). The second was applied to RPA/IPA providers due to their more holistic scope and included modified questions, for example, about integrated AI components and expectations for further technical development. While the interviews involved questions on both RPA and IPA, this paper focuses on the findings related to IPA. All interviews were recorded and transcribed verbatim. The transcripts were sent to the informants for review to ensure accuracy. Besides, supplementary material was included for data triangulation (Yin 2018), such as field notes, internal presentations, case documentations, client reports, product specifications, and the websites of the organizations.

The data analysis followed the principles of a systematic qualitative content analysis proposed by Mayring (2014) to ensure validity and reliability. The included data sources were iteratively coded with the software MAXQDA 2020. Firstly, the data were structured according to main categories, which were deductively elaborated from the interview guidelines and literature (e.g., the *PSM process wheel* of van Raaij (2016) to structure application areas, and the *technology-organization-environment (TOE) framework* of Tornatzky and Fleischer (1990) to classify challenges). Secondly, a line-by-line text analysis was conducted to inductively develop related subcategories (e.g., specific IPA tasks, benefits, and challenges). Anchor samples were assigned to illustrate each category, and codes were grouped into themes. Then, the themes were contrasted, outlining similarities and differences. In the ultimate iteration, the final category system was applied to all collected data and emerged patterns were linked to relevant literature (Stuart et al. 2002). In addition, two peers were asked to code half of the interviews with the applied coding scheme to reduce bias, enhance reliability, and clarify discrepancies. The study ensures internal construct validity through a combined within-case and cross-case analysis to generate general impressions and cross-case patterns rather than individual insights (Mayring 2014; Yin 2018).

Table 1. Anonymized overview of the 19 participating organizations

Org.	Field	Number of employees	Revenues (in EUR M)	Positions of informants	Duration (in min)
Priv.A	Automotive	>50,000	>1,000	IT Project Manager Purchasing	25
Priv.B	Automotive	>50,000	>1,000	Senior Purchasing Manager, IT Project Manager Purchasing	42
Priv.C	Automotive	>50,000	>1,000	IT Project Manager Purchasing	50
Priv.D	Energy	1,000–50,000	>1,000	2× Senior Purchasing Managers	48
Priv.E	Engineering	1,000–50,000	>1,000	Senior Purchasing Manager	29
Priv.F	Fashion	1,000–50,000	100–1,000	Senior Purchasing Manager, IT Project Manager Purchasing	70
Publ.A	Energy	1,000–50,000	>1,000	Senior Purchasing Manager, Head of IT Competence Center, IT Project Manager	43
Publ.B	Finance	1,000–50,000	>1,000	Head of IT Competence Center	58
Publ.C	Research	1,000–50,000	>1,000	Head of Purchasing	51
Publ.D	Research	1,000–50,000	100–1,000	Senior Purchasing Manager	49
Publ.E	Research	1,000–50,000	100–1,000	Head of Purchasing, Senior Purchasing Manager	52
Publ.F	Research	1,000–50,000	100–1,000	Head of Purchasing, IT Project Manager Purchasing	40

(*continued*)

Table 1. (*continued*)

Org.	Field	Number of employees	Revenues (in EUR M)	Positions of informants	Duration (in min)
Cons.A	Procurement	<1,000	>1,000	Senior IT Consultant	62
Cons.B	Procurement	<1,000	<100	Senior IT Consultant	51
Cons.C	Procurement	<1,000	<100	Chief Executive Officer	65
Cons.D	Procurement	<1,000	<100	Senior IT Consultant	66
Prov.A	RPA/IPA	1,000–50,000	100–1,000	Head of Pre-sales	68
Prov.B	RPA/IPA	1,000–50,000	100–1,000	2× Senior IT Consultants	60
Prov.C	RPA/IPA	<1,000	<100	Head of Research	43

Priv./Publ. = Private/public procurement dept.; Cons. = Consultancy; Prov. = Software provider.

Table 2. Excerpt of the first interview guideline with IPA-related questions

Category	Selected questions
Application areas	Which procurement tasks have you already automated/can/could you imagine automating with IPA? Why? How are they characterized and prioritized?
Benefits	What were/are/would be the motives for your organization to implement IPA? Which benefits and capabilities of IPA did you realize/do/would you expect? How is/would the performance impact (be) measured?
Challenges	Which challenges and barriers did/do/would you face? How did/do/would you cope with them? Which lessons did you learn from IPA/similar projects?
Outlook	Which consequences and effects of large-scale IPA implementations do you see/would you expect, with particular emphasis on PSM processes and employees? Which IPA-related issues should be addressed with future research?

4 IPA in Purchasing and Supply Management

This chapter addresses the research questions by presenting the results on IPA's application areas, benefits, challenges, and impact on PSM development. The following section introduces the providers' perspective.

4.1 The RPA/IPA Software Providers' Perspective

The providers' overall business goal is to offer an efficient and comprehensive software solution for business processes automation. Therefore, enhancing RPA with AI is regarded as a central objective. Depending on the providers' individual AI capabilities and strategies, considerable efforts are made to either incorporate AI components directly into RPA (Prov.A) and/or provide a functional and compatible IPA platform for third-party software integration (Prov.A, B, C). Although the IPA term differs among the providers due to unique selling propositions and marketing reasons (Prov.B), they concurred on the remaining of the umbrella term RPA as the basic and underlying technology. None of the examined RPA/IPA providers pursues a specialization strategy for individual branches or business functions, as Prov.A points out: "*RPA [and IPA] is about accessing systems through user interfaces in the same way a human user would do, and that's completely universal.*"

Currently, the providers develop IPA systems by integrating RPA with the following AI components: Image recognition, ML, NLG, and NLP, with the last two being the primary focus as they enable the reading, processing, and transferring of unstructured data. IPA is usually more appropriate than RPA as it goes beyond operational processes and extends the application scope towards more strategic and value-adding tasks. Consequently, the providers stressed the high applicability and flexibility of IPA, i.e., there are, theoretically, almost no limits of use. However, they also emphasized that most AI technologies are still in an initial developmental stage and not yet applicable on a large scale. Therefore, the decision on how to supplement the IPA system with what AI feature lies with each customer and depends on the expected benefits (e.g., feasibility, profitability, and user value) and individual technological, organizational, and environmental conditions.

4.2 Application Areas

IPA adoption is still at a very initial stage among the interviewed private and public procurement organizations. The consultancies and providers substantiated this observation. All informants agreed on RPA requiring AI upgrades to broaden its application areas. Thus, RPA experience was considered crucial for IPA implementation. Priv.A, B, C, D run mature RPA bots and already own initial IPA applications. In contrast, Priv.E and Publ.C, D, E, F are still on an early RPA level. Hence, they seek RPA experience before integrating AI features. Publ.A and Publ.B successfully finished initial RPA projects in the PSM function and currently pursue a broader roll-out and evaluation. Both organizations already plan the introduction of IPA. Priv.F refrained from RPA and IPA due to bad experiences and an already high degree of process automation through advanced e-procurement systems. However, the company currently prepares for the adoption of Machine Learning.

In sum, the informants named multiple suitable procurement tasks for IPA, which are structured according to the cyclical *PSM process wheel* of van Raaij (2016). The process wheel comprehensively visualizes the operational, tactical, and strategic activities of PSM (Bäckstrand et al. 2019). Thereby, the *identification of the buying need*, *purchase order management*, *order fulfillment*, *invoice processing/approval*, and *payment* are considered rather operational activities. Invoices provide inputs for more strategic and tactical procurement processes, such as *sourcing analyses*, *need specification*, *sourcing strategy development*, *supplier selection*, and *contracting*. Signed contracts initiate the next iteration of the PSM process wheel, i.e., buying need identification (van Raaij 2016). Table 3 responds to the first research question by summarizing procurement tasks for IPA. Many of them were mentioned by both private and public organizations. To the date of the interviews, none of the public participants had an IPA system in use. However, they expressed their ideas and plans for application areas of IPA in PSM, which mainly comprised strategic application areas related to need specification, tendering, and contracting.

According to the participants, intelligent bots are mainly applied in the back-office to scan, digitize, standardize, capture, correlate, compare, and validate the vast amount of unstructured data (e.g., different supplier templates, structures, and units used for quotations, orders, and invoices). IPA's pattern recognition capabilities allow to predict demands and market trends, anticipate supply chain problems, initiate proactive approaches, and conduct in-depth spend analyses and supplier evaluations (Priv.B, C; Cons.A, C). IPA could support the extensive preparation of service descriptions for public organizations while ensuring compliance with the procurement law. In the subsequent tendering process, intelligent bots might recommend suitable tenderers and handle much of the communication (Publ.C, E).

In line with the efforts of RPA/IPA providers, the focus of recent IPA projects in the industry is the seamless interaction with internal (Priv.A, B, C, D) and external (Priv.C) stakeholders. Internally, chatbots are applied for *"guided buying"*, i.e., they answer queries of human operators to generate targeted reports and lead the buyer to the ideal supplier for the desired product (Cons.A). In contrast, Priv.C also deploys IPA for "*long-tail-optimizing*" in the front-office to negotiate with suppliers for "C-Class purchases", i.e., non-recurring or low-frequent, non-strategic, indirect spends, which account for the minority of purchase volume but the majority of supplier and item numbers. Since Priv.C does not maintain an active relationship with those suppliers, the chatbot autonomously negotiates the contracts. Thereby, Machine Learning is used to define the optimal starting price as well as the maximal price for contract conclusion. Another bot then generates the purchase order.

Table 3. Suitable areas of IPA adoption in procurement, according to the PSM process wheel (van Raaij 2016)

PSM process	Suitable tasks for IPA
Identification of buying need	Integrated category and inventory management (i.e., continuous real-time monitoring and taking of inventory; joint forecasting and balancing of supply and demand; automatic replenishment; monitoring and prediction of market trends; real-time e-catalog updates based on current inventory)
Purchase order management	Guided buying; generation, verification, categorization, and intelligent distribution of requests for quotation; digitization, standardization, and evaluation of responses (e.g., format and data); optimized purchase order generation, approval, and sending to suitable suppliers based on real-time indices, exchange rates, and raw material prices; purchase order updates
Order fulfillment	Planning and status tracking of consignments based on order numbers; sending of notifications, alerts, and reminders to operators and suppliers; comparison of the delivery note with the order; booking of incoming goods
Invoice processing and approval	Matching of request for quotation, purchase order, and invoice; checking, processing, authorization (up to predefined limits), and posting of invoices; digitization and standardization of various invoice formats
Payment	Payment (up to predefined limits); posting of records and accounts payables
Sourcing analyses	Pattern recognition and classification of transactions with suppliers (spend analyses); answering queries and generating reports for supplier evaluation and risk management (e.g., scoring data to create risk profiles and potential analyses); KPI tracking and benchmarking
Specification of need	Supply market research; product, price, and quality analyses; preparation of service specifications; interpretation of procurement law
Sourcing strategy development	Standardization of templates for tendering; requesting information from potential suppliers; regular internet searches for current information on suppliers (e.g., negative press releases, difficulties, insolvency)
Supplier selection	Comparison of tenderer's responses; objective sourcing recommendations based on supply market intelligence and analyses

(*continued*)

Table 3. (*continued*)

PSM process	Suitable tasks for IPA
Contracting	Supplier negotiation (e.g., optimized quantities and pricing), supplier onboarding and communication (e.g., send evaluation forms, request (legal) documents and quality certificates, check their validity and highlight discrepancies, process and answer questions and complaints); reviewing, creating, and updating contracts and comparison to best-in-class templates; analyses of contract usage to negotiate on adjustments, discounts, or penalties

4.3 Benefits

The informants concurred that IPA promises several benefits for PSM regarding *IT systems and data*, *operational efficiency*, *process quality*, and *employee satisfaction.* Table 4 responds to the first part of RQ2 by summarizing the participants' expected and experienced IPA benefits. Since most of the participants are yet on an early level with IPA, quantitative performance measures and concrete data are scarce. The consultancies and providers pointed out that further potentials might be discovered as many use cases still need to be explored, realized, and evaluated.

Table 4. Benefits of IPA adoption in procurement

IT systems and data	Operational efficiency	Process quality	Employee satisfaction
Standardization of unstructured data	Fast data processing and exchange	Process optimization and monitoring	Workload reduction to focus on cognitive tasks
Flexibility	Time savings	Objectivity	Knowledge resource for decision-making
Scalability	Productivity gains	Compliance	Natural communication
Connectivity	Cost savings	Accuracy	Training and innovation

IT Systems and Data. IPA enables the processing and standardization of vast amounts of unstructured data and "hidden" information (Cons.C) in procurement (e.g., non-standardized oral and textual communication, non-machine-readable data like printed or scanned documents). Thereby, the technology enhances data quality and allows for flexible reactions to changing input and different supplier-dependent workflows and exceptions (Priv.C). Since bots are single software licenses, IPA platforms are scalable to the organization's current needs. Besides, they show high connectivity to many software applications and e-procurement systems and offset their shortcomings (Prov.A, B). Thus, IPA facilitates supplier integration and enables the complete automation of entire processes (Cons.C). An IT consultant of Prov.B summarized: "*IPA is a platform to* *integrate future [AI] technologies into a business process without having to restructure the entire organization.*"

Operational Efficiency. The high computing power of IPA systems allows for fast data processing and information exchange. Priv.C noticed substantial time savings. Since bots can autonomously operate day and night, they enhance efficiency and productivity and decrease the process cycle and idle times (Priv.A; Publ.A). Cons.B speculated that IPA, if well-integrated with the supply chain partners, could minimize supply chain inefficiencies that result from poor demand forecasts, unknown inventory, and delayed communication. Particularly private procurement organizations face much cost pressure and, therefore, apply intelligent bots to realize personnel savings (Priv.D; Cons.C). Priv.C implemented RPA and IPA to insource multiple processes formerly done by the shared service center and realized cost savings of around 50 external full-time equivalents. IPA constitutes an adequate alternative for traditional back-end automation depending on the application areas since IPA's return-on-investment (ROI) is usually higher (Cons.A, C, D).

Process Quality. IPA facilitates the data-driven optimization, automation, and monitoring of procurement processes through pattern recognition and in-depth analyses. Bots provide objective results based on data instead of subjective feelings, thereby ensuring regulatory compliance (Publ.A; Cons.A). The informants agreed on a decreasing error rate as the bots' learning and experience levels increase, resulting in more appropriate behavior and accurate predictions. Priv.C reported that the quality of the automated results is at least as good as that of human operators.

Employee Satisfaction. IPA frees up PSM professionals from tedious tasks and allows for a more valuable utilization of their skills and working time. Priv.A and Cons.C reported on workload savings of up to 60 percent. Thus, buyers can focus on activities that require human interaction and advanced cognitive capabilities, e.g., communication with essential suppliers and strategic sourcing decisions (Priv.B, D; Cons.D). Intelligent bots support decision-making with targeted analyses and objective recommendations (Cons.A). IPA can also store and pool the employees' knowledge (Cons.C). Priv.C, Publ.B, and Prov.B emphasized that the communication between a well-trained chatbot and humans proceeds naturally, which fosters its acceptance. Along this line, the informants agreed on higher satisfaction of employees and suppliers due to IPA, facilitating an innovative corporate culture and momentum for further automation. Affected employees are trained to handle AI systems and develop, maintain, monitor, and optimize bots (Priv.C, D; Publ.B). Cons.C reported: "*[With IPA,] the know-how develops to higher levels.*"

4.4 Challenges

Multiple obstacles impede the nascent adoption of IPA in procurement. The participant's expected and experienced *technological, organizational*, and *environmental* challenges are summarized in Table 5, responding to the second part of RQ2. The classification follows the *TOE framework* of Tornatzky and Fleischer (1990), which is a widely used approach to explain the adoption challenges of digital technologies (Kosmol et al. 2019).

Table 5. Challenges of IPA adoption in procurement, according to the TOE framework (Tornatzky and Fleischer 1990)

Technological challenges	Organizational challenges	Environmental challenges
Integration in the IT landscape	Governance	Labor market availability
Requisite standardization and optimization	Internal communication and collaboration	Diverse IPA platforms and providers
Data collection and preparation	User resistance	Insufficient supplier readiness
Training of AI algorithms	Lack of supportive culture	Supply chain risks
Monitoring and maintenance	Lack of management support	Legal regulations
Security issues	Lack of technical expertise	
Lack of transparency	Deskilling	
Restricted capabilities	Implementation costs	

Technological Challenges. Many participants mentioned complex and disparate IT landscapes that impede the integration of new technologies. IPA challenges existing IT infrastructures as it requires more computing power than legacy ERP and e-procurement systems. Proper IT environments are needed to efficiently identify patterns, process data, and infer recommendations for decision-making (Prov.B, C). Intelligent bots require deep IT integration and usually receive their own user profiles and logins. Therefore, high data quality and reliability are crucial prerequisites for IPA since fragmented and disconnected information results in higher efforts for data collection and training (Priv.C). Thus, the comprehensive standardization and optimization of the IT, data, and process landscape before implementing IPA were key learnings of IPA adopters. The consultancies and providers reported on many procurement departments facing difficulties in providing a sufficient and comprehensive data pool on which IPA can be trained. That applies specifically to public organizations due to the high amount of non-recurrent purchases and frequently changing suppliers (Publ.A; Cons.D). Emphasizing the importance of the learning phase, the providers warned of excessive expectations since AI algorithms need a specific time to improve and learn how to separate relevant from irrelevant data.

Once deployed, intelligent bots require continuous monitoring and maintenance due to the higher complexity and more sensitive application than standard RPA (Priv.A). Priv.C and Publ.B pointed out that the proper programming of chatbots, reflecting human behavior as naturally as possible, is crucial for their acceptance and performance. The participants also emphasized the necessary security of data and IT systems. Hacker attacks and potential exposure of employees must be prevented, specifically, if IPA bots handle confidential and personal information (Priv.B; Cons.B). Manipulated training data could result in bias and severe consequences. Thus, IPA platforms need to be reliable, auditable, and scalable (Prov.B).

Although IPA increases data transparency, the underlying AI algorithms are considered "*black boxes*" and lack transparency (Priv.A). Despite considerable efforts undertaken by research and software providers, the still insufficient maturity of relevant AI components currently restricts IPA application areas to rather predictable and routine tasks (Priv.A, C; Cons.D). Besides, a zero-error rate is not yet realizable as the results are based on probabilities (Prov.B). Particularly public organizations raised concerns on IPA's applicability due to the complex nature of their procurement processes, e.g., the high number of indirect spend and human interactions (Publ.C, D, E). Priv.A pointed out: "*The [IPA] algorithms are already good, but not mature yet. Currently, I wouldn't rely on the results.*"

Organizational Challenges. Governance poses a critical issue for the trust and reliability of IPA. The informants found it challenging to establish control mechanisms, define clear responsibilities and rules, detail the human-bot communication, and determine the bot's scope of autonomy and decision-making. The importance of adequate communication and change management for IPA projects was strongly emphasized to yield intra-organizational synergies, prevent excessive expectations, and diminish user resistances (Priv.B; Publ.B). Besides, the issue of job loss anxiety should not be underestimated, particularly with intelligent bots capable of automating the more complex and creative tasks of employees (Cons.A, C).

The lack of supportive culture, specifically in public organizations, was also considered an impediment for IPA initiatives (Publ.C, F). Some participants experienced excessive bureaucracy and powerful yet obstinate works councils, resulting in high and tedious efforts for documentation, justification, and implementation (Priv.D; Publ.A; Cons.A). Therefore, rigid organizational structures need to become more agile, providing time and budget capacities to realize essential IT projects.

It was also reported on lacking strategies and readiness for the digital transformation of PSM (Cons.B; Publ.D). Thus, IPA adoption suffers from poor sponsorship and guidance of the top management. Furthermore, skills required for Procurement 4.0 (e.g., technical and analytical capabilities, holistic and open-minded thinking) are yet to be developed through training (Priv.E, F; Cons.A). In contrast, the concern of potential deskilling was raised (Cons.D). With IPA, employees could be tempted to rely excessively on the bot's recommendations instead of using their minds. Therefore, professionals need further training to evaluate IPA's outcome critically and to prevent the loss of their creative and judgment capabilities.

Considerable implementation costs constitute another crucial adoption barrier (Priv.E, F). The ROI of IPA is much lower than for RPA due to the more complicated and deeper IT integration, higher initial investments, and license costs (Cons.A, C; Prov.A). That also includes higher costs for bot onboarding and maintenance. Cons.C and Prov.C speculated that those expenses could impede the adoption at SMEs. The polar case organization Priv.F terminated an initial IPA project due to the high costs for implementation and training as well as lacking capabilities and performance of IPA. Priv.E explained: "*With RPA, we're talking about 50,000 Euros per process. With AI, we're talking about a factor of ten.*"

Environmental Challenges. Since most interviewed organizations seek the implementation and upscaling of AI technologies, qualified experts for such projects pose a scarce resource. Due to the rigid hierarchies and salary structures, public organizations struggle to find skilled employees (Publ.C, D, E, F). Another challenge is the growing variety of IPA providers and platforms, each with different functionalities and license models. Therefore, the crucial in-depth analysis of suitable partners and systems is very time-consuming (Priv.A, C; Cons.B). AI also dehumanizes buyer-supplier relationships (Priv.C). While Priv.C and Cons.C stated that the suppliers' collaboration and digital readiness are neglectable for IPA, their importance was strongly emphasized by Cons.A, B, D since lacking supplier readiness impedes the adoption of new technologies within the supply chain. Faulty and untuned bots could cause severe consequences, e.g., distribution delays and supply shortages due to incorrect purchase orders or payments.

Legal regulations, specifically national and transnational procurement law, constitute a substantial challenge for public organizations. They do not necessarily maintain strong buyer-supplier relationships due to the mandatory objective tendering of most purchases. Therefore, the restrictive rules could impede an optimization mindset and limit the scope for action (Publ.B, C, E). Thus, bots need continuous and extensive training on interpreting different legal regulations to ensure high compliance when they are applied in public tendering processes. Cons.A summarized: "*Process automation is always a sensitive topic, especially in the public sector.*"

4.5 Impact on the Future Development of Procurement

Providing implications for future research and responding to the third research question, the mentioned impacts of IPA adoption on the future development of procurement can be classified into three major issues: the *technology, PSM function*, and *PSM employees.*

Technology. The participants concurred on the importance of the flexible IPA platform approach and profound RPA experience for successful projects. RPA will remain cheap and more applicable for specific rule-based and structured procurement tasks. Therefore, IPA and RPA often go hand in hand (Priv.A; Publ.B; Cons.C; Prov.B): IPA can structure and standardize data before passing to an RPA bot. In contrast, AI technologies can be applied to the RPA output to conduct more in-depth analyses, pattern recognition, predictions, and decision-making (Priv.C; Cons.A). Due to the high complexity of IPA, the consultancies and providers recommended organizations not to develop their own solutions and reported on negative experiences of respective customers. Indeed, all IPA adopters rely on external software platforms and support. However, building internal know-how to develop, deploy, and maintain intelligent bots was strongly emphasized and regarded as a vital prerequisite for further adoption (Priv.A, C; Publ.A, B). Besides, voice recognition and deep learning are highly desired capabilities (Priv.D; Cons.C, D). Although most participants considered AI components crucial for achieving a high degree of process automation in procurement, the experts of the polar case organization Priv.F stated: "*AI would have only made sense if we had pursued a large-scale implementation to save people. But that wasn't the case.*"

PSM Function. Many interviewed purchasing managers drive their organizations' digital transformation. The informants concurred that procurement departments need to become more agile and provide a sufficient data pool for IPA training by restructuring and standardizing their workflows. Besides, highly digitized departments within the same enterprise, innovative start-up companies or suppliers, and specialized fairs provide suitable possibilities for mutual exchange and learning (Priv.B; Publ.B). All informants agreed on IPA accelerating the ongoing change of the PSM function towards an increased strategic focus. Operational activities will be decreasing and performed by bots and other intelligent systems. In return, the communication and quality of internal and external relationships will become more relevant, e.g., due to supplier integration. Cons.B claimed: "*In my opinion, operational purchasing and buyers will definitely disappear.*"

PSM Employees. Although process automation naturally evokes employee anxieties, the informants reported that most PSM professionals are open-minded towards IPA and give higher weight to the resulting workload relief than corresponding fears and reservations. In light of the upcoming demographical change, digital transformation and automation are vital to enhance the organization's attractiveness and recruit necessary experts (Priv.D, E; Publ.A, C, D). However, IPA adoption should go hand in hand with holistic change management, involving affected employees as future buyers need an adjusted skill set, e.g., profound abilities related to IT, automation, analyses, communication, and strategic thinking (Cons.B, C). Therefore, procurement departments must undertake high training, coaching, and reskilling efforts, resulting in new job profiles (Priv.A, C; Cons.A) and potentially higher salary grouping of the employees (Publ.D, E). Priv.C and Publ.B emphasized the allocation of responsibilities to facilitate seamless human-bot collaboration. Finally, the experts of Priv.D disagreed with Cons.B's statement: "*We don't think that an operational buyer is completely replaceable with AI.*"

5 Discussion

Since this study is among the first that qualitatively examines IPA adoption in procurement, it provides initial yet profound insights into suitable application areas, related benefits and challenges, and IPA's impact on the future development of the PSM discipline. In the following, the findings are discussed with relevant literature to outline theoretical and managerial implications. Thereby, future research directions and practical recommendations are deduced to facilitate the still-nascent adoption of IPA in procurement. Moreover, the study's limitations are explained.

5.1 Theoretical Implications

The results outline the increasing impact of IPA on the PSM function and indicate its value potentials, thereby substantiating and enriching the rather general findings of the limited IPA research in purchasing (Allal-Chérif et al. 2021; Nicoletti 2020; Teli and Prasad 2018). It was found that most of the discovered benefits and challenges of IPA for PSM also apply to other business functions like accounting or auditing (Gotthardt et al. 2020; Zhang 2019).

This study complements and extends prior work by presenting novel application areas and emphasizing previously neglected aspects of IPA, such as IT integration, restricted capabilities, lack of supportive culture and technical expertise, implementation costs, legal regulations, and supplier issues. However, the findings also deviate from the literature in specific points. Thereby, aspects that might not be mentioned do not necessarily imply irrelevance but indicate that other factors might be more relevant to the participants. In the study, for example, the cost-saving potentials of IPA were predominantly related to personnel savings. Beyond that, IPA also decreases the costs for transactions and maverick buying due to a higher spending control and improved sourcing (Allal-Chérif et al. 2021; Nicoletti 2020). Furthermore, the experts highlighted substantial training efforts of employees, while IPA can also decrease the training need on legacy e-procurement systems and applications (Nicoletti 2020). Most informants neglected the "*black box problem*" of IPA's underlying AI algorithms. However, this essential issue should be addressed by developing transparent and interpretable models (Gotthardt et al. 2020).

The participants require more detailed guidance for IPA implementation in PSM and transition from RPA than currently provided by the literature. Therefore, corresponding to RQ3, future conceptional and empirical research should build on the technical, organizational, and environmental challenges identified in this study and provide answers to urgent questions of the informants, such as: How to implement and upscale RPA and IPA in PSM? Which platforms, license models, and sourcing options are appropriate for which contexts? How to build know-how and realize the knowledge transfer from private to public procurement? How to identify and select suitable processes and measure the performance impact? How to increase the transparency of IPA procedures? When to trust a bot and allow for autonomous decisions? What type of human-bot or bot-bot collaboration is appropriate, and which capabilities of humans and bots are required? How to develop and communicate an appropriate digital transformation strategy for PSM? How to facilitate IPA adoption on both sides of the buyer-supplier dyad? How to establish and maintain good buyer-supplier relationships with IPA? How to attract and retain qualified experts with IT and AI skills for procurement departments, particularly in the public sector?

5.2 Managerial Implications

The study findings can serve as reference points for managers in the private and public sector to facilitate IPA adoption in procurement and identify initial application areas. While the technology promises high potentials, the results indicate that the related technological, organizational, and environmental challenges should be tackled first. The often lacking digital readiness of procurement departments impedes IPA adoption, particularly in the public sector (Hartley and Sawaya 2019; Kosmol et al. 2019). However, as a central and vital business function, purchasing needs to foster the digital transformation and become more internally integrated and strategically focused since isolated AI initiatives quickly fizzle out (Allal-Chérif et al. 2021; Bienhaus and Haddud 2018). Besides, AI dehumanizes buyer-supplier relationships (Allal-Chérif et al. 2021; Bals et al. 2019; Kosmol et al. 2019). While the positive and forward-looking attitude of the participants' employees reflects the prevailing scientific discourse (e.g., Van Looy

2020; Willcocks 2020; Zhang 2019), low-skilled workers could find it challenging to compete with intelligent bots and, thus, resist the fundamental digital transformation. Therefore, procurement department managers should consider the changing skill sets and job profiles of future buyers and increase the awareness for Procurement 4.0 among their employees and supply chain partners. In addition, the top-level management has to enhance digital readiness by developing a targeted PSM digitalization strategy that includes IPA.

Although the providers stressed the high applicability and flexibility of IPA, intelligent bots are still restricted to rather repetitive, non-creative, and not-knowledge-intensive processes. Workflows that require contextual decisions or social activities based on human interaction and empathy (e.g., for motivating or convincing) are currently less suitable for IPA (Van Looy 2020). Therefore, software providers need to enhance the capabilities. At the same time, organizations should provide the prerequisites for IPA adoption by standardizing complex IT landscapes and workflows and ensuring high data quality and reliability.

Before introducing the technology, organizations should conduct profound cost-benefit calculations and provider analyses since the high implementation costs pose a considerable challenge (Chakraborti et al. 2020; Gotthardt et al. 2020; Zhang 2019). Therefore, RPA can be a cheap and sufficient alternative for specific tasks and an initial step for large-scale process automation. However, training efforts for employees as well as the comprehensive and reliable data pools required for the efficient learning of intelligent bots, should not be underestimated. Therefore, holistic change management guides the adoption of IPA, dissipating employee resistances and preventing excessive expectations.

Furthermore, decision-makers should expand the scope of IPA projects on other departments and the supply network to drive joint initiatives. The co-evolution of the buyer-supplier dyad fosters the digital readiness and implementation of intelligent technologies for procurement (Kosmol et al. 2019). When preparing IPA projects and bot deployment, particularly public organizations need to consider procurement law and legal regulations regarding AI integration. Finally, organizations should invest in enhancing their attractiveness to recruit and retain qualified experts early on.

5.3 Limitations of the Study

Despite the applied methodological rigor, this empirical paper is subject to some limitations that need to be considered when interpreting the findings.

Firstly, as a qualitative interview study, the number and variety of the examined organizations are restricted. Although the chosen approach yielded rich primary and secondary data, particularly from providers and consultancies (e.g., client reports), the results mainly build on large organizations headquartered in Europe. However, IPA adoption is expected to grow also in emerging countries and SMEs (Markets and Markets 2020). Thus, future studies should involve organizations from different geographical locations (e.g., North America, Asia), branches, and sizes.

Secondly, although the inclusion of informants from various hierarchical levels and domains enriched the debate, interviews with more than one expert could suffer from a potential bias as informants might not speak freely or could be tempted to just agree with another opinion. Therefore, more objective, quantitative approaches could confirm, complement, or disprove the presented findings.

Finally, IPA adoption is still in its infancy in most examined procurement organizations, particularly in public ones. Therefore, this study seeks to provide practitioners and scholars with initial empirical insights on application areas, benefits, and challenges to successfully start and conduct an IPA initiative. However, future research should go beyond and also tackle issues related to the upscaling of IPA and AI technologies that still lack profound practical experiences and theoretical underpinning (Chakraborti et al. 2020; Gotthardt et al. 2020). For example, potential synergies and interrelations with other business functions and suppliers could be investigated.

6 Conclusion

This pioneering multiple case study contributes to the nascent body of literature by providing comprehensive insights on the PSM impact of the rapidly disseminating IPA technology. Nineteen organizations were interviewed, including private and public procurement departments, procurement consultancies, and RPA/IPA software providers. The implications of this paper could provide a starting point for further research and practical adoption. IPA facilitates the saving of time and costs as well as thorough decision-making, prediction, data gathering, preparation, and analysis. Thereby, the technology is applicable for multiple operational, tactical, and strategic procurement tasks. Organizations benefit from the increasing level of standardization, operational efficiency, process quality, and employee satisfaction. However, for more widespread adoption in PSM and other business functions, IPA needs to overcome various technological, organizational, and environmental challenges detected by this study. The quote of an IT project manager of Priv.B summarizes the paper's essence: "*IPA has much potential and will definitely emerge. The adoption is just a matter of organizational readiness and courage. However, the movie "Terminator" used to amuse me, but now it just scares me.*"

Acknowledgments. This research was supported by the EU project iDev40. The project iDev40 has received funding from the ECSEL Joint Undertaking (JU) under grant agreement No 783163. The JU receives support from the European Union's Horizon 2020 research and innovation programme. It is co-funded by the consortium members, grants from Austria, Germany, Belgium, Italy, Spain, and Romania. The content of this article does not reflect the official opinion of the Joint Undertaking ECSEL. Responsibility for the information and views expressed in the article lies entirely with the author. In addition, the author would like to express his sincere gratitude to Lena Otto, who has contributed to the improvement of earlier versions of this paper.

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MAP 4.0 – Proposal for a Prescriptive Maturity Model to Assess the Digitalization of Procurement

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Abstract. The digitalization of supply chains offers great opportunities, especially with regard to procurement. To effectively implement innovative concepts, it is necessary to evaluate procurement departments' current situations and create target-oriented recommendations for action. Suit-able maturity models can help to achieve these goals effectively. However, most existing models do not consider the specifics of pro-curement and Industry 4.0 technologies and fail to define realistic digitalization goals. In this paper, a model called MAP 4.0 is proposed to assess procurement organizations' maturity and derive realistic tar-get conditions. A qualitative and deductive methodology is applied to analyze existing maturity models. Based on the findings, the maturity assessment model MAP 4.0 is developed according to the methodolo-gy of de Bruin et al. (2005). By focusing on the specific field of Procurement 4.0, the requirements and needs can be considered in more detail. In addition, target states and recommendations for actions can be devel-oped. The model includes the relevant dimensions of digitalization and defined weighted items for measurement. In this way, the study lays the foundation for future research, provides valuable insights for procurement managers, and can contribute to the digitization of procurement.

1 Introduction

The digitalization of industry will fundamentally change the way manufacturing organizations function. The phase of the fourth industrial revolution is often referred to as Industry 4.0. This revolution is characterized by global, digitalized environments, interconnected value chains, and automated production systems (Bibby and Dehe 2018). It is driven by advancements in the field of information and communication science. The term Industry 4.0 became popular through the international trade fair in Hannover, Germany, in 2013 (Bauernhansl et al. 2014). While the innovations of Industry 4.0 are often reduced to the use of innovative technologies, there are many more factors that shape this industrial revolution. Merz and Siepmann (2016) formulate five fundamental paradigms of Industry 4.0: vertical and horizontal integration, decentralized intelligence, decentralized control, end-to-end digital engineering, cyber-physical production systems. These paradigms have a particular influence on the categories of products, personnel and corporate strategy.

U. Buscher et al. (Eds.): *Logistics Management*, LNLO, pp. 90–104, 2021.
https://doi.org/10.1007/978-3-030-85843-8_6

All functions of companies are affected by this revolution and will experience radical changes, including procurement departments (Sony and Naik 2019). Implementing the Industry 4.0 initiative in procurement is often referred to as Procurement 4.0 (Nicoletti 2018). During this revolution, the role of procurement will change from a purely internal service provider to a strategic partner with a central control function. Operational activities will be increasingly automated, and strategic tasks will gain importance. Instead of focusing solely on cost reductions, the procurement department is increasingly required to create added value for the company and support supplier innovations. Furthermore, the role of procurement departments in terms of the provision of information, with regard to efficiency, effectiveness and profitability, is becoming increasingly important, as more and more internal and external data can be collected and analyzed (Bienhaus and Haddud 2018). The development towards Procurement 4.0 can enable companies to generate improved short-term adaptability through increased flexibility in procurement processes and help the company be more competitive (Bag et al. 2020). To meet the growing expectations of customers, business partners, and internal stakeholders, procurement must become faster, more interconnected, and more agile (Nicoletti 2018). The concept of Industry 4.0 demands a comprehensive use of innovative technologies and process re-engineering.

However, companies must overcome particular challenges that go hand in hand with the Industry 4.0 revolution. Businesses need to manage the complex value chains in an agile and responsive manner amid aggressive competition, volatile markets, and individual customer requirements (Pirola et al. 2019). The innovative technologies and concepts associated with Industry 4.0 also demand detailed understanding and organizational capabilities to leverage them. Organizations need the capabilities to respond to these changes on a global scale to achieve sustainable success (Asdecker and Felch 2018).

According to the Dynamic Capability Theory, maturity models can help companies react to the changes in a meaningful way and overcome challenges and fully flourish under these new conditions (Winter 2003). An organization must continuously realign itself, evolve and support change through innovation and its dynamic capabilities to ensure long-term competitive success (Teece et al. 1997; Winter 2003). This paper aims to uncover the current state of maturity models in the field of Procurement 4.0 and propose a model based on the findings. Therefore, the following two research questions are formulated:

RQ 1: Are existing maturity models sufficient to adequately assess the development of Industry 4.0 in procurement departments?

RQ 2: How would a comprehensive maturity model for evaluating the Industry 4.0 initiative in procurement be constructed?

The paper is structured as follows. Section 2 provides the theoretical background of maturity models and compares relevant models represented in the literature. Section 3 presents the methodology used for developing and validating the model. The MAP 4.0 model is presented and validated in the following chapter 4. Section 5 concludes the paper. The appendix to this paper can be found in the OpARA open access repository (http://dx.doi.org/10.25532/OPARA-113).

2 Literature Review and Theoretical Background

The digitalization of procurement and assessment of companies' maturity are discussed in a broad field of literature. The following literature review provides the basis for a comprehensive analysis of available literature on maturity assessment models for the digitalization of procurement and identifying the main research gaps.

Maturity models are conceptual structures with elements for determining an object's development status under consideration, described by dimensions and levels (Santos and Martinho 2019). In addition to determining the object's current maturity level, the definition of target states usually plays an essential role. The collection of the relevant data is typically done through expert surveys, interviews or questionnaires. Some models resort to the possibility of weighting the elements and dimensions to obtain a more precise result (de Bruin et al. 2005). Maturity models are used in economics and other disciplines, such as medicine and computer science. According to Santos and Martinho (2019), when designing these maturity models, it is crucial to define four key elements: (1) dimensions, (2) transformation capabilities, (3) assessment questions, and (4) maturity levels. All these elements are to be considered in their interconnectedness to assess the maturity level of an object. Starting points for development can be found in the respective individual elements.

Maturity models can be roughly divided into descriptive, prescriptive and comparative models (de Bruin et al. 2005). These categories can also be understood as development stages. The descriptive models serve exclusively to describe the current condition based on a unique collection of the relevant measured data. These models are primarily suitable for obtaining a detailed and specific overview of the current situation of the object of observation. The second stage is formed by the prescriptive models, which also establish a reference to performance and reveal indicators of how best to achieve a higher level of maturity. This includes the definition of target states and corresponding instructions for action. For a precise assessment, regular repetitions of the measurement are necessary to recognize developments. The maturity models with the highest level are the comparative models, which consider an object of observation and compare it with other objects of the same industry or region (de Bruin et al. 2005).

A systematic literature search was conducted to acquire an overview of existing maturity models in the field of Procurement 4.0. The search took place in September 2020 and was based on the SLR model of Tranfield et al. (2003). Common databases were used to identify relevant models, including *ScienceDirect*, *Emerald Insight*, *Scopus*, *Web of Science*, *SpringerLink*, *Business Source Complete*, *Wiso*, and *Google Scholar*. The search terms covered "Industry 4.0", "Fourth Industrial Revolution", "Industrial Internet", "eProcurement", "Procurement 4.0", "Internet of Things", "IoT", and "Digitalization" in combination with "Maturity Model", "Capability Model", "Assessment", "Roadmap", "Implementation", and "Readiness". The literature was examined for relevance based on titles, abstracts, and, finally, full text. In total, 32 Papers that presented a model with significance were included for further analysis. This analysis was based on the quality criteria according to Teeuw and van den Berg (1997).

Teeuw and van den Berg (1997) constructed an evaluation framework for business process models and introduced six quality criteria for conceptual models: (1) Completeness, (2) Inherence or Propriety, (3) Clarity, (4) Consistency, (5) Orthogonality or

Modularity, and (6) Generality. For this study, these quality criteria were combined and partly specified to focus on Procurement 4.0 (Table 1). In addition to the adapted quality criteria, the criterion "Definition of a target state" was added to determine whether the models have reached the level "prescriptive" (de Bruin et al. 2005). For the adjusted criterion "Inclusion of all relevant Industry 4.0 technologies", the work of Bai et al. (2020) was used.

Table 1. Evaluation criteria for maturity models

Generic criteria	Specification	Description
Generality, Inherence or Propriety, and Orthogonality or Modularity	Applicability to procurement	Construct models essential features of the object of consideration. The independence/dependence of model constructs is the same as the independence/dependence of corresponding real-world aspects
Completeness	Inclusion of all relevant Industry 4.0 technologies	Constructs are sufficient to capture all essential aspects of Industry 4.0 technologies, including additive manufacturing, artificial intelligence, blockchain, cloud computing, cybersecurity, big data, web analytics, internet of things, simulations, and mobile technology
Comparability and Consistency	Description of assessment method	The study provides a complete description of the assessment method to make the studies comparable and repeatable. Measurements do not conflict, are not ambiguous, and are parsimonious
Clarity and comprehensibility	–	The conceptual model is understandable by the user. The appearance, media used, and content visually appeal on the physical layer (Falkenberg et al. 1998)
Definition of a target state	–	The model defines a target state for the practitioners to aspire to

The results of the analysis are shown in Table 3 (appendix). The main limitations of existing maturity models relate to their applicability in procurement and the complete representation of the relevant Industry 4.0 technologies. It was also found that a large number of models do not deal with the description of target states. Furthermore, it was determined that many maturity models do not meet the modularity criterion due to their monolithic structure. Answers by participants forced to respond to questions outside their realm of competence can lead to distorted results. Against this background, RQ 1 can be answered with the fact that existing maturity models are incomplete in the field of Procurement 4.0, and therefore a research gap could be identified. To close this gap, the following sections describe the development of the MAP 4.0 model, which attempts to address these limitations by combining existing models and integrating new elements.

To develop the model, reference is made to the knowledge already gained from existing models. Therefore, two outstanding models were chosen as the basis for development. These models were selected according to the following procedure. In the first step, those models were chosen that apply to procurement since this is considered the most crucial criterion. From these nine models, the five models were sorted out, which fulfil less than three criteria. The four remaining models all met the same number of criteria (three out of five). The Kleemann and Glas (2017) model was ultimately selected because it accurately describes the assessment method, is highly comprehensible and lends itself well to expansion. However, it does not provide appropriate target states for practitioners. Therefore, the model of Wagire et al. (2020) was used as an extension since the definition of target states in this model is remarkably well proposed, and the two models, therefore, complement each other exceptionally well. Therefore, these models serve as a structural starting point for creating the MAP 4.0 model in the following sections.

3 Methodology

This section illustrates the procedure adopted for the development and validation of the model. To this end, this paper is theoretically grounded in design science. According to Hevner et al. (2004), design science tries to improve organizations' capability to employ innovative artefacts. To create compelling artefacts, such as maturity models, a rigorous approach must be applied to their creation and evaluation. A generic methodology has proven to be useful for developing highly generalizable and standardized models that can be incrementally improved over time. Hence, this paper rigorously follows the generic model development methodology of de Bruin et al. (2005), which includes the following six phases: scope, design, populate, test, deploy and maintain (Fig. 1).

Fig. 1. Phases of the model development process (de Bruin et al. 2005)

The first phase serves to generally define the scope of the model and thus establishes the general framework for further model development. All subsequent steps are based on definitions of this first phase. De Bruin et al. (2005) distinguish between domain-specific and general oriented models. Also, de Bruin et al. (2005) request the definition of the stakeholders interested in creating the model and contributing to its creation.

The second phase aims to shape the model by outlining further criteria. Firstly, this includes the intended audience. The model can distinguish between internal and external parties. While the internal group is interested in the current level of maturity and potential improvement approaches, the interest of external groups usually consists exclusively in the current state to compare it with other companies. Further criteria are the application method, drivers of application, respondents and application. The definition of the application includes the application area and the determination of the frequency of the implementation. The application ranges from a one-time survey in one region, multiple surveys in one region and multiple surveys in several regions. Furthermore, it is necessary to define a scale with degrees of development, whereby the individual levels need to be clearly defined and the transitions between the levels recognizable.

The population phase represents the core of the model development process. Specific components and subcomponents that best capture the model object's requirements and relationships are introduced, and suitable measurement instruments to quantify these (sub-) components are defined. The relevant components should be derived from the systematic review of the literature and empirical methods such as stakeholder interviews and case studies (de Bruin et al. 2005). Suitable measurement instruments are required for the precise determination of the defined components. To collect the relevant data, assessment questions are designed for each sub-component, usually answered based on a Likert scale. These questions are based on existing models and further developed with the help of expert interviews.

After the model's basic creation, phase four calls for testing the model and ensuring quality criteria such as validity, objectivity, reliability, and resonance in practice. To this end, several methods are suggested, including case studies, surveys, and literature reviews (de Bruin et al. 2005). For the validation of the MAP 4.0, a case study according to Göthlich (2003) and Yin (2009) was conducted. Yin (2009) describes the procedure for a case study using the following steps: (1) planning and design; (2) data collection; (3) analysis; and (4) report. The first step is to develop the research protocol, which describes the case study's complete process. In particular, the problem and the goal of the case study must be clearly defined. Afterwards, the data collection method and number of cases need to be determined. The planning phase is concluded with a pilot test to obtain initial feedback on the designed case study (Göthlich 2003; Yin 2009). In the second step, the data is collected using the specified data source. The third phase aims to analyze the collected data to identify patterns and solve the problem posed at the beginning. The last step consists of the quality assessment of the case study itself. The study should provide information about the new model's applicability regarding the quality and suitability of the individual sub-aspects and the scientific quality of the model in its entirety.

Phases five and six of the model development process aim to deploy the model for actual use and ensure its lasting relevance through subsequent changes and adaptations. However, these phases are not part of this paper but represent the starting point for future research.

4 Development and Validation

This chapter describes the creation of the MAP 4.0 model by strictly following the procedure of the framework of de Bruin et al. (2005) presented in chapter 3. For this purpose, the dimensions and subcategories are introduced before the calculation of the maturity level is presented. The validation concludes this chapter.

4.1 Scope and Design

The model's focus is domain-specific since its goal is to comprehensively analyze and evaluate procurement departments' current Industry 4.0 maturity status to uncover potential action needs. The relevant development stakeholders consist of a combination of academics and practitioners. The input by academics occurs with the model development by derivation of essential structures, aspects and factors from current research. The influence of practitioners especially takes place in the introduction and evaluation of the model.

The MAP 4.0 model's primary use is to evaluate the company's procurement department regarding their development status in the context of Industry 4.0. Although the results may serve for benchmarking, it is not its primary purpose. Therefore, the target group can be defined as internal. The maturity measurement is carried out by means of self-assessment and should be repeated regularly to ensure long-term control and target achievement. While the target group is mainly internal, the drivers for performing the maturity measurement can generally be internal and external. One of the most common internal drivers is the improvement of processes and structures in times of technological and global change. Especially the pressure of digitalization forces organizations to evaluate internal aspects. Moreover, topics such as internal benchmarking or investment planning may be reasons for evaluation as well. The most common external driver is the pressure exerted on the company by the competition, by cooperating partners, and by customers.

In addition to the definition of conceptual framework aspects, the formulation of the maturity levels and their characteristics is crucial. Figure 2 presents the MAP 4.0's five consecutive levels and the corresponding overall maturity index (MaI), the calculation of which is described in chapter 4.2. These maturity levels are derived in part from the models according to Wagire et al. (2020) and Kleemann and Glas (2017) and also from pre-surveys of the development stakeholders.

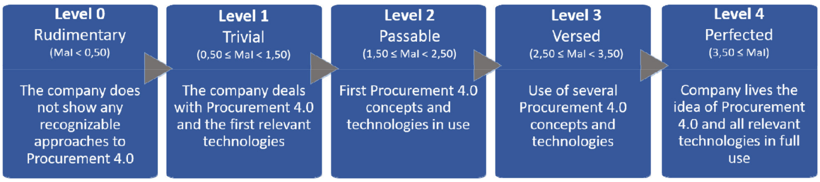

Fig. 2. MAP 4.0 maturity levels

Both operational and strategic inputs are necessary to gather the required information and draw a clear picture of the maturity level. Therefore, it is essential to survey both executives and employees. For permanent monitoring of the maturity level and its development, it is crucial to carry out several measurements at regular intervals. Although not the primary purpose of this model, measurement at multiple sites would be conceivable and facilitate internal benchmarking.

4.2 Populate

This section describes the dimensions, transformation capabilities, and how to calculate the maturity. These aspects are based on the findings of the literature review and the discussions with development stakeholders. For the complete evaluation of procurement departments' Industry 4.0 maturity, the assessment model must cover four relevant categories. These four relevant categories are "technologies", "organization", "strategy" and "personnel" (Kleemann and Glas 2017; Lichtblau et al. 2014; Pirola et al. 2019; Wagire et al. 2020). The MAP 4.0 covers those four main aspects and defines the primary dimensions as "IT structure and Industry 4.0 technologies", "Corporate strategy and culture", "Organization and processes", and "Employees". After the conceptualization of the dimensions, the associated weightings are defined (Table 2). The weighted importance of dimensions plays a decisive role (Wagire et al. 2020). The weighting of the individual dimensions was determined in collaboration with the development stakeholders and is based on a subjective assessment. However, these weightings can be customized should an organization choose to focus differently.

Based on the dimensions, subcomponents, called transformation items, are defined. These elements serve as measurement items of the respective sub-aspects of the dimensions, which in turn determine the overall maturity. A large number of categories were selected to achieve a high level of granularity. Omitting subcomponents could jeopardize completeness. Related assessment questions are formulated to measure each component's degree of fulfilment (Table 6, appendix). An expanded 5-step Likert scale is available to interviewees to evaluate these assessment questions. A Likert scale is the most common method for evaluating the assessment questions in maturity models and has proven to be very useful in practice (de Bruin et al. 2005). The five levels of evaluation are as follows: (0) "does not apply at all", (1) "applies slightly", (2) "applies partly", (3) "applies largely", and (4) "meets completely". Additionally, the option (N) for "not relevant" or "not assessable" within the questionnaire is available to ensure that subcomponents that would falsify the assessment can be eliminated. That way, MAP 4.0 aims to meet the modularity criterion presented in Table 2.

As part of the evaluation by the MAP 4.0, the respondents must not only provide an assessment of the current status quo but also of what they consider to be the desirable target status. It is important to note that the desired target state does not always have to correspond to the maximum level, as this is not always necessary for different companies or industries. While some subcomponents, such as "training" and "automated order initiation", will usually have a maximum level as target states, factors like "artificial intelligence" or "additive manufacturing" won't always be necessary to be fulfilled to the maximum. The idea of the additional definition of target states originated from Wagire et al. (2020). It was otherwise pursued by only a few other models and no models with a focus on procurement. However, this approach appears to be extremely promising, as it offers companies the opportunity to uncover focal points for action by calculating the most promising aspects for improvement. Maturity models in the area of Procurement 4.0 should define target states to reach the next level of models, the "prescriptive" models.

The following section describes the procedure for calculating the Procurement 4.0 maturity based on the defined components and identifying promising focal points. In the first step, the respective average of the ratings given for both the actual and target state is calculated for each subcomponent queried. Once this calculation is complete, an averaged actual state and an averaged target state are available for all 50 subcomponents. These values form the averaged actual and target state for each of the four dimensions. With the weightings of the dimensions (Table 2), the overall maturity index (MI) and the overall target maturity can now be determined. According to MaI's value, a Procurement 4.0 level can be assigned to the respective procurement department (Fig. 2). Based on the actual and target values, relevant focal points of action can be derived. Companies should focus on the transformation items with the most significant deviation between actual and target state to improve overall maturity. These components promise the highest potential for improvement and are therefore the optimal starting point for deploying resources in a targeted manner, increasing the overall maturity of procurement, and ensuring approval among the questioned employees.

Table 2. MAP 4.0 dimensions and transformation items

Dimension (Weighting)	Transformation Item	
I. Employees (25%)	1. Knowledge / Understanding	6. Openness
	2. Recognizing Opportunities	7. Autonomy
	3. Employee Support	8. Flexible Working Models
	4. Skills	9. Interdisciplinarity
	5. Training / Education	
II. Corporate strategy and culture (20%)	10. Change Awareness	15. Corporate Model
	11. Digitization Strategy	16. External Partners
	12. Defined Resources	17. Organizational Involvement
	13. Communication of Benefits	18. Open Innovation
	14. Progress Monitoring	
III. Organization and processes (30%)	19. Automated Ordering	26. Automated Supplier Assessment
	20. Automated Decision Support	27. Automated Supplier Forecasting
	21. Automated Contracting	28. Supplier Integration
	22. Automated Key Figure Reporting	29. Decentralization

(*continued*)

Table 2. (*continued*)

Dimension (Weighting)	Transformation Item	
	23. Automated Demand Determination	30. Cooperation within the company
	24. Real-Time Information	31. Accountability
	25. Potential Scenario Modelling	32. External Support
IV. IT structure and Industry 4.0 technologies (25%)	33. Cyber Security	42. Automated Data Collection and Analysis
	34. Networking	43. Cloud Computing
	35. Specialized Software	44. Blockchain
	36. Risk of System Failure	45. Internet of Things
	37. Mobile Devices	46. Internet of Services
	38. IT Hardware	47. Big Data & Web Analytics
	39. IT Support	48. Simulation Tools
	40. Data Availability	49. Artificial Intelligence
	41. External System Compatibility	50. Additive Manufacturing

4.3 Test

A case study was conducted in one of the largest German bread and baking goods manufacturer, methodically following the procedure of Göthlich (2003) and Yin (2009). In addition to validate the model's quality and suitability, the surveyed employees were asked to compare the Map 4.0 with the models by Wagire et al. (2020) and Kleemann and Glas (2017). Of the ten interviewees, four worked in operational purchasing, three in strategic purchasing, and two employees worked in the IT department. Furthermore, one managing director of production was interviewed.

The survey was conducted with each interviewee individually. The participants were presented with all three questionnaires separately to prevent answer transferring between the questionnaires. The questionnaire of Kleemann and Glas (2017) was visually adapted to ensure uniformity (Table 4, appendix). The questionnaire of Wagire et al. (2020) was not attached to the journal article. Therefore, assessment questions were introduced to conduct the survey (Table 5, appendix). The MAP 4.0 questionnaire (Table 6, appendix) is visually based on the works of Kleemann and Glas (2017). The results of the MAP 4.0 measurement are depicted within a diagram (Fig. 3). The blue line symbolizes the subcomponents' actual maturity, while the red line represents the target states. The subcomponents with the most significant potential for improvement can be identified visually by the greatest deviation of the two lines. For example, subcomponent 20 has a very low actual maturity and an extremely high target maturity and therefore has an exceptionally high potential for improvement. On the other hand, the current development level of Item 8 is already extremely high and therefore the potential improvement to get to the measured target state is very low. Item 50, for example, also offers little room for improvement. Although item 50s actual state is considered extremely low in this survey, the target state was also very low.

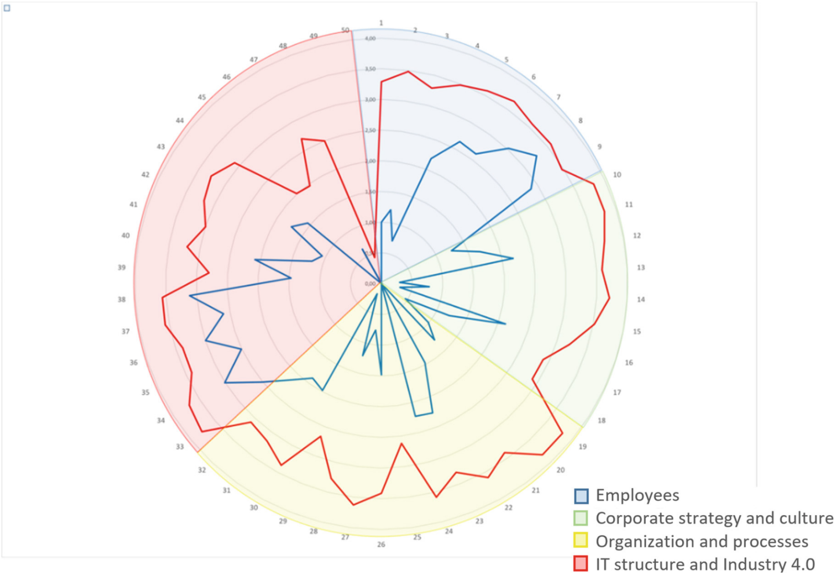

Fig. 3. MAP 4.0 diagram

After visualizing the results, the models were compared to each other. In the first step, the structure of the models and the survey results were compared. The first finding is that the level of detail of the MAP 4.0 is much higher than the comparative models due to the use of numerous subcomponents. These components were chosen to ensure the most accurate picture of reality. The participants' feedback pointed out that the high number of components helped promote completeness and did not demand excessive effort.

When comparing the dimensions and categories of the three models, other differences can be observed. Kleemann and Glas (2017) focus firmly on the procurement business area. However, tangential topics such as IT and organizational structure are not given the importance they should receive in a connected company. The model of Wagire et al. (2020), on the other hand, is not purchase-specific enough. The MAP 4.0 tries to remedy this issue by utilizing a balanced mixture of two purchasing-specific and two general dimensions.

Furthermore, by helping to define target states and resulting derivation of action courses, the MAP 4.0 aims to help procurement departments to reach a higher Industry 4.0 maturity. Merely pointing out the current maturity does not necessarily allow optimal courses of action to be found. Just because a subcomponent is particularly poorly developed does not mean improving it helps the company optimize its Industry 4.0 maturity. The attempt to enhance aspects with low potential leads to a wrong allocation of resources.

The participants were also asked to determine the model they considered most suitable. Of the ten participants, seven chose MAP 4.0 as their preferred model. Three respondents chose the model by Kleemann and Glas (2017), and none of the interviewees chose the model by Wagire et al. (2020).

For the results of this case study to be valid, they must meet the quality criteria according to Göthlich (2003). By the transparent execution of the model development and the case study, the adherence to the principles of proper case study research, controllability, and objectivity were met. The constant critical illumination of the results and potential interpretations were done to achieve internal validity. In contrast, the principle of external validity was achieved by involving the development stakeholders and respondent's feedback and the theory-driven development of the model using various sources in the process. The reliability principle is fulfilled by digitizing and archiving the survey results and continuous and transparent protocol management.

5 Conclusion, Limitations, and Future Research

The literature review shows a lack of maturity models for the assessment of procurement in the context of Industry 4.0 that reached the level "prescriptive model". Mainly the focus on procurement, relevant Industry 4.0 technologies and the definition of appropriate target states were insufficiently covered in existing models. This article proposes a theoretically grounded, methodologically rigorous developed, prescriptive maturity model for the assessment of procurement in the context of Industry 4.0. It maps the specifics of procurement departments and shows potentials through the trend of Industry 4.0. In addition, the model is used to identify target states and areas for action. It addresses the most influential dimensions concerning the research topic.

A subsequent case study was conducted within a company from the food industry to test the model. It was shown that the model was able to paint an accurate picture of the procurement department´s Industry 4.0 maturity. Of the participants, 70% confirmed that they preferred the MAP 4.0 to the two reference models. Moreover, the model enabled the derivation of action priorities by providing the subcomponents with tremendous improvement potential. To meet scientific quality standards, the model was successfully tested with regard to objectivity, validity, reliability, usefulness, completeness, dependability and generalizability. However, to become fully established, the model requires further application in other companies and long-term testing.

Despite the methodically structured approach, the research results are subject to limitations. A certain degree of inaccuracy cannot be ruled out in literature research due to too narrowly defined exclusion criteria. The model, however, was based on the shortcomings of the findings of the literature search. Furthermore, the validation of the model was exclusively conducted within a single company. Since the model's applicability also depends on the individual company, further case studies in other organizations could provide additional insights and validity. Furthermore, the proposed model only reaches the level of "prescriptive models". Future research should aim for "comparative" models. In addition, agile concepts prevail in digitalization projects these days. As a result, shorter sprints are preferred over long-term roadmaps. Therefore, future prescriptive maturity models should integrate the agile aspect of digitization in dynamic roadmaps.

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Supply Chain Operations

A Robust Berth Allocation Optimization Procedure Based on Machine Learning

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Abstract. In berth allocation planning, container vessels are to be assigned to berthing locations and times at the quay of a container terminal. Terminal operators often aim to provide the best possible service quality to the shipping companies, i.e. especially short waiting times. However, the actual arrival times of vessels are uncertain due to external influences, e.g. wind and current or technical defects, which impedes the planning and may lead to conflicts with respect to scheduled berths. In this work, Machine Learning techniques are applied to enable the determination of patterns in AIS data and hence to develop forecasts of the arrival times. Moreover, with a robust optimization approach based on Dynamic Time Buffers, uncertainty is proactively considered in the planning phase, resulting in a robust berthing schedule. The results of this new approach are evaluated from an ex post perspective using real ship data and actual ship arrival times. It is shown by a numerical study that the average number of conflicts can be reduced significantly by this approach and that the new concept improves the schedules' robustness.

1 Introduction

Container terminals (CTs) operate as an interface between sea-bound and hinterland transportation. Since the available quay capacity is limited by the physical quay length and the terminal's working hours, only a finite number of container vessels can moor simultaneously alongside the quay. In order to use the limited quay space efficiently, CTs plan their berth occupancy beforehand (Imai et al. 2005). Therefore, the corresponding Berth Allocation Problem (BAP) is critical to CT's productivity and good solutions can lead to higher competitiveness (Liu et al. 2017, Umang and Bierlaire 2012). The BAP aims to assign ships optimally to berths which results in the CT's berthing schedule (Xiang et al. 2017).

As the BAP is a real-world problem, information is uncertain and disruptions can occur (Liu et al. 2017). Uncertainty mainly occurs regarding the vessels' arrival times (Xiang et al. 2017), whereas handling times differ less from their estimations (Umang et al. 2017). In terms of berth scheduling, especially late vessel arrivals are problematic. These can occur due to, e.g. bad weather conditions, sea current or technical breakdowns (Xu et al. 2012), and can influence the feasibility and optimality of a schedule (Umang and Bierlaire 2012).

U. Buscher et al. (Eds.): *Logistics Management*, LNLO, pp. 107–122, 2021.
https://doi.org/10.1007/978-3-030-85843-8_7

Different approaches for handling uncertainty in the BAP were suggested in the literature, but publications regarding data-driven terminal optimization are still scarce. However, Machine learning (ML) can discover hidden patterns and derive knowledge from big data sets and hence can reduce uncertainty regarding the optimization model's parameters (Heilig et al. 2020).

Robust optimization (RO) aims to determine optimal solutions that stay feasible also under uncertainty (e.g. Ben-Tal and Nemirovski 2002, Xiang et al. 2017). In the given context, RO of the BAP provides a berthing schedule that remains feasible when vessel arrival times deviate from the expectation (Rodríguez Molins 2015).

The contributions of this work are two-fold: On the one hand, the use of ML methods for vessel arrival time prediction is presented, and on the other hand, an RO model based on dynamic time buffers is developed for the BAP and tested on real-world data.

The remainder of this paper is organized as follows: Sect. 2 provides an overview on RO of BAP. The ML-based Dynamic Time Buffer approach is developed in Sect. 3, and the RO model is presented in Sect. 4. In Sect. 5, the numerical experiments are discussed and evaluated. Conclusions are given in Sect. 6.

2 Robust Berth Planning

2.1 The Berth Allocation Problem

The Berth Allocation Problem (BAP) is aimed at assigning berths at the quay to incoming container vessels. A vessel's berthing schedule is defined by its berthing time and position (Liu et al. 2017; Meisel 2009, Umang et al. 2017). The capacity of the quay is determined and limited by its length and the time horizon respectively. Vessels cannot moor until they arrive at the CT (Ma et al. 2011). Therefore, the arrival time is one major parameter for the optimization model (Yu et al. Yu et al. 2018). In most models, a pre-scheduled berthing position, where the lowest costs of horizontal transportation between quay-side operations and container yard arise, is assumed to be given for each vessel (Liu et al. 2017, Xiang et al. 2017). Considering the length of the vessel (and additional safety margins on either side), in a BAP solution a section of the quay is assigned to each vessel for the period of its handling time and thus is not available to other vessels during that time.

BAP formulations can be distinguished by the characteristics of their attributes according to the classification by Bierwirth and Meisel (2010): (1) vessel arrival times (temporal attribute), (2) quay layout (spatial attribute), (3) the handling time and (4) the objectives (performance measure). As this work concentrates on uncertain vessel arrival times, the focus is on the dynamic BAP with a continuous quay and deterministic (fixed) handling times; the relevant objectives are discussed in Sect. 4. More details on the BAP can be found in, e.g., Bierwirth and Meisel (2010 and 2015) and (Carlo et al. 2013).

2.2 Uncertainty and Robustness

In mathematical optimization, complete information is often assumed although in reality it is rarely available and, moreover, information accuracy often can hardly be judged.

Hence, a solution which has been determined as optimal under certain assumptions regarding the available data may turn out to be not even feasible in the end. The concept of robustness has been developed for mitigating such outcomes. A solution is considered to be robust if it leads to acceptable results regarding the objective(s) for the majority of possible future scenarios (Scholl 2001), and RO aims to find feasible solutions which are stable for uncertain input data (Ben-Tal and Nemirovski 2002, Xiang et al. 2017).

A berthing schedule's robustness can be increased by raising its stability or flexibility respectively. Stability means that the schedule does not need to be updated or adapted even if information changes or disruptions occur. Flexibility on the other hand measures how well an initial schedule can be adjusted if new information occurs (Scholl 2001).

According to Umang et al. (2017) real-world uncertainty can be addressed *proactively* and *reactively* in optimization problems and in berth scheduling in particular. The proactive approach which is taken here takes uncertainty into account already in the planning phase, i.e. before and during the berth planning. It enhances the stability and thus the robustness of the plan. The second approach aims to find a feasible solution reactively in (near) real-time, whenever new data becomes available or disruptions occur. Therefore, this approach is aimed at an increase of flexibility, which leads to more robust schedules as well.

When using stochastic optimization, berth scheduling is executed proactively with multiple datasets, also called scenarios. This approach is aimed at an overall optimal solution, taking the scenarios and their probabilities of occurrence into account. RO, in contrast, tries to find a solution to cover even the least attractive situation considered, i.e. the worst-case scenario. This can, e.g., be achieved by using sufficiently large time buffers, where a berthing schedule stays feasible as long as the deviation of the actual arrival time from the predicted arrival time is smaller than the assigned buffer (Xu et al. 2012). Hence, a robust schedule can be determined by proactively considering uncertainty and the influence of a changing environment, but without relying on – often unknown – probabilities. The aim is that no further adaptions to the schedule have to be made later on, e.g. when a vessel is delayed. However, it has to be noted that the goal of robustness will often be in conflict with other goals as, e.g., the maximization of the number of ships served. Hence, an appropriate compromise between these objectives has to be found.

2.3 Literature Review

There are different approaches suggested in the literature for adopting and handling uncertainty in berth allocation models.

Hendriks et al. (2010) consider berth allocations for periodically arriving vessels on a strategic level using a scenario-based proactive approach. The BAP for multi-terminal ports, where calling vessels are assigned to a terminal and afterwards to a related berth, is presented by Thorisson et al. (2019), considering uncertainty in arrival times and handling times respectively in a proactive scenario-based approach as well. On an operational level, Han et al. (2010) solely take uncertain arrival times into account, while Xiang et al. (2017) consider scenarios for uncertain arrival times as well as handling times when proactively solving the BAP. Liu et al. (2020) develop a two-stage proactive-reactive approach, taking possible disruptions and recovery operations into account on the second stage; these authors also present a structured summary of relevant literature on the BAP under uncertainty.

Xu et al. (2012) are the first to introduce time buffers for enhancing the BAP schedules' robustness. (Note that similar approaches to enhance robustness are well known from other areas. In flight scheduling, time buffers are used as a means against (perceived) delays, see, e.g., Lederer and Nambimadom (1998), Baumgarten et al. (2014). In production management, e.g., for single-machine scheduling (Leus and Herroelen 2007), buffers are applied to derive schedules which are robust against disruptions.) Xu et al. also consider uncertain vessel arrival times and uncertain handling times.

Using time windows for the vessels' arrivals, Golias et al. (2014) solve the discrete BAP with uncertain handling times. In a bi-objective approach, they optimize the schedule's robustness and efficiency.

With the aim of providing a robust schedule for berths and quay cranes simultaneously, Wang and Guo (2018) proactively consider uncertain arrival times in the integrated Berth Allocation and Quay Crane Assignment Problem (BQCAP) by minimizing the risk of delayed vessel departures. Since handling time depends on the number of quay cranes assigned per vessel and the number of containers to handle, Rodriguez-Molins (2014a, 2014b) apply time buffers to proactively deal with uncertain handling times, which may, e.g., occur due to defects in quay equipment.

Li et al. (2019) provide a scenario-based approach to overcome handling time uncertainties in BQCAP proactively. Uncertainty in both, arrival times and handling times, are considered only by Zhang et al. (2014) for BQCAP, enhancing the robustness through proactively assigning time buffers.

As this short review shows, the use of scenarios is a common approach for the dynamic BAP, and the application of time buffers is promising for proactively increasing a schedule's robustness. A combination of both is adopted in this work: A new ML-based approach is suggested for the construction of "scenarios" (but without the requirement of probability specifications) as well as time buffers, which are subsequently used in an RO model.

3 Berth Allocation with Dynamic Time Buffers

3.1 Arrival Time Prediction

ML techniques are applied to find patterns in (noisy) data (Bose and Mahapatra 2001, Langley and Simon 1995). In supervised learning, the target values that are to be predicted, so called labels, are known and the algorithm learns the label specification from the related features in the training data. Each data point, including the features and the related label, is called an instance. A representing model is derived from the training data, which enables the prediction of the label for the features of an unknown sample. The accuracy of the learned model, and thus how well it generalizes, can be evaluated by comparing the predicted label to the original label in the test data (Richter 2019). In supervised learning, classification and regression tasks can be distinguished. For classification tasks, known discrete classes are learned from the training data and are then predicted for an unknown sample. Regression tasks address the learning and prediction of numerical values for the labels (Géron 2018, Sugiyama 2016). However, prediction on real world data may be inaccurate, e.g. in case of outliers.

In this work, three ML approaches are applied to derive predictions of arrival times which are then used to construct time buffers: k-Nearest Neighbors (kNN), Linear Regression and Regression Trees. Due to their different approaches, each of these algorithms performs differently for various patterns in the training data and therefore the suitability of the methods for different instances varies. However, if the predicted arrival times of all forecast methods are similar, it can be concluded that this is due to a low level of uncertainty.

The kNN algorithm considers the k nearest neighbors according to the overall distance of an unknown sample's features from the features of all training data, to predict its label based on the labels of these neighbors (Langley and Simon 1995). The advantage of kNN is that only the k neighbors which are considered influence the prediction, hence in noisy data, outliers do not affect it. The main disadvantage is the high computational effort to calculate the distances individually for each new sample (Bose and Mahapatra 2001). kNN has already been used for a similar application in the field of shipping, as Virjonen et al. (2018) predict the position of vessels in the Gulf of Finland based on AIS data using the kNN algorithm in order to conduct emission monitoring.

Linear Regression, where a linear function is learned from the training data (Frochte 2019, Géron 2018), is the second algorithm used in this work. Since the maneuverability of a container vessel is restricted by its size, it is expected that vessels drive with relatively constant speed. Hence, a linear relation between the distance to the target port and the time needed to travel this distance can be assumed, where the travel time determines the arrival time at port, i.e. the label.

Decision Trees divide the training data by its features' characteristics to increase the information gain according to the prediction of a certain label with each split. Ideally, in the end there are training data of one specific label exclusively in each leaf, and further splitting does not provide any additional knowledge (Bose and Mahapatra 2001, Frochte 2019, Yu et al. 2018). Regression Trees are a special form of Decision Trees that accumulate the labels of the training data in each leaf using a linear regression line (Frochte 2019).

The three ML approaches are used in this work to derive a set of predictions for ships' arrival times based on AIS data, as the aim is not to achieve the single "best" forecast, but to capture the uncertainty of the ships' arrivals by more than one number, an approach similar to modelling uncertainty by scenarios.

3.2 Dynamic Time Buffers

Following Liu et al. (2017), in this work the service level of a berthing schedule is defined as the proportion of vessels calling at a port that can be served without conflicts with other vessels, and it is used to measure the schedule's robustness. A conflict arises whenever two vessels' schedules overlap. This can occur because the arrival time of a container vessel is uncertain until the vessel actually reaches the port (Rodríguez Molins 2015, Xiang et al. 2017), but the berth planning has to be conducted beforehand. Therefore, conflicts between any two vessels become only known *ex post*. Hence, robustness is measured as the number of vessels that effectively can be served, considering their actual arrival time, i.e. the true service level.

As stated above, time buffers can be employed to reduce the risk of conflicts, and the length of the time buffer assigned to each vessel is decisive for the robustness of the berthing schedule. Making use of the ML based arrival time predictions, the concept of Dynamic Time Buffers (DTB) is introduced in this work.

For the development of the DTB, the following aspects are relevant: A vessel cannot be berthed before it reaches the port. Hence, it is not efficient to schedule its berthing time before the earliest predicted arrival time. It is possible, on the other hand, to assign a berth (much) later than the latest predicted arrival time, but this is not recommendable as it will impair customer satisfaction due to the resulting potential waiting time.

The length of a vessel j's DTB (see Fig. 1 below, dotted areas) is therefore determined by the earliest predicted arrival time ($a_j(1)$) and the latest predicted arrival time plus handling time ($a_j(3) + t_j$) respectively, where the different predictions are derived by the three ML approaches. Consequently, the length of the assigned buffer depends on the level of uncertainty regarding the vessel's arrival time, as in case of high uncertainty, the deviations of the predicted arrival times of a vessel and therefore the time span between the earliest and latest arrival times will usually be high as well. On the other hand, if uncertainty is low, the predicted arrival times should be similar independent of the method used, and hence the DTB will be narrow.

The DTBs are not communicated to the vessels approaching the port, but they are used for the purpose of scheduling only. Just its planned berthing time is revealed to the respective vessel. To avoid waiting times, a vessel's berthing time should be scheduled as close as possible to its earliest predicted arrival time. However, if another vessel already has been assigned to the related berthing position, the berthing time of the succeeding vessel cannot be assigned anywhere during the DTB of the former vessel. I.e., whenever a vessel arrives on time, after the handling is complete and the vessel leaves the CT, the quay remains idle during the buffer time which reduces the productivity of the quay (Yu et al. 2019) and may lead to an inefficient schedule. This illustrates the above-mentioned conflict of the different relevant objectives. However, the aim of this work is to maximize service quality, and hence robustness, not productivity, is focused on.

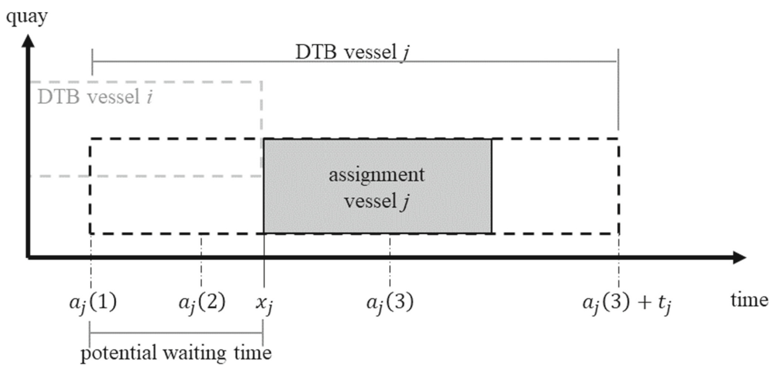

Fig. 1. Dynamic Time Buffers in berth assignment

As domain knowledge is acquired regarding the subject over time when using ML methods, uncertainty decreases, leading to more similar predictions of the different methods. Therefore, the DTBs will become smaller, making the schedule more efficient, but at the same time this reduces the stability of the berthing schedule and may cause conflicts if one vessel is unexpectedly delayed. Therefore, also in the long run, the conflict between smaller DTBs, i.e. efficient quay usage, and the robustness of the schedule persists and cannot be completely resolved.

4 Model Description

The RO model with DTB for the BAP with continuous quay (ro-DTB-BAPc) assigns a set of vessels V to the available quay space, taking a set of forecasts Ω into account. It is based on the "Model 1" by Liu et al. (2017) which uses a scenario-based approach and hence can be adapted to the situation at hand. Here, each "scenario" consists of the arrival times that are predicted for all relevant vessels by one of the forecast methods described above. The additional adaptations and changes made to the model in order to increase the robustness of the resulting berthing schedule are explained below. Note that the original "Model 1" will also be used as a benchmark to evaluate the new robust model.

Liu et al. (2017) base their approach on a finite number of scenarios$S$. Each of their scenarios contains estimations of the arrival time and the handling time per vessel (here: only arrival times). The probabilities of all scenarios – here: weights of the forecasts – are assumed as identical in Liu et al (2017) as well as here, i.e. $p(\omega) = \frac{1}{S}, \omega \in \Omega$, as there is no knowledge about the likelihood of any forecast being better than another. Each forecast $\omega \in \Omega$, derived by one of the ML methods, provides a predicted arrival time $a_i(\omega)$ for each vessel $i \in V$.

The capacity of the quay depends on its length L and the time horizon T, during which $N = |V|$ vessels are to be assigned. Based on the forecasts, the berth is planned for a vessel $i \in V$ with respect to the (approximate) handling time t_i, the vessel's length (including safety distances) l_i and the pre-scheduled berthing position b_i. The latter is planned in the pre-scheduling step by optimization of a baseline schedule; it can be any feasible BAP solution (Umang et al. 2017).

In the ro-DTB-BAPc, the berthing schedule is optimized from a CT point of view. The CT operator aims to offer the best service, i.e. the highest possible customer satisfaction which is quantified in the model below by three objectives: (1) minimization of the potential waiting times of incoming vessels, (2) minimization of the deviation from the pre-scheduled berthing positions and (3) minimization of the number of rejected vessels. The former two objectives are identical to Liu et al.'s "Model 1", while with respect to objective (3), in "Model 1" a minimal service level β_1 is defined which has to be accomplished. This service level measures the proportion of vessels that are served, i.e. not rejected. However, in the new model ro-DTB-BAPc, the service level is integrated into the objective function by a penalty costs approach. Therefore, the model stays feasible even if a required service level cannot be fulfilled (i.e. one or more vessels have to be rejected). In contrast to this, in the model of Liu et al. such infeasibilities can occur if there is not sufficient time for berthing vessels calling late in the planning horizon.

In the objective function, the cost rates c_i^1 and c_i^2 indicate the penalties for each minute the vessel $i \in V$ potentially has to wait for its berth and for each meter by which the berthing position differs from the pre-scheduled berthing position b_i, respectively. Moreover, an incoming vessel is rejected if no capacity is available at the quay in the time horizon T. In this case, the cost c_i^3 has to be incurred for rejecting vessel $i \in V$. The cost factors weight the relation between the three objectives, and different cost rates for vessels can be used for prioritizing them. As rejecting vessels is the *ultima ratio* if it is not possible to berth a vessel due to capacity limitations, c_i^3 needs to be significantly higher than the other cost rates. In fact, the cost rate c_i^3 represents the opportunity cost of rejecting vessel $i \in V$, i.e. the revenue that cannot be realized, when the vessel is not served. For a reasonable representation of these opportunity costs, vessel i's revenue and possible interdependencies with the revenue resulting from serving other vessels would have to be known. For reasons of simplicity and as the aim of this approach is to increase the plan's robustness, here the value of cost rate c_i^3 for rejecting vessel $i \in V$ is set to a sufficiently high value (i.e. much higher than c_i^1 and c_i^2), such that not serving a vessel only makes sense when no berth can be assigned due to the lack of capacity in the planning horizon. The exact size of c_i^3, however, does not matter here.

The decision variables berthing time, x_i, and berthing position, y_i, describe the berth assigned to a vessel $i \in V$. The deviation of the berthing time from the predicted arrival time of vessel $i \in V$ according to forecast $\omega \in \Omega$ is modelled by the variables for the waiting time $m_i(\omega)^+$ or the delay $m_i(\omega)^-$. If an actual berthing position differs positively (negatively) from the pre-scheduled berthing position, then variables n_i^+ (n_i^-) contain the respective distance in meters.

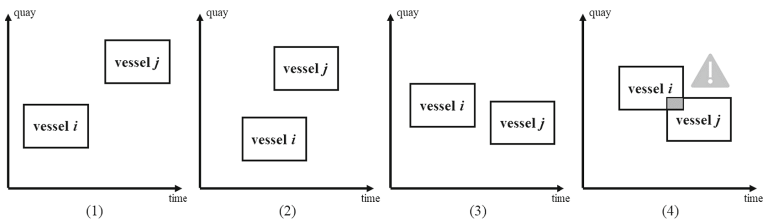

Fig. 2. Vessel relations and conflicts. (See Liu et al. 2017)

To model possible conflicts in the berthing schedule, different types of variables are used (as in Liu et al. 2017): The binary decision variables θ_{ij}^x (θ_{ij}^y) are used to model whether two different vessels i and $j \in V$ are in conflict with respect to time (quay position). Figure 2 shows four cases that can be distinguished regarding the positions of two vessels $i, j \in V$ on the berth space-time plane (where the vessel i's berth is considered to be lower in position than or left in time of vessel j): (1) there is no overlapping neither in time perspective ($\theta_{ij}^x = 1$) nor in quay perspective ($\theta_{ij}^y = 1$). (2) The berths of both vessels do overlap in time perspective ($\theta_{ij}^x = 0$) but not in quay perspective ($\theta_{ij}^y = 1$). (3) The berths of the two vessels do not overlap in time perspective ($\theta_{ij}^x = 1$) but in quay perspective ($\theta_{ij}^y = 0$). Since in these three cases the vessels do not overlap in at least one dimension, there is no conflict between these two vessels (the pairwise conflict variable

u_{ij} is equal to 1). (4) The two vessels overlap in time perspective ($\theta_{ij}^x = 0$) and in quay perspective ($\theta_{ij}^y = 0$). In this case there is a conflict between the two berths (and thus $u_{ij} = 0$) as can be seen in the rectangular representations in the berth space-time plane.

If a vessel is not conflicting with any of the other $(N-1)$ vessels, the vessel's service decision variable w_i takes value 1; otherwise, $w_i = 0$.

Using the notation introduced above, the model formulation of the *ro-DTB-BAPc* can be presented now:

$$\min \sum\nolimits_{\omega \in \Omega} \sum\nolimits_{i \in V} p(\omega) \cdot c_i^1 m_i(\omega)^+ + \sum\nolimits_{i \in V} c_i^2 \cdot \left(n_i^+ + n_i^-\right) + \sum\nolimits_{i \in V} c_i^3 \cdot (1 - w_i) \tag{1}$$

$$a_i(\omega) + t_i \le x_j + 2 \cdot T \cdot \left(1 - \theta_{ij}^x\right) \forall i, j \in V, \omega \in \Omega, i \ne j \tag{2}$$

$$x_i + t_i \le a_j(\omega) + 2 \cdot T \cdot \left(1 - \theta_{ij}^x\right) \forall i, j \in V, \omega \in \Omega, i \ne j \tag{3}$$

$$y_i + l_i \le y_j + L \cdot \left(1 - \theta_{ij}^y\right) \forall i, j \in V, i \ne j \tag{4}$$

$$\theta_{ij}^x + \theta_{ji}^x + \theta_{ij}^y + \theta_{ji}^y \ge u_{ij} \forall i, j \in V, i \ne j \tag{5}$$

$$\sum_{j \in V, j \ne i} u_{ij} \ge w_i \cdot (N-1) \forall i \in V \tag{6}$$

$$y_i + l_i \le L \forall i \in V \tag{7}$$

$$x_i + t_i \le T + T \cdot (1 - w_i) \forall i \in V \tag{8}$$

$$x_i \ge \min_{\omega} a_i(\omega) \forall i \in V \tag{9}$$

$$x_i - a_i(\omega) = m_i(\omega)^+ - m_i(\omega)^- \forall i \in V, \omega \in \Omega \tag{10}$$

$$y_i - b_i = n_i^+ - n_i^- \forall i \in V \tag{11}$$

$$m_i(\omega)^+, m_i(\omega)^-, n_i^+, n_i^-, x_i, y_i \ge 0,$$

$$\theta_{ij}^x, \theta_{ij}^y, u_{ij}, w_i \in \{0, 1\} \forall i, j \in V, i \ne j, \omega \in \Omega \tag{12}$$

The objective (1) of the ro-DTB-BAPc model is to minimize the penalty costs for deviations in service quality. The potential waiting times $m_i(\omega)^+$ of a vessel are weighted by the penalty costs c_i^1 and the weights $p(\omega)$ of the forecasts ω in order to derive the expected waiting time. (Note that as the weights $p(\omega)$ are identical for the three forecasts, they do not have to be explicitly taken into account. However, the aim is to use a notation which is as similar as possible to that of Liu et al. (2017) to facilitate direct model comparisons.) The spatial deviation of vessel i from a pre-scheduled berthing position is penalized by cost rate c_i^2 and, in contrast to Liu et al., rejections of vessels are integrated into the objective function in the third term, weighted by c_i^3.

Compared to "Model 1" from Liu et al. (2017), constraint set (2) is new and constraint set (3) has been modified to capture the new DTB approach. Constraints (2) ensure that, if there is no conflict between vessel i and j with respect to time, the berthing time of vessel j is not planned earlier than the departure time of vessel i which is given by the maximum of its predicted arrival times $a_i(\omega)$ (hence the condition is required for each of the forecasts ω) plus its handling time t_i. Similarly, constraints (3) ensure that, if there is no conflict, the departure time of a vessel i given by its berthing time x_i plus the handling time t_i is not planned later than the arrival time $a_j(\omega)$ of vessel j (again for each forecast ω). Conflicts in the spatial dimension are considered in constraints (4). No conflict occurs between two vessels i and j if the berth of the former ends on a lower berthing position than the latter begins. If there is at least one of the binary variables θ_{ij}^x, θ_{ji}^x, θ_{ij}^y or $\theta_{ji}^y = 1$ (no conflict in this dimension), these two vessels have no conflict at all, as constraints (5) state. According to constraints (6) a vessel i can only be served if there is no conflict with any of the other $(N - 1)$ vessels. Constraints (7) ensure that the berth of a vessel i, defined by its berthing position y_i and the vessel's length l_i, may not exceed the length of the quay L. The berthing time x_i plus handling time t_i of a vessel i may only exceed the time horizon T, if it cannot be served ($w_i = 0$), as constraints (8) state. Constraints (9) limit the earliest possible berthing time x_i of each vessel i to the earliest predicted arrival time $\min_{\omega} a_i(\omega)$ of all forecasts ω. Constraint sets (10) and (11) measure the waiting times (or delays) with respect to the predicted arrival times and the deviations of the vessels' berthing positions y_i from their pre-scheduled berthing positions b_i. In (12), the non-negativity and binary conditions for the variables are given.

5 Numerical Experiments

5.1 Arrival Time Prediction and Generation of Test Cases

The PortMiami in Florida, USA, serves as the use case for the evaluation of the ro-DTB-BAPc model. There are 1860 m quay length available for container handling at this port. Since no real data for handling times are known, it is assumed that there is a linear relation between vessel length and the number of containers transported. As planning time horizon, 24 h are considered.

In order to train the three ML algorithms on the AIS data, the latter have to be reduced to the relevant information, i.e. features. In data cleansing only the vessel trajectories to the PortMiami are retained. Moreover, only moving cargo vessels are considered. To cover the influence of external factors, i.e. sea current and crosswind, an attribute "drift" is calculated which contains the deviation between the vessel's heading (i.e. the direction in which the bow is pointing) and the course over ground (COG, the direction in which the vessel actually moves). The more the vessel's trajectory is influenced by these external factors, the higher is the value of the attribute "drift" which is taken into account by the ML procedures in forecasting the ship's arrival time.

The training data set contains AIS data from October 2016 to September 2017. Therefore, the training data include all seasons and, when used for training an ML method, are expected to lead to well generalizing models. In the test data, instances from October to December 2017 are considered. It has to be noted that weather conditions in this time of a year potentially differ from other seasons. However, as overfitting generally is a problem in ML (Géron 2018), data from all seasons are included to avoid this effect, even though the test data refers to the fall period only.

For the training and test data the labels are calculated by following each vessel trajectory to the port. The moment where the vessel reaches the port is considered to be the actual vessel arrival time. For each instance before the arrival, the duration until the actual arrival is calculated as the instances' label, and this information is learned by the procedure.

The ML procedures were implemented using the open source library scikit-learn for Python programming language. The three ML algorithms are trained applying 10-fold Cross Validation (Géron 2018, Richter 2019) considering different sets of attributes and adjusting the algorithms' parameters via the grid search method. Subsequently, their accuracy is evaluated on the test data. An often used measure of the accuracy of predictions in ML regression tasks is the Coefficient of Determination (R^2) which indicates the relation of explained deviation (by the trained ML model) to the total deviation of the label from the mean over all labels. For all forecasts, the Coefficient of Determination R^2 turned out to be larger than 0.9, hence more than 90% of the total deviation in arrival times is explained by the learned models.

For every instance in the test data set an individual arrival time prediction can be made by each ML approach. While from each vessel's trajectory numerous instances are available on its journey to the port, here only one instance per vessel is chosen randomly at a time to derive the ML forecasts from it. Each of these sets of choices leads to one test case for the numerical experiments. Consequently, the parameter set of each case contains different predicted arrival times for the vessels and hence the distribution of the arrival times and the density of the resulting schedules differ as well. Therefore, data settings with different structures can be generated by this approach, although the data base remains the same. For the study below, 100 test cases were randomly created as described above.

5.2 Numerical Results

The solutions of the ro-DTB-BAPc and the "Model 1" of Liu et al. (2017) are to be compared regarding the resulting berthing schedules' robustness and service quality. Robustness can be determined by evaluating whether the berthing schedules of any two vessels are in conflict considering their *actual* arrival times. Two cases can be distinguished: (1) the delay of one vessel prevents the berthing of the following vessel at the respective berthing position or (2) the following vessel at the respective berthing position arrives too early and thus is in conflict. While each single conflict occurs only between two vessels, a vessel may have multiple conflicts. Therefore, the number of conflicts and the number of affected vessels are compared for the ro-DTB-BAPc and the "Model 1".

The performance of the optimization models with respect to service quality can be measured by the negative deviation of the actual arrival time from the planned berthing time, i.e. the earliness of the vessel against the berthing schedule and hence its (potential) waiting time. The less the deviation from the schedule, the better does the model adapt to the uncertainty of the arrival times beforehand. As both models are applied to the same data from the three forecasts, provided by the three ML procedures, the accuracy of the predicted arrival times is identical and hence does not influence the comparison of the models' qualities with respect to the service quality reached.

Both models were implemented using the Gurobi library and solver for Python. The optimization was conducted on a 2.8 GHz 12-core CPU with 72 GB RAM.

In order to determine a reasonable number of vessels calling at the port in the specified time horizon, a preliminary test series was conducted, where in each run one vessel was added and both models were solved. For operational berth planning, the BAP needs to be solved in reasonable time, but the computational effort rises strongly with the number of vessels that has to be rejected. Therefore, the size of the vessel set is specified to be the maximum number of vessels that can be assigned by the ro-DTB-BAPc without rejecting a vessel.

In Fig. 3, the number of vessels that can be served according to the different models' solutions and the computation times are illustrated. The resulting number of conflicts arising with respect to actual arrival times is given as well.

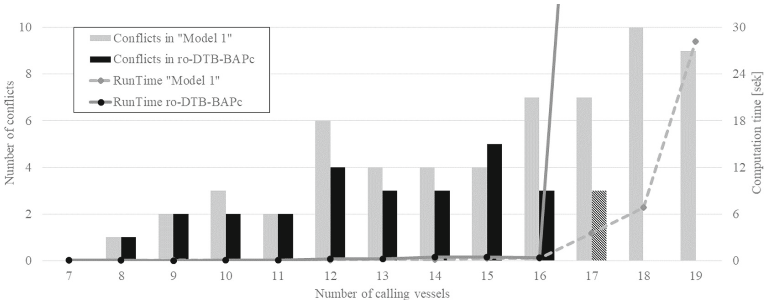

Fig. 3. Conflicts and computation time by increasing number of vessels to assign

With the ro-DTB-BAPc, it is possible to assign a maximum of 16 vessels without rejecting any vessels, while for the case of 17 vessels the ro-DTB-BAPc was unable to assign all vessels to the quay (hence the number of conflicts is given in crosshatched black in Fig. 3, as – in contrast to the other cases – one of the vessels had to be rejected). Because of the time buffers, ro-DTB-BAPc consumes more capacity per vessel than the "Model 1", therefore "Model 1" is able to assign more vessels which, however, may lead to more conflicts. Indeed, it turns out that in most cases where both models can assign all vessels, the number of conflicts is lower (or of the same size) for the ro-DTB-BAPc than for the "Model 1", with the exception of the case of 15 vessels (see Fig. 3).

For all cases including 16 vessels or less, the computation time is lower than one second for both models. With the ro-DTB-BAPc, it is possible to solve the 17 vessel case in about 90 s, whereas the "Model 1" only needs 3.58 s. In this preliminary test, the ro-DTB-BAPc was not able to assign 18 vessels within the time limit of 24 h. The "Model 1", however, could be solved in about 7 s for the same 18 vessels. Hence, it can be observed that, once a critical number is reached (here: 17 vessels), the dynamic time buffer approach requires significantly larger computation times, compared to the "Model 1", which, on the other hand, leads to solutions with more and more conflicts that in fact also cannot be implemented.

It can be concluded that capacity limits should already be considered in the (tactical) baseline scheduling. On the operational level, a vessel is only rejected by the ro-DTB-BAPc when, due to arrival time uncertainties, large buffers have to be assigned and therefore berths consume more capacity than originally assumed in the baseline schedule.

The quality of the results of the preliminary test is confirmed in the numerical study of the 100 test cases with 16 vessels. Note that the minimal service level β_1 which is needed for "Model 1" (see above) was defined beforehand by the proportion of vessels that the ro-DTB-BAPc could successfully assign. Therefore, the resulting berthing schedules are comparable.

Overall, "Model 1" on average results in 2.38 conflicts affecting 4.26 vessels, and the vessels are on average a total of 155.9 min earlier than the respective planned berthing times, which may lead to corresponding waiting times. In contrast to that, ro-DTB-BAPc results in only 0.86 conflicts regarding 1.63 vessels on average. The average potential waiting time is 142.9 min compared to the related planned berthing time. Therefore, the results indicate a significant improvement mostly in terms of robustness, but also in service quality, of the ro-DTB-BAPc model compared to "Model 1".

Only in two cases the ro-DTB-BAPc results in more conflicts than the "Model 1". In the remaining 98 cases the ro-DTB-BAPc performs at least as well as "Model 1" with respect to the number of conflicts occurring, in 78 out of these cases the number of conflicts is lower for ro-DTB-BAPc.

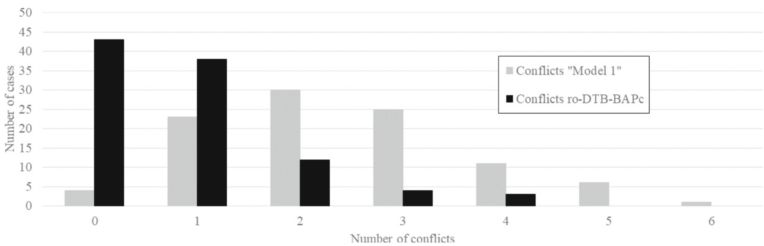

Fig. 4. Number of conflicts per test case in "Model 1" and ro-DTB-BAPc

In Fig. 4 the distribution of the numbers of resulting conflicts over the 100 test cases is presented. It shows that "Model 1" reaches a perfectly robust schedule without any conflicts only in 4 cases, and approximately 40% of the schedules feature three or more conflicts. In contrast, the ro-DTB-BAPc's schedules are perfectly robust in 43 of 100 cases, and in less than 10% of the cases three or more conflicts occur.

6 Conclusion

The aim of this paper is to improve the robustness of berthing schedules at CTs and to enhance the terminals' service quality. In order to achieve this aim, three ML algorithms are used to predict the arrival times of vessels based on past AIS data. Moreover, the concept of DTB is introduced and implemented. In a numerical study, the solutions of the ro-DTB-BAPc and the “Model 1” by Liu et al. (2017) are compared. Here, as a measure of robustness the true service level is used, i.e. the number of vessels that can be served without conflicts in relation to the total number of calling vessels, based on their actual arrival times. It can be shown that the DTB approach leads to significant improvements, as in 78% of the cases the ro-DTB-BAPc achieves a solution of higher robustness. Also with respect to service quality, the presented approach turns out to be advantageous.

It has to be noted, however, that the ro-DTB-BAPc could only schedule 16 vessels in the planning horizon, whereas the “Model 1” was able to assign more vessels. This is due to the addition of time buffers which leads to higher capacity consumption per vessel under the DTB approach.

The accuracy of the predicted arrival times influences the robustness of the schedules as well. Whenever the actual arrival time deviates strongly from the predictions, both models cannot address this uncertainty. Hence, in future research, the forecast accuracy should be focused on and, e.g., other (ML) methods for developing better forecasts might be studied. Moreover, in order to appropriately weight the objectives and to prioritize vessels, e.g. those of important customers, if necessary, the influence of shifting berths in time and space on revenue and costs, as well as the opportunity costs resulting from rejecting vessels, have to be determined and used in the optimization to derive even more realistic results. Furthermore, other berth layouts and uncertainty regarding handling times could be considered as well.

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Greenhouse Gas Emissions of Shunting Operations - A Simulation Study

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Abstract. Marshalling yards are nodes in rail networks where incoming trains are decoupled and sorted to outbound trains. An algorithmic approach to sort wagons of incoming trains is to apply sorting schemes. Well investigated sorting schemes are *Sorting by train*, *Sorting by block*, *Triangular Sorting* and *Geometric Sorting*. Throughout the applying of sorting procedures greenhouse gases are emitted, e.g. by shunting locomotives. A simulation study is conducted in which emissions in marshalling yards can be calculated. For this purpose a formula based analysis of the sorting schemes is carried out. The simulation shows that *Sorting by block* performs best w.r.t. less emissions for most scenarios. On the other hand *Geometric Sorting* is the worst sorting scheme, i.e. for most scenarios emissions are higher in comparison to other sorting schemes.

1 Introduction

Greenhouse gas emissions (GHG) from freight transportation contribute considerably to global warming and have increased constantly in recent years. From 1991 to 2019 total freight transport performance in Germany (measured in tonne-kilometres) rose about 75%. One part of the freight sector is railway traffic which comprises about 19% of total transport performance in Germany in 2019 (Umweltbundesamt (2021)). Although railway traffic is considered as an eco-friendly alternative to conventional diesel-powered road transportation, rail traffic also emits GHGs. Particularly Diesel-powered trains emit considerable GHG quantities while electricity-powered trains show much less GHG emissions typically (depending on the eco-friendliness of the energy mix).

In general, rail freight transport services can be categorized into unit-load traffic and wagonload traffic. In unit-load traffic, a transport order is serviced by assigning it to one specific train which ships the order's wagons from their origin to their destination. Thus, the block train is led through the railway network without altering its payload. In wagonload traffic, a transport order is serviced by sequence of subsequent rail services which are operated regularly between rail yards. Thus, a transport order is assigned to multiple trains on its route to its destination. Thus, at those rail yards (also called marshalling, classification or shunting yards), trains are composed by grouping wagons of

U. Buscher et al. (Eds.): *Logistics Management*, LNLO, pp. 123–136, 2021.
https://doi.org/10.1007/978-3-030-85843-8_8

multiple transport orders which have to be shipped in the same direction. For shunting wagons at marshalling yards most often diesel-powered locomotives are used. More eco-friendly hybrid locomotives (combining a diesel drive with a battery electric engine) are available, but their market share is small so far (about 2% in Germany in 2018, see Bundesnetzagentur 2019). Thus, shunting operations cause GHG emissions which are, however, often neglected when assessing the environmental impact of rail operations (Knörr et al. 2019). Douglass et al. (2010) report empirical GHG emissions from nine American marshalling yards. Among the various vehicles moving at the yards shunting locomotives and line haul locomotives are the main drivers of GHG emissions.

Thus, in this paper the GHG emissions at shunting yards are studied. Therefore, the GHG emissions of shunting locomotive are modelled which are used to compose trains. For composing trains, so called sorting schemes are used to reassemble wagons from multiple inbound trains to multiple outbound trains. In the following it is analysed which GHG emissions for shunting operations are incurred by applying different sorting schemes. For calculating the GHG emissions of shunting locomotives the emission model proposed by Kirschstein and Meisel (2015) is used.

The outline of the article is as follows. In Sect. 2 a brief overview on typical shunting processes are given along with a description and analytical analysis of four sorting schemes. The emission model for shunting operations is described in Sect. 3. In Sect. 4 the results of a simulation study are presented analysing the GHG emissions of the different sorting schemes in various settings. The paper closes with a summary and outlook in Sect. 5.

2 Shunting Operations

The management of shunting operations is challenging due to many interrelated processes and limited capacities. For an overview on strategic, tactical and operational planning tasks in marshalling yards, see Boysen et al. (2012). Shunting operations can be summarized into a) decoupling wagons of incoming trains, b) sorting wagon groups according to their shipment direction, and c) composing outgoing trains. Thus, marshalling yards usually consist of 3 parts: a receiving area, a classification area, and a departing area, see Fig. 1.

In the first step, incoming trains roll into the receiving area which consists of multiple parallel inbound tracks. After the inspection and the decoupling of the trains, the wagons are shunted by shunting locomotives. Shunting locomotives move the wagons to a hump which is the connection point between the receiving and classification area. The wagons roll over the hump to a set of parallel classification tracks. On those classification tracks, outgoing trains are composed.

The wagons of the outbound trains composed on the classification tracks have to be assembled in a certain sequence. However, normally the wagons do not arrive in the correct order. Therefore, often wagons on a classification track need to be moved back to the inbound tracks. This process is called a pullback. Afterwards, the wagons are humped again and roll on the classification tracks

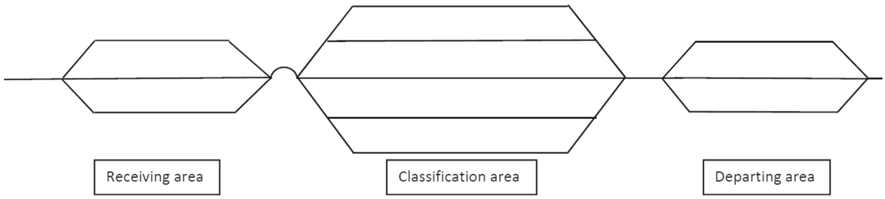

Fig. 1. Schematic layout of a marshalling yard, incoming trains arrive at the receiving area, wagons are sorted in the classification area and outgoing trains are prepared for departure in the departing area

again. Once the wagons of an outgoing train are completely assembled on a classification track in the correct order, the wagons are moved to the departing area where the final inspection takes place, all wagons are coupled, and the line locomotive is attached before the train leaves the yard.

Taking a closer look on operational planning reveals that most research is devoted to the wagon sorting process (Boysen et al. 2016). Wagon sorting is the core task at marshalling yards and determines their performance with respect to service level, total cost, and environmental impact. Therefore, a lot of models and procedures for optimizing wagon sorting have been developed (see e.g. Gatto et al. 2009; Hansmann 2010).

Sorting schemes can be distinguished into single-stage sorting and multi-stage sorting schemes. In single-stage sorting, wagons are humped only once and, thus, no pullbacks are allowed. Thus, all the outbound trains have to be build within one humping step. In extended single-stage sorting at most one pullback is allowed for building the outbound trains, see Boysen et al. (2012). Single-stage sorting and extended single stage sorting are applicable when the order of the wagon groups is not important or when the wagon groups arrive in the required order of the outbound trains. In practice, however, often inbound train schedule and the orders of outbound trains do not match well. In this case multistage sorting needs to be applied. The most prominent multistage sorting schemes are *Sorting by train*, *Sorting by block*, *Triangular sorting* and *Geometric sorting* (Gatto et al. 2009; Daganzo et al. 1983). These sorting schemes describe rules for assigning wagon groups to classification tracks. They differ in the number of pullbacks as well as the assignment of wagon groups to classification tracks.

To apply the following sorting schemes it is assumed that there are unlimited numbers of classification tracks and each wagon sequence fits on every track. In the following we assume that a number of incoming trains deliver wagons which need to be shunted to outbound trains at a given point in time. The set of wagons waiting for humping is subdivided into wagon groups which share a common part of their total route. Each wagon group belongs to a certain outbound train r and has an order number w. I.e., a wagon group with $w = 1$ is to sequenced first in the corresponding outbound train. In the following, wagon groups have to be humped to classification tracks such that each outbound train is composed in the correct sequence of wagon groups (labelled from $1, ..., n_r$ where n_r is the wagon group of train r sequenced at the end of the train).

2.1 Description of Sorting Schemes

The main idea of *Sorting by train* (SBT) is to sort the wagon groups according to their corresponding outbound train r. I.e., first all wagons of an outbound train are assigned to the same classification track irrespective of the their order w. Once all wagons of the outbound train are waiting on the corresponding classification track, all wagons are pulled back and humped again. Thereby each wagon group is assigned to an empty classification track. Finally, the wagons are pulled back sequentially according to their order number w. Thus, each wagon is humped three times with this sorting scheme (Gatto et al. 2009). Figure 2 illustrates the procedure for an example with 2 trains.

Applying *Sorting by block* (SBB) means to sort all wagon groups to the classification area based on their order numbers w irrespective of their outbound train r. I.e., all wagon groups with the same order w are shunted to the same classification track (irrespective their train assignment). Subsequently, the wagons are pulled back sequentially starting with the wagon groups with $w = 1$. When rehumping for each outbound train is assigned to a classification track and the corresponding wagon groups are shunted accordingly. Thus, each wagon group is humped twice (Gatto et al. 2009). An example is displayed in Fig. 3.

SBT and SBB are simple sorting rules, but require many classification tracks if the number of wagon groups or the number outbound trains is large. *Triangular sorting* (TS) is a more complex method than SBT and SBB, but requires less classification tracks. In TS, the order numbers of wagon groups are altered based on the total lengths of the corresponding outbound trains w.r.t. their total numbers of wagon groups. Let r' denote the index of outbound trains ordered by decreasing total length (i.e., $r' = 1$ indicates the longest train). Then, the altered order numbers of the wagon groups are calculated as follows (Daganzo et al. 1983)

$$\tilde{w}^{TS} = w + \frac{r' \cdot (r' - 1)}{2}. \tag{1}$$

Note that $\tilde{w}^{TS}$ still implies the correct ordering of wagon groups for a given outbound train but shifted by $\frac{r' \cdot (r'-1)}{2}$. After renumbering, the wagon groups are initially humped. In the following, k denotes the index of the classification tracks and $\widetilde{\mathcal{W}}_k^{TS}$ denotes the set of wagon groups assigned to classification track k. Thereby, wagon groups areassigned to tracks based on their altered order numbers $\tilde{w}^{TS}$ as follows (Daganzo et al. 1983)

$$\widetilde{\mathcal{W}}_k^{TS} = \left\{ \frac{k \cdot (k-1)}{2} + 1, g_2^k, \ldots, g_{j_k^{TS}}^k \right\} \tag{2}$$

whereby

$$g_j^k = \frac{k \cdot (k-1)}{2} + j \cdot k + 1 + \frac{(j-1) \cdot (j-2)}{2} \tag{3}$$

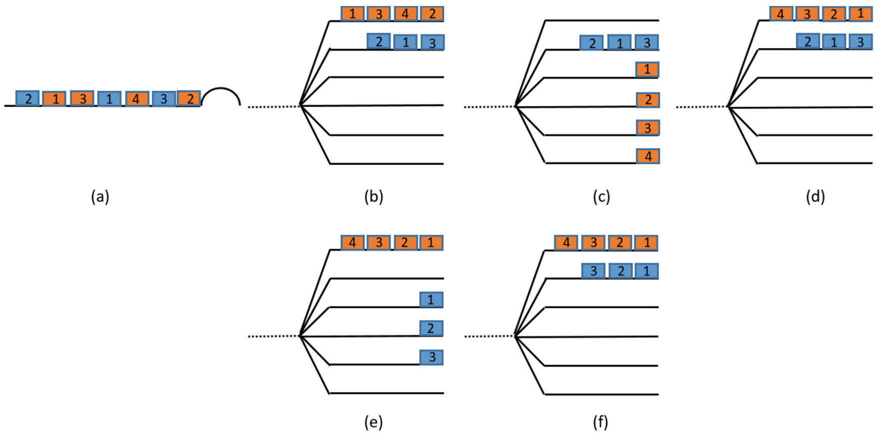

Fig. 2. Example for Sorting by train, (a) Initial situation (7 wagon groups, dedicated to two trains distinguished by color), (b) situation after initial humping, (c) 1st pullback & rehumping: split orange train, (d) 2nd pullback & rehumping: sequence orange train, (e)/(f) splitting & sequencing blue train

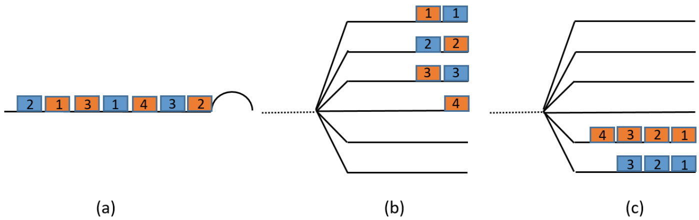

Fig. 3. Example for Sorting by block, (a) Initial situation (7 wagon groups, dedicated to two trains distinguished by color), (b) Initial humping: Sorting by block number, (c) Final result after 4 pullbacks

and

$$\bar{j}_k^{TS} = \left\lfloor -k + \frac{3}{2} + \frac{\sqrt{-8 \cdot k - 7 + 8 \cdot w_{max}}}{2} \right\rfloor. \tag{4}$$

Afterwards the wagon groups on the classification tracks are pulled back and humped again sequentially starting with track $k = 1$. All wagon groups with $w = 1$ are sorted to an empty classification track to start composing the corresponding outbound train. For all other wagon groups holds that if composing their corresponding outbound train has already started and they are to be sequenced next, they are assigned to the corresponding track. Otherwise, they are shunted to the classification track which contains their preceding wagon group w.r.t. the altered order number $\tilde{w}^{TS}$. This implies that to track k only wagon groups from tracks $1, ..., k-1$ can be shunted when $\tilde{w}^{TS} \leq \frac{k(k+1)}{2} + 1 = \bar{w}_k$ holds. Note that this implies that each wagon group is pulled back at most twice. A

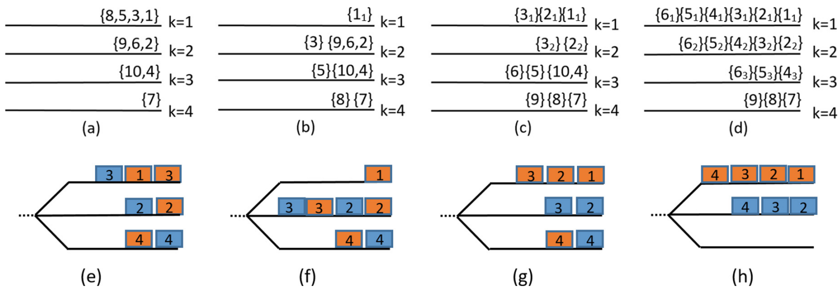

Fig. 4. Triangular Sorting: (a) Initial assignment of first 10 altered order numbers, (e) exemplary assignement for 2 trains, (b)/(f) general/exemplary assignment after first pullback, (c)/(g) general/exemplary assignment after second pullback, (d)/(h) general/exemplary assignment after third pullback

more detailed description of the scheme can be found in Gatto et al. (2009) and Daganzo et al. (1983). Figure 4 illustrates the general assignment for the first 10 altered order numbers. Figure 4(a) shows the assignment after initial humping and subfigures (b)–(d) illustrates the results after the first three pullbacks are made. Here, $\tilde{w}_r^{TS}$ indicates to which outbound train r the wagon group belongs. In Subfigures (e)–(h) shows the initial humping and the results of the first three rehumping steps for the example introduced above. Thereby, the wagon groups' altered order numbers $\tilde{w}^{TS}$ are displayed (blue train).

Geometric Sorting (GS) is similar to TS. The procedure employs a different renumbering procedure and is followed by same rehumping process as in TS (Boysen et al. 2012). In GS, the ordering numbers are altered as follows:

$$\tilde{w}^{GS} = w + 2 \cdot (r' - 1) \tag{5}$$

Similar to TS, w' preserve the wagon group order of each outbound train. The initial assignment of wagon groups to classification tracks follows a geometric sequence as follows

$$\widetilde{W}_k^{GS} = \bigcup_{j=0}^{\bar{j}_k^{GS}-1} \{2^{k-1} + 2^k \cdot j\} \tag{6}$$

whereby the maximum number of wagon groups assigned to track k is

$$\bar{j}_k^{GS} = \left\lceil \frac{\tilde{w}_{max}^{GS} - 2^{k-1} + 1}{2^k} \right\rceil. \tag{7}$$

Due to the different assignment schemes, typically less classification tracks are occupied than in TS, but wagon groups are pulled back more frequently (Gatto et al. 2009). Similar to TS, the wagon groups are pulled back sequentially starting with track $k = 1$. Again, the wagon groups with $w = 1$ are shunted to an

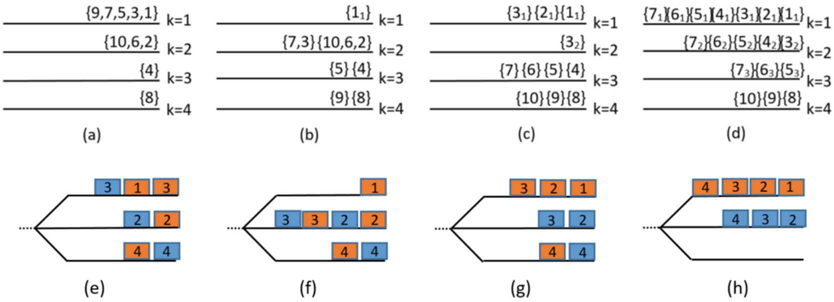

Fig. 5. Geometric Sorting: (a) Initial assignment of first 10 altered order numbers, (e) exemplary assignement for 2 trains, (b)/(f) general/exemplary assignment after first pullback, (c)/(g) general/exemplary assignment after second pullback, (d)/(h) general/exemplary assignment after third pullback

empty track to start composing an outbound train. Other wagon groups are shunted to their corresponding outbound train or to the classification track with contains the direct predecessor w.r.t. the altered order number. More information regarding GS can be found in Gatto et al. (2009). Figure 5 illustrates the process for GS.

2.2 Theoretical Analysis of Sorting Schemes

In this section the sorting performance $SP^i(\mathcal{W}, \mathcal{R})$ of a sorting scheme i for a given set of incoming wagon groups $\mathcal{W}$ and outbound trains to be composed $\mathcal{R}$ is analyzed. The sorting performance is defined as a set of pullbacks whereby each pullback is characterized by the number of wagons attached to it. Therefore, let $v_{w,r}$ denote the number of wagons belonging to wagon group w of train r. The sorting performances are used as inputs to the emission model outlined in Sect. 3 in order to evaluate the GHG emissions of the four different sorting schemes.

For SBT, the number of pullbacks consists of $|\mathcal{R}| + |\mathcal{W}|$ pullbacks as each of the $|\mathcal{R}|$ outbound trains is pulled back once and, afterwards, each wagon group is pulled back again. Thus, for the sorting performance $SP^{SBT}(\mathcal{W}, \mathcal{R})$ holds

$$SP^{SBT}(\mathcal{W}, \mathcal{R}) = \bigcup_{r \in \mathcal{R}} \left\{ \sum_{w=1}^{n_r} v_{w,r}, v_{1,r}, \ldots, v_{n_r,r} \right\} \tag{8}$$

For SBB, the number of pullbacks is determined as the maximum number of wagon groups over all outbound trains $w^{max} = \max_{r \in \mathcal{R}} n_r$. In each pullback, all wagon groups with the same order number are pulled back. Thus, for the sorting performance $SP^{SBB}(\mathcal{W}, \mathcal{R})$ holds

$$SP^{SBB}(\mathcal{W},\mathcal{R}) = \bigcup_{w\in 1,\ldots,w^{max}} \left\{ \sum_{r\in\mathcal{R}|w\leq n_r} v_{w,r} \right\} \tag{9}$$

To derive sorting performances for TS and GS, the number of pullbacks can be determined easily while the number of wagons shunted per pullback are derived in two steps. Due to the renumbering in TS, the total number of classification tracks occupied is given by $\bar{k}^{TS} = \left\lfloor \sqrt{2 \cdot \tilde{w}^{TS}_{max} - \frac{7}{4}} + \frac{1}{2} \right\rfloor$ (Daganzo et al. 1983). For GS, the initial number of classification tracks used is $\bar{k}^{GS} = \lfloor \log_2 \tilde{w}^{GS}_{max} \rfloor + 1$. For each classification track k the set of initially shunted wagon groups are outlined in (6). Thus, $\sum_{\tilde{w}\in\widetilde{\mathcal{W}}^{TS/GS}_k} \sum_{r\in\mathcal{R}} v_{w(\tilde{w}),r}$ denotes the total sum of wagons initially shunted to track k for TS and GS, respectively. Here, $w(\tilde{w})$ indicates the original order number associated to $\tilde{w}$.

Next to the initially shunted wagon groups on a specific classification track k, additional wagon groups from tracks $1, \ldots, k-1$ are shunted to track k. Due to the TS shunting scheme, only those wagon groups are shunted to track k for which $\tilde{w} < \bar{w}$ holds as outlined above. Thus, the subset of wagon groups additionally shunted to track k from the tracks $1, .., k-1$ is given by $\overline{\mathcal{W}}^{TS}_k = \left\{ \tilde{w} \in \widetilde{\mathcal{W}}^{TS}_i \mid \bar{w}_{k-1} < \tilde{w} < \bar{w}_k, i = 1, \ldots, k-1 \right\}$. For GS, the set of wagon groups added to track k summarizes all wagon groups whose direct predecessor w.r.t. $\tilde{w}$ is at track k such that $\overline{\mathcal{W}}^{GS}_k = \left\{ 2^k \cdot j - t \mid t = 1, \ldots, 2^{k-1} - 1, j = 1, \ldots, \bar{j}^{GS}_k \right\}$. Therefore, the total sum of wagons additionally shunted to track k is $\sum_{r\in\mathcal{R}} \sum_{\tilde{w}\in\overline{\mathcal{W}}^{TS/GS}_k} v_{w(\tilde{w}),r}$. Summing up, the sorting performance for TS and GS is derived as follows

$$SP^{TS/GS}(\mathcal{W},\mathcal{R}) = \bigcup_{k=1,\ldots,\bar{k}^{TS/GS}} \left\{ \sum_{r\in\mathcal{R}} \left(\sum_{\tilde{w}\in\widetilde{\mathcal{W}}^{TS/GS}_k} v_{w(\tilde{w}),r} + \sum_{\tilde{w}\in\overline{\mathcal{W}}^{TS/GS}_k} v_{w(\tilde{w}),r} \right) \right\} \tag{10}$$

3 Emission Model for Shunting Operations

In this section the emission model for calculating GHG emissions of shunting operations is presented. The model is the basis for the simulation study described in Sect. 4. In the following, we use the emission model described by Kirschstein and Meisel (2015). The model calculates emissions based on the power demand for overcoming resistances of rolling P^{roll}, air drag P^{air}, ascent P^{grade} and acceleration P^{inert}. To approximate the energy demand (in kWh) of an object with mass m (in tons) moving constantly with speed v (in km/h) over a distance d (in km) the power demand is multiplied with the duration of the movement and energy demand for n^{acc} acceleration processes (to speed $\bar{v}$) is added as follows:

$$\bar{E}(d, m, \bar{v}, \bar{i}, n^{acc}) = \frac{d}{\bar{v}} \left(P^{roll}(\bar{v}, m) + P^{air}(\bar{v}) + P^{grade}(\bar{v}, \bar{i}, m) \right) + n^{acc} \cdot \widehat{E}^{inert}(v, m). \tag{11}$$

For details on calculating power demands and acceleration energy demand we refer to Kirschstein and Meisel (2015).

Based on Eq. 11, total GHG emissions of a diesel train along its route can be calculated as

$$GHG(d, m, \bar{v}, \bar{i}, n^{acc}) = \frac{\bar{E}(d, m, \bar{v}, \bar{i}, n^{acc})}{\epsilon} \cdot p \cdot k \tag{12}$$

where ϵ denotes the energy transformation efficiency of the locomotive (in %), p represents the fuel energy coefficient of Diesel (in l/kWh), and k is the GHG emission coefficient of Diesel (in CO_2-equivalents per litre Diesel).

For calculating the GHG emissions in marshalling yards, three main processes can be distinguished: a) inbound train processing, b) shunting operations, and c) outbound train processing. Inbound and outbound train processing refer to activities like routing the complete trains within marshalling yards, line locomotive positioning as well as coupling/decoupling procedures. Both main processes mainly depend on the number of inbound and outbound trains to be processed within a given time. In a marshalling yard, complete trains cover only small distances. Therefore, inbound and outbound train processing are causing only minor parts of GHG emissions in marshalling yards (Douglass et al. 2010). Therefore, in the following inbound and outbound processing are neglected when calculating GHG emissions.

To assess the GHG emissions of shunting operations, a shunting process is subdivided into three subprocesses: a) repositioning of shunting locomotives, b) pullback transport, c) wagon group humping. Step a) comprises a movement of a shunting locomotive at the end of a classification track. I.e., only the empty shunting locomotive is moved. Afterwards, the shunting locomotive pushes the wagon groups back into the receiving area summarizes as step b). Here, all wagons of the corresponding wagon groups and the shunting locomotive moves into the receiving area. Finally, in step c) the wagon groups are pushed over the hump and roll into the classification area again. In order to calculate GHG emissions for each step, the mass, speed, grade and number of acceleration processes are to be determined. For the sake of simplicity, in the following we assume homogenous wagons and movements as well as equipment. I.e., each wagon is assumed to have a fixed gross weight m^{RC} (in tons) and length l^{RC} (in meters). Likewise, the weight of the shunting locomotive is denoted as m^{loc}. Likewise, we assume fixed distances for repositioning shunting locomotives d^{rp} and pullbacks d^{pb}. For calculating energy demand of the humping process, the track grade i is calculated based on the height of the hump h (in meters). In the remaining subprocesses a track grade of $i = 0$ is assumed. Similarly, we assumed that in each subprocess the object accelerates once to speed $\bar{v}$ such that $n^{acc} = 1$. Thus, GHG emissions of a shunting process involving s wagons is given by

$$GHG^{pb}(s) = GHG\left(d^{rp}, m^{loc}, \bar{v}, 0, 1\right) + GHG\left(d^{pb}, m^{loc} + s \cdot m^{RC}, \bar{v}, 0, 1\right) + GHG\left(s \cdot l^{RC}, m^{loc} + s \cdot m^{RC}, \bar{v}, \frac{h}{s \cdot l^{RC}}, 1\right) \quad (13)$$

Using shunting performance information SP^i, the GHG emission quantity of sorting scheme i is calculated for a given set of inbound wagon groups $\mathcal{W}$ and outbound trains $\mathcal{R}$ by applying (13) to each element $s \in SP^i(\mathcal{W}, \mathcal{R})$ and summing up all GHG emissions. Additionally, in all sorting schemes, all incoming wagons $\bar{s} = \sum_{r \in \mathcal{R}} \sum_{w=1}^{n_r} v_{w,r}$ have to be humped initially. I.e., the total GHG emissions for a sorting scheme i are given by

$$GHG^i(\mathcal{W}, \mathcal{R}) = \sum_{s \in SP^i(\mathcal{W}, \mathcal{R})} GHG^{pb}(s) + GHG\left(\bar{s} \cdot l^{RC}, m^{loc} + \bar{s} \cdot m^{RC}, \bar{v}, \frac{h}{\bar{s} \cdot l^{RC}}, 1\right). \quad (14)$$

4 Simulation Experiments

4.1 Experimental Design

In the following the total GHG emissions of the aforementioned sorting schemes are investigated. Therefore, random problem instances are generated consisting of a set of incoming wagon groups and a set of outbound trains. Along with experimental variables, the remaining fixed parameters used in the simulation study are summarized in Table 1.

Table 1. List of fixed parameters in the simulation study

Repositioning distance d^{rp}	Pullback distance d^{pb}	Hump height h	Shunting loc. weight m^{loc}	Wagon gross weight m^{RC}	Wagon length l^{RC}	Speed $\bar{v}$
1 km	1.5 km	2 m	80 t	55 t	14 m	8 km/h

The marshalling yard parameters are inspired by a medium-sized marshalling yard located in Halle/Saale (Germany). The distances for repositioning and pulling back are set to $d^{rp} = 1$ km and $d^{pb} = 1.5$ km. Usually, classification tracks show a length of about 1 km. This length gives enough space to assemble trains with maximum length (835 m in Germany, Allianz pro Schiene (2016)). For repositioning a conservative estimate is chosen by assuming that shunting locomotives have to travel at least once across the classification area to be available again in the receiving area and vice versa. For the pullbacks its assumed that the classification track length plus the train length has to be travelled. The hump at the marshalling yard in Halle/Saale has a height of about 2 meters which is used as a reference.

We assume an average speed of 8 km/h for shunting operations. Although regulations prescribe a maximum of 25 km/h, usually the average speed is considerably lower in real-world processes. Thus, we use a rather conservative speed estimate which leads, in turn, to a rather conservative estimate of GHG emissions. As parameters for the shunting locomotive and wagons we use default values used e.g. in Knörr et al. (2019). The gross weight of an average wagon is assumed to 55 tons which consist of the tare weight of 25 tons plus an average payload of 30 tons (assuming a payload capacity of 55 tons and a maximum gross weight of 80 tons). The remaining parameters of shunting locomotive and wagon required to apply the emission model are summarized in Table 2 in the Appendix.

To study GHG emissions of SBT, SBB, TS and GS sorting, a variety of problem instances are generated to study the effects of two parameters: The number of outbound trains as well as the number of wagon groups. We vary the number of outbound trains $|\mathcal{R}|$ in the interval $1, \ldots, 20$. Likewise, we vary the number of wagon groups per outbound train n_r. In order to reflect the heterogeneity of train compositions, n_r is considered as a Poisson distributed random variable with $n_r \sim Poi(\lambda)$. Parameter λ is varied systematically in the interval $1, \ldots, 10$. For each combination of λ and $|\mathcal{R}|$, 50 instances are generated. Thereby, in each instance, the number of wagons per wagon group and outbound train $v_{w,r}$ is also modelled as a Poisson distributed random variable with $v_{w,r} \sim Poi\left(\frac{30}{n_r}\right)$. Thus, in expectation each outbound train consists of 30 wagons. Note that both Poisson-distributed parameters are winsorized at a value of 1. I.e., observations sampled as 0 are replaced by 1 to obtain non-empty wagon groups. The simulation model is implemented in Java and run on a AMD Ryzen 7 4800H with 8 GB memory.

4.2 Results

In the following we analyse average GHG emission quantities for each sorting scheme grouped by the number of outbound trains and the expected number of wagon groups per train. Figure 6 shows the average GHG emissions per sorting scheme depending on λ and the number of outbound trains. Results are obtained by the presented simulation and the simplified real world assumption in Subsect. 4.1.

Analysing Fig. 6a reveals that GHG emissions increase with increasing number of outbound trains as more wagons have to be shunted. Consistently, SBB shows the smallest GHG emissions among all sorting schemes while the gap to other sorting schemes increases with increasing number of trains. The remaining sorting schemes increase at similar rates except for GS. It turns out that GS is superior to SBT for $\lambda \leq 16$, while it is inferior for $\lambda > 16$.

Figure 6b shows more diverse patterns for the different sorting schemes. While for $\lambda \leq 2$, TS and GS show the smallest emissions, SBB is superior for larger

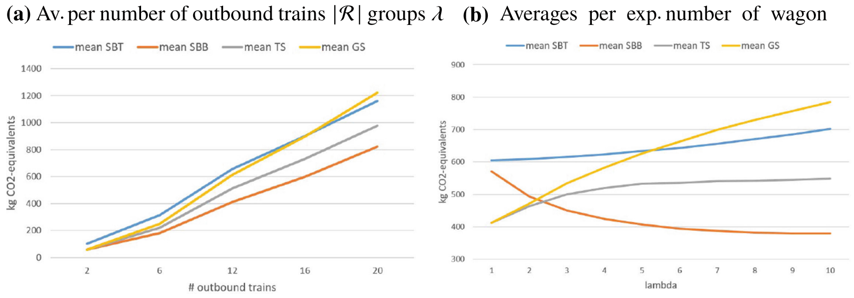

Fig. 6. Average GHG emissions (in kg CO_2e) grouped by sorting scheme and experimental variables

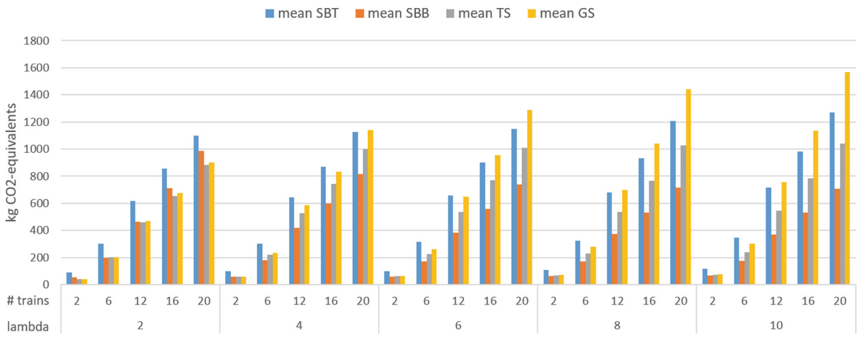

Fig. 7. Average GHG emissions (in kg CO_2e) for all sorting schemes grouped by selected levels for λ and the number of outbound trains

values of λ. Interestingly, GHG emissions decline with increasing λ for SBB, while the remaining sorting schemes show increasing emissions. This because SBB scales with the maximum number of wagon groups over all outbound trains. This somewhat counter-intuitive result effect reduces when looking at both experimental variables jointly as displayed in Fig. 7.

Figure 7 shows the average GHG emissions for a subset of the results grouped the number of outbound trains and λ. It appears that for instances with less than 12 outbound trains, average GHG emissions of SBB do not change noticeably with increasing λ. For instances with more than 12 outbound trains, a decrease in GHG emissions is observed. This is caused by an rounding effect. When λ increases the number of wagons per group becomes small. Due to the winsorized Poisson distribution wagon groups with just 1 wagon are more frequently generated. As a consequence the total number of wagons decreases with increasing λ. In SBT, TS, and GS the effect of declining total numbers of wagons is overcompensated because the total number of pullbacks increases with λ. In contrast, for SBB the maximum number of wagon groups over all outbound trains drives the number of pullbacks which is less affected by λ than the total numbers of wagons.

Furthermore, Fig. 7 reveals that GS is inferior to all other sorting schemes w.r.t. total GHG emissions except when only few wagon groups are present. In case of many outbound trains with few wagon groups, however, an advantage over SBB and SBT exists. However, GS is never superior to TS which ranks second in all settings except when $\lambda = 2$ where it shows the lowest GHG emissions among all sorting schemes. I.e., among the two complex sorting schemes, TS dominates GS. Regarding the two simple sorting schemes, SBT and SBB, it is clear that SBT is dominated by SBB in all setings. As SBT usually requires more classification tracks than SBB, SBB seems to be the superior sorting scheme.

5 Outlook

In this paper, GHG emissions of shunting operations in marshalling yards are studied. Four sorting schemes are evaluated w.r.t. their associated GHG emissions for a given set of shunting tasks. Therefore, new analytic expressions for calculating the numbers of wagons on a classification track as well as the number of pullbacks for geometric and triangular sorting are derived. Analysing GHG emissions for a variety of settings reveals that sorting by block shows lowest emissions among the four sorting schemes followed by Triangular sorting ranking second best in most settings. For instances with only different wagon groups to be sorted, Triangular sorting dominates Sorting by block.

The outlined model and simulation shows that considerable GHG emissions are generated by shunting operations. Therefore, potentials for reducing the environmental impacts of rail operations exist. The sorting procedures investigated here are comparatively simple heuristics omitting some relevant real-world restrictions. Taking into account optimization-based sorting schemes, usually employed in highly automatized shunting yards to achieve fast and timely shunting, is necessary to gain further insights. Also more realistic assumptions about shunting capacities (like the number of classification tracks or track lengths) as well as organizational constraints (like due dates or workforce schedules) potentially affect sorting performance. Usually both components, time and capacity restrictions, lead to more extensive shunting as rail cars have to moved more frequently. Thus, it is to be expected that in more complex optimization-based shunting scheduling models incorporating emissions is not only technically demanding but also offers large potentials for emission reduction. Additionally, trade-offs between traditional objectives (like minimizing delays or used classification tracks) and environmental objectives possibly exist.

Acknowledgments. This research is funded by the German Research Foundation (DFG), under reference BI 555/4-2.

Appendix

Table 2. Technical parameters for shunting locomotive and wagons used in the emission model of Kirschstein and Meisel (2015)

ϵ	k	p	c_{roll}^{loc}	c_{roll}^{wagon}	c_{roll}^{aux1}	c_{roll}^{aux2}	c_{air}^{loc}	c_{air}^{wagon}	A	n_{axles}
0.4	3.15	0.1004	0.003	0.0006	0.0005	0.0006	0.8	0.218	9	4

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What is the Right Home Delivery Option for Your Online Shopping?

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Abstract. Although retailers and logistics service providers offer various last mile delivery options, the level of individualisation regarding integrating consumer demands and expectations for home delivery is currently low. In order to offer such individualised delivery options, it is necessary to understand consumers' home delivery needs and wants. Accordingly, this paper examines consumer preferences regarding delivery options, focusing on online grocery retailing using a discrete choice experiment approach. Our results show that consumers can derive high benefits from the individualization of delivery options, especially in the areas of vehicle type and place of delivery. Also, packaging and delivery time are relevant delivery options for consumers but considered to be less useful than transport vehicles and place of delivery, while consumers do not prefer the selection of a time window on the day of delivery.

1 Problem Background and Research Question

More and more private consumers are using e-commerce for their purchases, which leads to an increasing individual order frequency. Thus, the number of home deliveries, especially within urban areas, are increasing and create major challenges for urban logistics (Savelsbergh and Van Woensel 2016). Retailers and logistics service providers face new challenges in terms of cost pressure and complexity as their existing logistics structures are not designed for such a high number of home deliveries. Especially the last mile, which is considered an expensive, inefficient, and environmentally damaging part of the supply chain, is becoming the focus for logistics service providers (Gevaers et al. 2011). Therefore, logistics service providers are working on new concepts and innovative delivery options (Mangiaracina et al. 2019).

In addition, there is an increased demand for the delivery of online ordered goods with a growing desire for more individuality in delivery, as consumers want to decide for themselves when and where to receive their delivery (Witten and Schmidt 2019). They also expect a high level of quality and flexibility as well as a high delivery speed while keeping costs low or even decreasing and also taking sustainability aspects into account (Mangiaracina et al. 2019).

U. Buscher et al. (Eds.): *Logistics Management*, LNLO, pp. 137–150, 2021.
https://doi.org/10.1007/978-3-030-85843-8_9

Although retailers and logistics service providers can vary their delivery options, direct consumer involvement is relatively low when it comes to the design of last-mile logistics (Nguyen et al. 2019). However, when offering individualisation options, it is necessary to identify consumer preferences for the delivery of online ordered goods. So far, there has been no detailed research on the individualisation of such logistics options, so this paper tries to close this gap and examines which logistics options are preferred by consumers in online grocery retailing. We focus on the food industry because it has unique requirements for packaging and transport (Dworak and Burdick 2002; Vahrenkamp et al. 2012). This investigation results in specific recommendations for online retailers and logistics service providers. We strive to create an ideal scenario to provide online retailers and logistics service providers with an overview of customers' preferred delivery options. These can be integrated into strategic planning, resulting in a customer-specific service improvement and consequently an improvement of the own competitive positioning. This leads to the following research question:

How do consumers prefer their online ordered groceries to be delivered?

The remainder of the paper is as follows: After an introduction, the theoretical basics are presented. These include the topics of consumer individualisation, online grocery retailing, the associated logistics characteristics and the last mile, including its logistics options. Subsequently, the methodology of discrete choice experiments (DCE) is explained, which is used to identify consumers' preferred last mile delivery options. The evaluation and discussion of the DCE follow before the paper ends with a conclusion, limitations and an outlook for further research.

2 Theoretical Background

2.1 Individualisation

A key objective of an individualisation strategy is to achieve greater consumer loyalty due to the individualised services and an increase in benefits for the consumer (Reichwald et al. 2009). In the manufacturing industry, modularisation and postponement strategies offer consumers many options for individualisation, which have been established for many years (Kölmel et al. 2019; Shaik et al. 2015). In contrast, the individualisation of logistics in the last mile is hardly developed.

Our understanding of consumer individuality is based on Gausmann (2009), who defines this as an adaptation to the consumer's individual preference structure. Individualised logistics describes the possibility for the consumer to make an individual selection from several delivery options. Delivery options in our approach contain different attributes, which in turn are described by different levels. For example, one attribute represents the place of delivery or the transport packaging used. In the case of the place of delivery, the associated levels are home delivery or collection by the consumer from the store.

An important objective is to achieve the right degree of individualisation. If individualisation is pushed too far, benefits will decrease while costs will increase (Eversheim and Schuh 2003). Complete avoidance of individuality leads to maximum economies of scale being achieved through standard services. At the same time, essential consumer needs are no longer met (Eversheim and Schuh 2003).

Accordingly, it is important to identify the essential areas for individualisation for last mile logistics to achieve a high benefit while simultaneously being able to achieve economies of scale.

2.2 Online Grocery and Its Logistical Challenges

Online grocery retailing is determined by various factors such as the frequency of internet use, the spread of internet-enabled devices, the further development of mobile payment methods, the legal framework, and also social aspects such as generational change and the associated trust in e-commerce (Dederichs and Dannenberg 2017). Challenges in online grocery retailing arise due to strong competition, a good local supply situation through stationary retailing stores, low margins, and high price sensitivity on the part of consumers, who are often unwilling to pay additional delivery costs (Grant et al. 2014; Heinemann 2020). Overall, online grocery retailing is expected to increase significantly (Rumscheidt 2020).

Regarding the logistics processes in online retailing, there are clear differences compared to stationary retailing, where logistics operations such as order-picking, packaging and delivery are handled by consumers. In online grocery retailing, these operations retailers are executing these operations, so the responsibility for the fulfilment process returns from consumers to retailers (Kämäräinen and Punakivi 2002).

There are particular legal requirements for the logistics processes of groceries (Dworak and Burdick 2002; Vahrenkamp et al. 2012). These refer to regulations and controls in the areas of food hygiene, temperature safety, data protection and product traceability. For example, food is guaranteed by law to remain fresh until the best-before date (Hagenmeyer 2006). This is particularly relevant for fresh products such as meat and sausage products, fruits and vegetables. For this guarantee, an uninterrupted cold chain between producers and consumers is essential (Vahrenkamp et al. 2012). The transport of fresh food requires active or passive cooling for this purpose, which causes additional costs. In active cooling, the vehicle has integrated cooling elements, while in passive cooling, isolating packaging is used (Arnold et al. 2008). Furthermore, traceability is regulated by law for food products, making documentation and planning of logistics in this area more difficult (Arnold et al. 2008).

These additional logistics requirements for the delivery of online ordered groceries result in costs for the retailer. Due to consumers' high price sensitivity, they are not always willing to contribute to these logistics costs (Grant et al. 2014).

2.3 Last Mile Logistics and Its Delivery Options

The last mile is the part in which an order is delivered from the last distribution centre, collection point or local warehouse to its destination (Umundum 2020). The final destination can be a private end user but can also be represented by a company (Clausen et al. 2016). This stage of the value chain often turns out to be inefficient, costly, and environmentally harmful (Gevaers et al. 2011). The shopping behaviour of consumers triggers many small orders, which results in increasing transport volumes. This creates significant problems for logistics in the last mile, while at the same time, high cost pressure is developing in this area (Mihatsch et al. 2018). One of the main reasons for the high costs of the last mile is that deliveries are not scalable. Packages often cannot be bundled, as usually only one package is delivered to one person (Pronello et al. 2017). This results in a large number of transports with simultaneously more insufficient utilisation of the means of transport (Schnedlitz et al. 2013). Therefore, retailers and logistics service providers are confronted with significant challenges due to the increasing number of delivery options and rising requirements demanded by government regulations and consumers (Brabänder 2020). The last mile offers a wide range of individualisation options. Below we briefly describe the most important functions of online retailing in terms of logistics processes.

Transportation: The use of different transportation vehicles is subject to continuous further development to meet last mile logistics' challenges. A wide range of options in this area already exists, including classic transporters whose engines are based on fossil fuels. This is still the most common type of vehicle used to deliver parcels (Bretzke 2020). Furthermore, vehicles with electronic drives, like e-cars or e-bikes, continue to gain in importance. Particularly in urban areas, cargo bikes are also taking on an increasingly important role in managing the last mile (Saenz et al. 2016). For the future, work is being done, particularly on the possibilities of autonomous vehicles, parcel robots and drones, as well as on the concept of crowd shipping (Boysen et al. 2020; Mangiaracina et al. 2019).

Delivery Speed: Furthermore, the time dimension of the delivery offers possibilities for individualisation. First, the speed of the delivery can be considered. In this context, major challenges arise for logistics service providers. Short delivery times lead to rising costs, as the lack of lead time makes route planning more complicated, the capacity utilisation of vehicles is reduced, and CO_2 emissions per package increase (Witten and Schmidt 2019). For the individualisation of the speed of delivery, the consumer already has several selection options. There is the classic standard delivery, which takes 3–5 working days on average. Nevertheless, same-day or next-day deliveries are also becoming increasingly popular in online retailing (Winkenbach and Janjevic 2018).

Time Slots: Furthermore, the consumer can be offered different time slots for delivery. Giving the consumer a choice of a time slot should ensure the consumer's presence on the delivery day and improve consumer service and delivery efficiency (Agatz et al. 2008). In contrast, failed delivery attempts result in high costs as redeliveries are caused. This also reduces consumer satisfaction and has a negative effect on sustainability. Time windows for deliveries are often limited to date and often collide with consumers' work schedules. Therefore, after-hours delivery options are crucial for this market's growth (Grant et al. 2014).

Delivery Place: The place of delivery provides many opportunities for individualisation for consumer and optimisation of the last mile as a whole. Offering different delivery locations for delivery also reduces failed delivery attempts and keeps logistics costs low. The most common delivery option is still traditional home delivery. Here, goods are delivered to the consumer's front door and handed over in person (Brabänder 2020). Traditional home delivery is supplemented by the options of home delivery with an individual drop-off location or dropping off the package at a neighbour's home. An alternative to home delivery exists, for example, with the click and collect model, which includes self-collection by the consumer from the store or a packing station (Mangiaracina et al. 2019; Schnedlitz et al. 2013). Advantages arise from the fact that the consumer does not have to be present to receive the package with these options and is also not bound to specific times.

Packaging: Packaging is also suitable for the individualisation of delivery. Different materials, such as paper, wood, glass, and plastic, are used as materials for transport packaging (Escursell et al. 2021). In online retailing, packaging provides the opportunity to close potential information gaps and thus offers the consumer added value (Kölmel et al. 2019). Also, the increasing environmental awareness of many consumers can be met by environmentally compatible packaging (Schmidt 2019). Packaging not only has an impact on shipping costs but also on energy consumption during transportation (Schnedlitz et al. 2013). It also contributes to the problem of excessive waste production and environmental pollution, as especially disposable packages, are often perceived as a throwaway product (Pålsson et al. 2017). For these reasons, reusable packaging is increasingly being used alongside conventional disposable containers, even if it is sometimes assumed that reusable packaging is less economically efficient (Mollenkopf et al. 2005).

The individual adjustments in the last mile logistics can result in considerable additional costs for the retailer or logistics service provider, which leads to an increase in costs for the end consumer (Witten and Schmidt 2019). Since consumers are usually not willing to pay the cost for deliveries, they will only accept an extra charge if the individualisation of delivery options is seen as a competitive factor in consumers' purchasing decisions (Doch 2015). One of such competitive factors for the consumer can be that individualisation enables sustainable delivery. Consumers are increasingly demanding that companies behave in an ecologically sustainable manner. As a result, resource efficiency is becoming a decisive purchasing criterion for many consumers (Straube et al. 2009). Logistics is also affected by this change due to the high proportion of CO2 emissions. Therefore, it is expected that consumers will increasingly prefer sustainable deliveries and that this will increase their willingness to accept the associated costs.

3 Discrete Choice Experiments

3.1 Introduction and Selection of Attributes and Levels for the DCE

DCE are a multivariate method for analysing the preferences of individuals (Backhaus et al. 2015). In DCE, simulated or real selection decisions are examined. Individuals are offered various alternatives for an investigated good, from which the preferred alternative can be selected. The chosen alternative has the highest preference and offers the highest utility to the individual (Louviere et al. 2000). Such investigated good can be the choice of a party, the purchase decision for a particular television or, as in the case of this paper, a potential decision about a delivery option in online grocery retailing.

As described in the theoretical background, there are different delivery options on the last mile, which can be classified into attributes and levels according to a DCE (Backhaus et al. 2015; Louviere et al. 2000). An attribute is e.g. the delivery place while associated levels represent attended or unattended home delivery or click and collect. We use the DCE because it allows us to estimate a utility for these different attributes and levels and thus, we can derive which constellation of attributes and levels represents the preferred delivery option for customers. Moreover, the DCE is suitable for our research question because the decisions in a DCE often reflect typical real-world situations (Hensher et al. 2015; Louviere et al. 2000). In our case this is the decision at the end of an online ordering process on how to deliver the selected goods.

In the beginning, DCE requires the selection of relevant attributes and levels (Backhaus et al. 2015). Regarding the specific procedure, there is no explicit prescription about the identification and determination of the attributes. Possible approaches include literature reviews, group discussions, surveys, or expert interviews (Kjaer 2005). There are no restrictions on how many attributes and levels should be used for a DCE, but there is no consensus about this in the literature on DCEs. However, with a larger number of attributes, the cognitive difficulties of the participants of the DCE increase. In order for individuals to be able to consider all of the listed attributes when making their choices, DCEs should have as few attributes and levels per attribute as possible (Backhaus et al. 2015).

We decided on a suitable number of 5 attributes and formed a maximum of 4 levels per attribute. To identify the relevant attributes for the delivery of online purchased groceries, a literature-based pre-selection is made (see the previous section), which is supplemented by an online survey as an instrument for collecting consumers' opinions. This resulted in the following five attributes and associated levels shown in Table 1.

Table 1. Attributes and levels for the DCE

Attributes	Levels			
Transport vehicle	Conventional transporter	E-vehicle	Cargo bike	
Speed of delivery	Standard shipping	Same Day	Next Day	
Time slot	No matter	08:00–15:00	15:00–22:00	
Place of delivery	Home delivery	Home delivery +	Click and Collect	Packing Station
Packaging	Disposable	Reusable		

3.2 Experimental Design and Data Analysis

Next, choice sets are constructed from the attributes and levels. The number of attributes and levels results in a complete set of 216 ($2 \times 3 \times 3 \times 4 \times 3$) possible combinations (or profiles). The JMP software (SAS Institute, Cary, North Carolina, USA) is used to design the DCE choice sets. The software uses a Bayesian D-optimal design to generate the DCE. The model assumes that the utility of the different attributes is different, thus allowing the regression to be more informative. Therefore, so-called prior values are needed to implement expected utility differences (Kessels et al. 2011). For this purpose, a pre-test was performed to obtain the required standard errors and variances of the attributes for the Bayesian D-optimal design. For the final DCE, five different surveys are created, each to be answered by 30 respondents. With this, 120 profiles in 40 selection situations are to be queried.

An online survey was conducted for data collection. According to Akremi (2019), a convenience sampling of the subjects was chosen with a snowball procedure. The questionnaire comprised three parts: 1. basic demographic information of the respondents, 2. question on people's experiences of online shopping behaviour and 3. eight pairs of choice sets, each containing three profiles. Fieldwork was conducted from 28 January - 14 February 2021. At least 30 participants took part in each of the five surveys. The first 30 participants were used for the analysis, resulting in a valid sample size of 150 participants. Most DCE participants are 20–40 years old (79%), are single (75%), run their own household (83%), and have no children (86%). Furthermore, students (42%) and full-time employees (34%) are predominant in the sample. Furthermore, 78% organise their own grocery shopping, and already 47% of the participants state that they have already bought groceries online.

The most important discrete choice model for representing individual decision behaviour when choosing between alternatives is the logit choice model (Hensher et al. 2015; Louviere et al. 2000). As soon as more than two alternatives are used, this is called a multinomial logit choice model (MNL model), which was primarily shaped by the work of McFadden (1974). This model reproduces the human decision-making process in a simplified form. Due to the simplification, the logit choice model can only indicate probabilities for the choice of an alternative and cannot represent an explicit decision (Backhaus et al. 2015). These probabilities are determined in the MNL model with the help of the differences in the utility values. The utility values for the evaluation must be estimated, for which a maximum likelihood method is used. This maximisation problem can be solved by default using different statistical programs (Backhaus et al. 2015). As mentioned before, we use the JMP software for this purpose.

4 Results of Discrete Choice Experiment

Table 2 shows the results of the MNL model. It includes the parameter estimates of the attribute levels, the L-R Chi-square, the degrees of freedom, and the attributes' significances. The attributes are ranked in order of importance.

The results indicate that all attributes are significant at the 5% level except for the attribute' time slot' of the delivery of online ordered groceries. Our findings show that consumers see the greatest benefits in choosing the transportation vehicle, followed by packaging and delivery speed options.

In order to provide more detailed information on the benefits of the individual attribute levels, the marginal utility effects are shown in Fig. 1.

Our findings provide the strongest utility value in the attribute of 'transportation vehicles'. Cargo bike and electronically powered vehicles provide a positive benefit, while a

Table 2. Results of the DCE

	Parameter estimate	L-R Chi^2	DF	p-value
Transport vehicle				
Conventional Transporter	0.272	193.832	2	<0.001*
E-Vehicle	0.427			
Cargo bike	−0.699**			
Place of delivery				
Click and collect	−0.578	168.958	3	<0.001*
Packing Station	−0.475			
Home delivery +	0.553			
Home Delivery	0.500**			
Packaging				
Reusable	0.270	42.737	1	<0.001*
Disposable	−0.270			
Speed of delivery				
Same Day	0.142	16.402	2	0.003*
Next Day	0.043			
Standard shipping	−0.185**			
Time slot				
08:00–15:00	−0.008	3.652	2	0.1611
15:00–22:00	0.079			
No matter	−0.071**			
LogLikelihood	−2252.727			

*Significant at 5% level
** Marginal utility values corresponding to the last level of each effects-coded attribute are calculated as minus the sum of all other marginal utility values of that attribute (Kupfer et al. 2016).

conventional delivery vehicle provides a clearly negative marginal utility. The marginal probabilities also indicate that consumers opt for the cargo bike with a probability of 46%, followed by the e-vehicle with a probability of 39% and the conventional vehicle with a probability of 15%.

Looking at the location of delivery, it becomes apparent that the positive utility of ‘home delivery’ and ‘home delivery with individual drop-off location’ even provides a greater utility than the options of the transport vehicles. In contrast, the two self-pickup options are associated with a negative benefit for the consumer. Therefore, self-collection from the store is selected with a probability of only 12%, while collection from a packing station is selected with a probability of 14%. Home delivery is selected with a probability of 36% and home delivery with an individual drop-off location with 38%.

The attributes ‘packaging’ and ‘speed of delivery’ follow with significantly lower benefits for the consumer. In the case of packaging, reusable packaging provides a greater benefit compared to disposable packaging. Reusable packaging is chosen with a probability of 63%, while disposable packaging is only chosen at 37%. In terms of ‘speed of delivery’, same day delivery has the greatest benefit and is chosen by consumers with a probability of 38%. Next day delivery provides only a small added value but is still selected with a probability of 34%. Standard delivery has a clearly negative benefit for the consumer and has a probability of only 27%.

Marginal probability	Marginal utility value	**Transport vehicle**
0,3929	0,27241	E-vehicle
0,4584	0,42663	Cargo bike
0,1487	-0,69903	Conventional transporter
Marginal probability	Marginal utility value	**Place of delivery**
0,1227	-0,57806	Click and Collect
0,136	-0,4752	Packing Station
0,3806	0,55347	Home delivery +
0,3607	0,49979	Home delivery
Marginal probability	Marginal utility value	**Packaging**
0,632	0,27032	Reusable
0,368	-0,27032	Disposable
Marginal probability	Marginal utility value	**Speed of delivery**
0,3806	0,14186	Same Day
0,3448	0,0429	Next Day
0,2746	-0,18476	Standard Delivery
Marginal probability	Marginal utility value	**Time slot**
0,3302	-0,00753	08:00 - 15:00
0,36	0,07896	15:00 - 22:00
0,3098	-0,07143	No matter

Fig. 1. Marginal utilities

5 Discussion and Implication

Our findings show that the attribute of transportation vehicle creates a great benefit for the consumer. Participants were particularly in favour of environmentally friendly alternatives such as the cargo bike or e-vehicle, while traditional transporters have a negative benefit for the consumer. This results in practical implications for logistics service providers and online retailers. So far in practice, there is almost no possibility for the consumer to choose the delivery vehicle, which should be changed in the future. Due to the high benefit for the consumer, this is an opportunity to increase service and retain consumers. We also recommend that logistics service providers expand their fleets with environmentally friendly alternatives such as electronically powered vehicles and cargo bikes. These provide consumers with a particularly high benefit and are clearly preferred over traditional transporters.

Furthermore, our findings present possibilities for optimisation in the area of the place of delivery. Our results show that home deliveries are particularly important to consumers, while they are negatively disposed toward picking up their items at a store or packing station. This result may be affected by the current pandemic situation, as consumers are currently avoiding movement in public spaces. Nevertheless, home deliveries with an individual drop-off location could be of particular interest. In this case, the consumer's presence on the delivery day is not mandatory and failed delivery attempts are avoided. On the one hand, this offers great benefits for the consumer, as demonstrated in our DCE, while at the same time keeping logistics costs low for the logistics service provider.

Likewise, offering consumers a choice between disposable and reusable packaging can be advantageous for retailers and logistics service providers. Offering reusable packaging increases the benefits for the consumer and also helps to reduce waste and conserve resources. Due to the positive effect on sustainability, we also expect consumers to be more willing to contribute to the additional costs in this area. Lastly, our results confirm the trend toward more and more timely deliveries. In particular, the grocery product group may become even more dependent on fast deliveries, as long delivery times for fresh food can have an impact on shelf life. Accordingly, logistics service providers should design their offerings in particular for same-day or next-day deliveries.

6 Conclusion, Limitations and Outlook

This paper aimed to identify individualisation possibilities for home deliveries of online-shopped groceries based on consumer preferences. The results of our study provide empirical evidence that offering individualisation options for home delivery offer consumer benefits. However, not all elements of home delivery offer the same value for consumers. Based on the DCE, the selection of vehicle types is the most important differentiation criteria followed by the place of delivery and packaging and delivery speed. Taking the notion of Fisher's (1997) right supply chain design, our study suggests the following combination of logistics options that consumers prefer when ordering food online: The delivery is made via cargo bike directly to the consumer's home with the option of an individual drop-off location. Furthermore, the goods are in reusable packaging, and the delivery takes place within one day.

This work's limitations are mainly related to the design of the DCE, which is based on a convenience sample of primarily students and interns between the age of 20 and 40. Apart from the expandable number of 150 participants in the DCE, it would have been possible to represent a broader age spectrum or focus, especially on people who already have experience in online grocery retailing. Furthermore, there are other possible delivery options, which are not considered in our design. These include, for example, shipment tracking, the ability to change delivery requests after the order, or the possibility to pay a surcharge for the compensation of emitted emissions. Further attributes would also have been conceivable with regard to the time dimension. These include, for example, the selection of a specific day of the week for delivery or after-work delivery. In order to ensure the independence of the attributes, only two attributes with a time dimension (speed of delivery and time slot) were selected. The price is also not considered in our study, although it is a decisive factor in deciding to order a product online. However, this work's primary goal is to examine the logistics delivery options, to which the price cannot be counted. Nevertheless, the number of attributes and levels had to be limited not to overwhelm the DCE participants (Backhaus et al. 2015).

For future research, it is particularly interesting to relate the delivery options to the issue of sustainability. If a sustainability score is assigned to the individual delivery attributes and levels, highly scaled order and delivery scenarios can be simulated. These show the environmental impact of the selected logistics option, allowing consumers to understand their chosen delivery options and reflect on their decisions (Freitag and Kotzab 2020). This gives consumers the option of both individualised and sustainable last mile logistics. Similarly, we expect that consumers will be more likely to share in the rising costs of logistics service providers due to individualisation if a link to sustainability becomes apparent. In this context, the so-called attitude-behavior gap should be mentioned. This states that there is a discrepancy between the attitude and the actual behavior of consumers. This applies, for example, to the consumption of sustainable or green products, where consumers indicate that they would prefer to buy these products. However, actual purchasing behavior shows that consumers do not correspond to their green attitudes (ElHaffar et al. 2020; Terlau and Hirsch 2015). In future research, it will therefore be necessary to investigate whether the green attitude of many consumers is sufficient to accept a possible surcharge for individualized and sustainable delivery of food ordered online. This is of particular importance because individualisation is associated with considerable additional costs for the logistics service provider (Witten and Schmidt 2019). Accordingly, the implementation of these individualisation options is always linked to the question of who can and should bear the costs for this.

Concerning the problems of attended home delivery, the approach presented here can also be viewed from other perspectives. For example, questions arise about optimal route planning, dynamic pricing, or delivery in certain time windows. There are already several contributions on these related issues from the field of operations research (Campbell and Savelsbergh, 2005; Cleophas and Ehmke 2014; Klein et al. 2019; Köhler et al. 2020; Yang et al. 2016). Our work should be related to these approaches in future research. Furthermore, future research should also consider to what degree customer orientation in regards to home delivery is practicable and actionable when executed by logistics service providers.

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Multi-skilled Worker Assignment Problem in Multi-shift Cell Manufacturing

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Abstract. We study a multi-skilled worker assignment problem with multiple shifts in cell manufacturing. The problem is motivated by a real planning problem in protective device manufacturing. Two assignment decisions must be made simultaneously: Requested orders and multi-skilled workers are assigned to production cells and shifts. Specifically, a certain number of workers process orders in one production cell, whereby the processing times of the orders vary depending on this number of assigned workers. We also take into account family setup times, invalid worker-cell combinations, and a limited number of possible shifts for each order to process. A 0–1 integer linear programming model that minimizes the total number of cells opened for production in all shifts is introduced. The model is tested using real-world data. We show that the generated solutions are suitable to support production planners and can be used to reveal problems of the production such as lack of workers and skills or disruption-prone cells with a high utilization.

1 Introduction

The balance between productivity and flexibility becomes more and more important in today's competitive industry. Workers play a crucial role for that balance: On the one hand, they have a decisive influence on their own productivity and that of the organization (Cavagnini et al. 2020). On the other hand, focusing on worker competencies and skills can maintain or increase flexibility. In particular, workers with a high variety of skills lead to higher flexibility (Liu et al. 2021, Nembhard and Bentefouet 2014).

The influence of workers on productivity and flexibility has already been discussed in the area of worker assignment. Typical worker assignment problems are often mentioned in the context of assembly line worker assignment and balancing problems (ALWABP) and dual resource constrained (DRC) problems. ALWABP was first studied by Miralles et al. (2008), who described the simultaneous assignment of tasks and workers to workstations. In addition to the assembly line balancing problem, workforce is included as a resource in the planning process. This inclusion involves one-to-one relationships for workers and workstations and mostly leads to task processing times that depend individually on the

U. Buscher et al. (Eds.): *Logistics Management*, LNLO, pp. 151–164, 2021.
https://doi.org/10.1007/978-3-030-85843-8_10

worker who processes it. Similarly, DRC problems consider labor as an important resource besides machines and aspire a worker-to-machine assignment considering different speed levels for the possible combinations (Bokhorst and Gaalman 2009, Thürer 2018). In most DRC contributions one-to-one assignments apply, as they do in most ALWABP. Contrarily to the assembly line focused ALWABP, DRC problems focus on the worker assignment, whereby the number of workers is less than the number of machines. Thus, workforce is the critical resource in DRC problems.

To classify recent papers we focus on the main aspects of the real-word problem in protective device manufacturing. For the categorization we identify proficiency levels, skill sets, the assignment of multiple workers per production cell (also referred to as cell), and multiple shifts as additional aspects to the previously described basic ALWABP and DRC problems. Moreover, we concentrate on problems with processing times depending on the number of assigned workers instead of the high range of papers that observe the impact of workers proficiency level on the processing time of tasks (among many others Cavagnini et al. 2020, Liu and Yang 2019, Niakan et al. 2016, Thürer et al. 2019). Furthermore, we consider manufacturing cells in a multi-shift environment that independently produce a certain set of products without allowing inter-cellular part moves (cf. Neufeld et al. 2019). Table 1 shows the result of the classification of the selected papers.

A heterogeneous workforce is taken into account by Lian et al. (2018), Liu et al. (2021), and Niakan et al. (2016), where the workers differ in proficiency level and owned skill set. In addition, the problem presented by Fırat et al. (2016) takes into account a heterogeneous workforce, but only diversifies the skill sets of the workers. In contrast, workforce is considered as homogeneous in the articles of Battaïa et al. (2015), Delorme et al. (2019), Dolgui et al. (2018), Liu et al. (2019), and McWilliams and Tetteh (2009). Processing times depending on the number of workers assigned to a production cell or workstation are recently addressed by Battaïa et al. (2015), Delorme et al. (2019), Dolgui et al. (2018), Fırat et al. (2016), Lian et al. (2018), Liu et al. (2019), Liu et al. (2021), and McWilliams and Tetteh (2009). One-to-one assignments of workers and workstations apply in the contribution of Niakan et al. (2016). The assignment in more than one shift is only considered by McWilliams and Tetteh (2009) and Niakan et al. (2016). None of the mentioned articles examines the assignment of various multi-skilled workers and orders to production cells and simultaneously to shifts. We address this assignment problem considering a heterogeneous workforce with varying skill sets, multiple workers per cell and multiple shifts. Within this research we mainly contribute an optimal solution driven by real-world data. Nonetheless also implications for research are given due to various extension possibilities of the presented problem, for example multi-criteria approaches or consideration of workstations and tasks.

The remainder of this paper is organized as follows. In Sect. 2 we describe the characteristics and particularities of the presented problem including a short example for a better understanding. The mathematical formulation of the prob-

Table 1. Comparison of the examined literature and this paper

Author (year)	Proficiency levels	Skill sets	Multiple workers per cell	Multi-shift
McWilliams and Tetteh (2009)			x	x
Battaïa et al. (2015)			x	
Niakan et al. (2016)	x	x		x
Fırat et al. (2016)		x	x	
Dolgui et al. (2018)			x	
Lian et al. (2018)	x	x	x	
Delorme et al. (2019)			x	
Liu et al. (2019)			x	
Liu et al. (2021)	x	x	x	
This paper		x	x	x

Note: "x" implies the consideration of the researchers, proficiency levels influence the processing speed, skill sets determine possible worker-task and/or worker-station combinations, column "multiple workers per cell" considers the assignment of multiple workers to one cell to reduce the processing time thereby, "multi-shift" implies the assignment across shifts

lem is introduced in Sect. 3 and computational results follow in Sect. 4. Finally, this work is concluded in Sect. 5 including an appraisal and possibilities for further research.

2 Problem Definition

In this paper, we study the following worker assignment problem. In a manufacturing system comprising several independent smaller organizational units called manufacturing cells (cf. Neufeld et al. 2014), orders are processed by a certain number of workers under consideration of multiple shifts. Therefore, two key decisions must be made:

- The assignment of orders to the production cells and shifts taking into account family setup times.
- The assignment of workers to the production cells and shifts considering the worker skill sets.

The order processing times depend on the number of workers assigned to a cell. Consequently, there are interactions between the two decisions.

Each order consists of a certain number of identical devices, which is given as order quantity. We consider each device of an order as a unit and refer to the time to process one device as base processing time. Furthermore, each order is characterized by a product family, whereby sequence independent family setup times need to be respected. Additionally, each order has to be processed within day-based time limits which are earliest start date and due date. Four processes are necessary to completely produce a single order: assembly (A), testing (T), final assembly (F), and packing (P). Skills for all four processes must be covered by the workers assigned to the production cell. These processes exist for one or more product families. All product families which require the same four process skills are summarized in a qualification group. Each cell is able to process orders of one or several qualification groups. The relation of production cells, qualification groups, and product families is shown in Fig. 1.

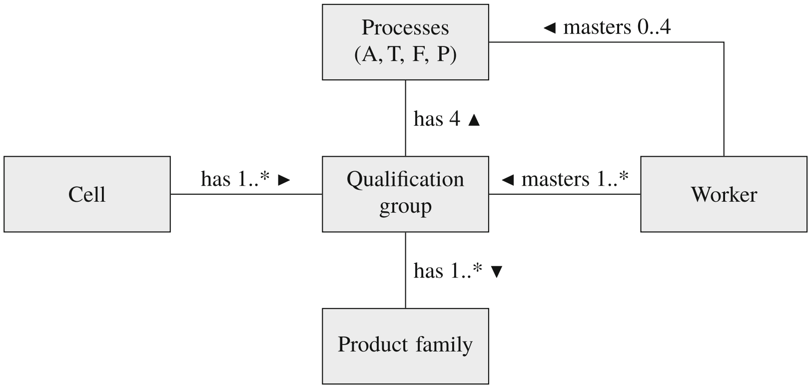

Fig. 1. Overview of the specified problem terms

The production cells are independent and correspond to a cell type, whereby parallel cells exist that have the same cell type. Moreover, the production cells differ in the shift system. Several production cells are available for only one shift per day (one-shift system), while others can process orders in three shifts per day (three-shift system). For each cell a lower bound and an upper bound exists for the number of assigned workers. The cell intensity level is defined by a certain number of assigned workers. For each intensity level a specific reduction coefficient exists, which can be determined based on measured data or expert estimation. The reduction coefficient affects the processing times of all orders assigned to the corresponding production cell in the considered shift. Additionally, the worker assignment is restricted by the availability of the workers, which is defined by the shift schedules. Another restricting aspect is the skill set of a worker. The skill set specifies the mastered process skills (A, T, F, P) within each individual qualification group, whereby each worker obtains from zero (none) to four (all) process skills per qualification group. The qualification groups are independent of each other. Thus, mastering a process of one qualification group does not automatically lead to mastering the same process of another qualification group. The relations between workers and qualification groups and processes are illustrated in Fig. 1. To process orders of a qualification group in a cell each of the four process skills must be covered at least once. Thus, it is irrelevant whether one worker occupies all or several workers cover them in summary. However, all assigned workers must have at least one process skill. In case orders of different qualification groups are processed within one shift, the intensity level and the corresponding reduction coefficient depend on the skill sets of the assigned workers and varies based on the qualification group. Several worker-cell combinations are impossible due to the lack of worker skills corresponding to certain cells. The assignment of workers is immutable during a shift, meaning switching production cells is impossible.

For better understanding, a small example with two cells and two shifts is discussed below. We assume that both cells have one qualification group each. In Cell 1 four product families can be produced, while five product families are associated with Cell 2. To get an idea of the problem, the solution of the small example is shown in Fig. 2. The assigned orders are marked according to the corresponding product family and the assigned workers are added for each cell and shift.

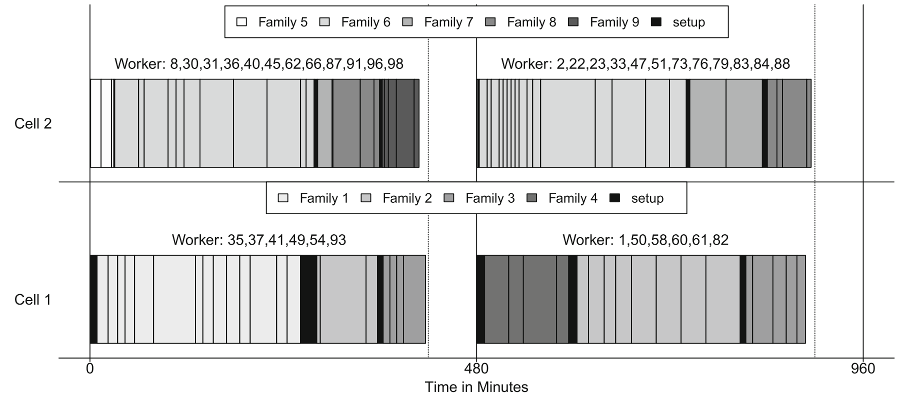

Fig. 2. Solution of the short example

In Cell 1 three of the four product families are processed in the first shift as well as in the second shift. The intensity level is identical in both shifts at six, which can be seen in the figure due to the six assigned workers. The setup times between different product families are marked black and accrue three times in each shift, since both times three families are produced. In Cell 2 all five product families are processed in the first and four in the second shift. Consequently, setup times are necessary five times in the first and four times in the second shift. Note that since some setup times are very short, they are barely visible in Fig. 2, e. g., Product family 5 in Cell 2 in the beginning of the second shift. The intensity level of Cell 2 is 12 in both considered shifts.

In sum 18 workers are assigned to both cells in the first shift. Table 2 shows six of them including the skill sets of the qualification groups of Cell 1 and 2. The minimum requirement of obtaining the skill of each process at least once is already reached by the displayed workers. The five workers 8, 30, 35, 36, and 37 shown in Table 2 would not be able to produce products on Cell 2 due to the lack of testing qualification. The consequences of the intensity level of cells and the resulting reduction coefficient can be shown by means of Cell 2 in the first shift. The summed duration of all assigned orders reached 408.56 min with the maximum intensity level of 12 and the corresponding reduction coefficient of 11.1. Reducing the number of assigned workers to 11 workers results in a reduction coefficient of 10.5 and causes a 23 min larger processing time of 431.90 min. Since we assume that the maximum working time of one shift is seven hours (420 min respectively) the reduction to 11 workers would already exceed this maximum and lead to an invalid solution.

Table 2. Data extract of the workers assigned to the cells in the first shift within the short example (Note: both cells have one qualification group, whose four process skills assembly, testing, final assembly, and packing are shown)

Worker	Cell 1				Cell 2				Cell
	A	T	F	P	A	T	F	P	
8	x	x	x	x	x		x	x	2
30			x	x			x	x	2
31	x	x	x	x	x	x	x	x	2
35	x	x	x	x	x				1
36	x	x	x	x	x		x	x	2
37	x	x	x	x					1

3 Model

In the following we introduce a 0–1 integer linear program (ILP) for the described problem. We define the set of cell types as T and the set of cells as C. Cells with the same type, i. e., parallel cells, are grouped in C_t. Each cell $c \in C$ has a set of qualification groups Q^c, a set of intensity levels I^c, a set of product families F^c, and a set of processes P^c. The set of shifts is defined as S. Not all cells can be opened in each shift due to the use of either one-shift or three-shift systems. We therefore also introduce set S^c as set of feasible shifts of cell $c \in C$. The set of all orders is denoted by O and O^c defines the set of orders that can be assigned to cell $c \in C$. Since there are parallel cells, we also introduce C_o as cells that can process order o. The set of workers W is divided into a set of real workers W^{r} and a set of dummy workers W^{d} such that $W = W^{\mathrm{r}} \cup W^{\mathrm{d}}$. Dummy workers are always available and have all skills. They might be necessary to completely satisfy the demand and indicate insufficient worker qualifications or availability. However, their use causes penalty costs. Furthermore, we introduce the parameters in Table 3 and the decision variables in Table 4. Note that all decision variables are binary.

Table 3. Parameters

π	Penalty costs for dummy workers
λ	Maximum working time in a shift
δ_o	Number of devices contained in order $o \in O$
τ_o	Base processing time of one device of order $o \in O$
ϵ_o^{S}	First shift $s \in S$ that satisfies earliest start date of order $o \in O$
ϵ_o^{D}	Last shift $s \in S$ that satisfies due date of order $o \in O$
σ_f^c	Setup time of product family f associated with cell $c \in C$
ϕ_i^c	Reduction coefficient of intensity level i of cell $c \in C$
η_i^c	Number of workers required for intensity level $i \in I^c$ in cell $c \in C$
α_w^s	Binary parameter indicating if worker $w \in W$ is available in shift $s \in S$
β_{wqp}^c	Binary parameter indicating if worker $w \in W$ can perform process $p \in P^c$ of qualification group $q \in Q^c$ in cell $c \in C$

Table 4. Decision variables

z^{cs}	1, if cell $c \in C$ is used in shift $s \in S^c$, 0 otherwise
x_w^{cs}	1, if worker $w \in W$ is assigned to cell $c \in C$ in shift $s \in S$, 0 otherwise
y_{oi}^{cs}	1, if order $o \in O$ is processed with intensity level $i \in I^c$ in cell $c \in C_o$ in shift $s \in S^c$, 0 otherwise
v_{qi}^{cs}	1, if intensity level $i \in I^c$ is used to produce products of qualification group $q \in Q^c$ in cell $c \in C$ in shift $s \in S^c$, 0 otherwise
u_f^{cs}	1, if any product belonging to product family $f \in F^c$ is produced in cell $c \in C$ in shift $s \in S^c$, 0 otherwise

Using the notation, we present the following 0–1 ILP for the introduced multi-skilled worker assignment problem in multi-shift cell manufacturing:

$$\min \sum_{c \in C} \sum_{s \in S^c} z^{cs} + \sum_{c \in C} \sum_{s \in S^c} \sum_{w \in W^{\mathrm{d}}} \pi \cdot x_w^{cs} \tag{1}$$

$$\text{s.t.} \sum_{c \in C_o} \sum_{s \in S^c} \sum_{i \in I^c} y_{oi}^{cs} = 1 \quad \forall o \in O \tag{2}$$

$$\sum_{c \in C} \alpha_w^s \cdot \max_{q \in Q^c} \left(\max_{p \in P^c} \left(\beta_{wqp}^c \right) \right) \cdot x_w^{cs} \leq 1 \quad \forall w \in W, s \in S \tag{3}$$

$$\sum_{w \in W} \alpha_w^s \cdot \max_{p \in P^c} \left(\beta_{wqp}^c \right) \cdot x_w^{cs} \geq \sum_{i \in I^c} \eta_i^c \cdot v_{qi}^{cs} \quad \forall c \in C, s \in S^c, q \in Q^c \tag{4}$$

$$\sum_{w \in W} \alpha_w^s \cdot \max_{p \in P^c} \left(\beta_{wqp}^c \right) \cdot x_w^{cs} \leq \eta_i^c \cdot v_{qi}^{cs} + \max_{i \in I^c} \left(\eta_i^c \right) \cdot \left(1 - v_{qi}^{cs} \right) \quad \forall c \in C, s \in S^c, q \in Q^c, i \in I^c \tag{5}$$

$$\sum_{w \in W} \alpha_w^s \cdot \beta_{wqp}^c \cdot x_w^{cs} \geq \sum_{i \in I^c} v_{qi}^{cs} \quad \forall c \in C, s \in S^c, q \in Q^c, p \in P^c \tag{6}$$

$$y_{oi}^{cs} \leq v_{q_o i}^{cs} \quad \forall c \in C, s \in S^c, o \in O^c, i \in I^c \tag{7}$$

$$\sum_{i \in I^c} y_{oi}^{cs} \leq u_{f_o}^{cs} \quad \forall c \in C, s \in S^c, o \in O^c \tag{8}$$

$$\sum_{o \in O^c} \sum_{i \in I^c} \frac{\delta_o \cdot \tau_o}{\phi_i^c} \cdot y_{oi}^{cs} + \sum_{f \in F^c} \sigma_f^c \cdot u_f^{cs} \leq \lambda \cdot z^{cs} \quad \forall c \in C, s \in S^c \tag{9}$$

$$y_{oi}^{cs} = 0 \quad \forall c \in C, o \in O^c, s \in S^c : s < \epsilon_o^{\mathrm{S}} \vee s > \epsilon_o^{\mathrm{D}}, i \in I^c \tag{10}$$

$$\sum_{i \in I^c} y_{oi}^{cs} \leq z^{cs} \quad \forall c \in C, s \in S^c, o \in O^c \tag{11}$$

$$z^{cs} \leq z^{c-1,s} \quad \forall c \in C_t \backslash C_{t,1}, t \in T, s \in S^c \tag{12}$$

The objective function (1) minimizes the total number of cells opened for production in all shifts plus the penalty due to dummy workers. Constraints (2) guarantee that all orders are fulfilled exactly once. Constraints (3) ensure that each worker is assigned to at most one cell per shift. The variable x_w^{cs} must be considered only if worker w is available in shift s $\left(\alpha_w^s = 1\right)$ and worker w is qualified to perform at least one process p of any qualification group q in cell c $\left(\max_{q \in Q^c} \left(\max_{p \in P^c} \left(\beta_{wqp}^c\right)\right) = 1\right)$. Constraints (4) and (5) determine that exactly η_i^c qualified, i. e., skill for at least one process, and available workers must be assigned to cell c if qualification group q is produced with intensity level i. Constraints (4) ensure that at least η_i^c workers are assigned, while Constraints (5) restrict that not more than η_i^c workers are assigned. Note that at most one intensity level can be selected and therefore we can sum over the intensity levels on the right-hand side in Constraints (4) and that the upper bound in Constraints (5) is not active if $v_{qi}^{cs} = 0$. Constraints (6) guarantee that the skill necessary for each process $p \in P^c$ is covered by at least one assigned worker if qualification group $q \in Q^c$ is produced in cell c in shift s. Since at most one intensity level can be selected for each qualification group, we can sum over the intensity levels on the right hand side as in Constraints (4). Constraints (7) state that an order o can only be processed with intensity level i if intensity level i is selected for its associated qualification group q_o in cell c in shift s. Constraints (8) link order o with its related product family f_o. Thus, if order o is processed with any intensity level in cell c in shift s, the product family f_o must be set up. Constraints (9) limit the maximum working time in a cell. The first term on the left hand side of (9) represents the time used for production. The total base processing time of an order o is $\delta_o \cdot \tau_o$. However, this has to be divided by reduction coefficient ϕ_i^c to obtain the actual processing time and must only be taken into account if order o is processed with intensity level i. The second term represents the setup times of all product families that are manufactured in cell c in shift s. Equations (10) exclude all infeasible assignments of orders to shifts that violate the earliest start date or the due date. Inequalities (11) and (12) are not necessary to define feasible solutions. However, Inequalities (11) improve the lower bound of the relaxation and Inequalities (12) partly break the symmetry between cells $c \in C_t$ of the same cell type $t \in T$, where $C_{t,1}$ represents the first element of C_t.

4 Computational Experiments

4.1 Test Instances

We use three large test instances generated from real-world data obtained from a protective device manufacturer. Each instance contains orders that must be produced within one workweek (Monday to Friday), i. e., earliest start date and due date are in this week. Note that these are not all orders that can be produced in this week. Orders that do not need to be produced this week, but can be produced, are excluded to keep problem sizes manageable. Therefore, we offer a basic plan that can be extended by planners to include optional orders depending on available cell capacities and workers. Table 5 shows the number of orders ($|O|$) and the number of protection devices (#Devices) for each instance.

Table 5. Number of orders and total order quantities (#Devices) of the test instances

Instance	$\|O\|$	#Devices
1	322	976
2	389	1089
3	518	1435

Information regarding the 12 production cells of the manufacturer are given in Table 6. There are two cells of Cell type 1 (1 and 2) and two cells of Cell type 2 (3 and 4). All other cells belong to different cell types. Six cells can be used in a three-shift system, while all others can only be used during the day shift. Since

Table 6. Cell information

Cell c	Type t	$\|O^c\|$	$\|Q^c\|$	$\|F^c\|$	$\|S^c\|$	ϕ_i^c											
						1	2	3	4	5	6	7	8	9	10	11	12
1	1	229	1	17	15		1.6	2.8	4.0	4.5	5.0						
2	1	229	1	17	15		1.6	2.8	4.0	4.5	5.0						
3	2	659	1	51	15				3.5	4.8	5.9	7.0	8.0	9.0	9.8	10.5	11.1
4	2	659	1	51	15				3.5	4.8	5.9	7.0	8.0	9.0	9.8	10.5	11.1
5	3	248	1	9	15		2.0	3.0	4.0	4.5							
6	4	21	1	5	15	1.0	2.0	2.4									
7	5	24	2	4	5	0.5	1.6	3.0	3.6	4.4							
8	6	18	2	3	5	1.0	2.0										
9	7	8	1	6	5	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0	
10	8	5	1	2	5	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0				
11	9	1	1	1	5	1.0	2.0										
12	10	16	1	4	5	1.0	2.0										

we consider a workweek with five days, this results in either 15 or five feasible shifts.

By far the most orders must be produced in Cell types 1, 2, and 3. Note that $|O^c|$ represents the total number of all orders in all three instances that must be assigned to cell c (no parallel cells) or can be assigned to cell c (parallel cells). Cells 7 and 8 produce products of two different qualification groups, while the other ten have only products of one. Note that usually more cell types consider products of different qualification groups, but they are not present in any of the three test instances. Likewise, only product families that exist in at least one instance are included in Table 6. The reduction coefficients ϕ_i^c are estimated by planners of the device manufacturer. Note that in some cells they do not increase in proportion to the number of workers, but are subject to cell specific conditions.

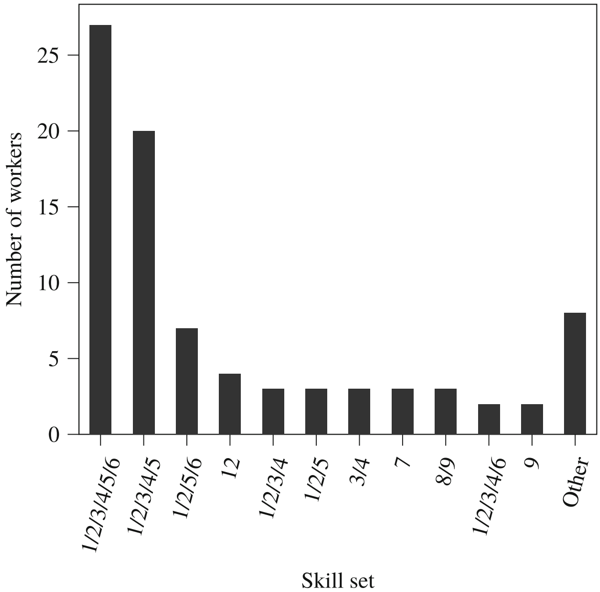

Fig. 3. Skill sets as combination of cells of all workers available in all instances

Figure 3 shows the different skill sets of all workers that are available in all three instances. A skill set is defined as a combination of cells for which a worker is qualified. A worker is qualified for a cell if there is at least one skill for any process of any qualification group. Only skill sets that are matched by at least two workers are explicitly displayed. Eight skill sets are occupied by a single worker and are grouped under "Other". Most workers are qualified for Cells 1 to 6. These cells operate in a three-shift system and also need to process most of the orders, with the exception of Cell 6. Therefore, it is important to have a high number of available workers for these cells. However, most of these workers are qualified for some or all of these cells with many orders. Hence, they must be shared among the cells. In contrast, some workers are qualified for only one type of cell and are less flexible in their assignments.

Finally, the maximum working time in a shift is set to seven hours and the use of a dummy worker is penalized with $\pi = 1$. Therefore, using a dummy worker costs as much as opening a cell for a shift. On the one hand, this is large enough that it is not beneficial to use a dummy worker when other workers are available. On the other hand, it is small enough not to inflate the value of the objective function.

4.2 Results

The model is implemented in C# with .NET Core 3.1 using Gurobi 9.1 as solver. All tests are performed on a Windows Server 2012 R2 with Intel(R) Xeon(R) CPU E5-4627 v2 @ 3.3 GHz processors with 32 cores and 768 GB RAM. However, we limit the number of cores to use to 12 and the memory consumption in only a small fraction of the available memory. We also use Gurobi's NoRel heuristic for 90 s to find high-quality solutions early on.

Table 7 shows the run time (Time) in seconds, the objective function value (Obj), the optimality gap at termination (Gap) in percent, and the number of dummy workers in use (#DW). All instances can be solved to optimality in less than two hours. The model is therefore well suited to support the planning process with high-quality solutions. Only Instance 3 requires a single dummy worker in Cell 12, otherwise there is no feasible solution. This indicates a shortage of available and qualified workers for Cell 12 during this week. The model thus helps the planner to identify potential difficulties during the planning process.

Table 7. Results for each instance

Instance	Time [s]	Obj	Gap [%]	#DW
1	1274.65	27	0.00	0
2	884.86	28	0.00	0
3	6698.34	32	0.00	1

Below we discuss some additional implications from the results for the decision making of planners. Table 8 shows detailed results for each instance and cell regarding the number of uses (#Use), i. e., in how many shifts the cell is open, average number of workers assigned per used shift (#W), the number of critical shifts (#Crit), and the average cell utilization (Util) as percentage of production times plus setup times to maximum working time λ. We call a shift critical when at most one unassigned but qualified worker is available. Note that not all workers need to be assigned to a cell, if they are not necessary to produce all mandatory orders in a week. However, they are available and can be scheduled by the planners to produce optional orders, or they can be used as backups for assigned workers. Cell 4 is not displayed in Table 8 as it is not used in any instance.

Table 8. Detailed solution information for each instance and cell

Cell c	Instance 1				Instance 2				Instance 3			
	#Use	#W	#Crit	Util [%]	#Use	#W	#Crit	Util [%]	#Use	#W	#Crit	Util [%]
1	4	6	0	89.9	5	6	0	99.8	5	6	2	93.5
2	–	–	–	–	2	6	0	99.5	2	6	1	84.9
3	8	11.6	1	92.6	8	12	1	99.5	10	11.4	2	99.4
5	7	4.9	1	87.8	5	5	2	98.4	5	5	2	97.9
6	1	1	0	36.4	1	1	0	95.5	3	3	0	97.9
7	1	5	1	79.8	2	5	1	70.8	1	5	1	99.1
8	1	2	1	94.4	2	2	2	74.5	1	2	1	84.8
9	1	4	0	45.1	1	2	0	40.3	1	2	0	53.7
10	1	1	0	5.7	1	2	0	26	1	1	0	10.5
11	1	1	1	14.9	–	–	–	–	–	–	–	–
12	2	1	1	71.7	1	1	0	83	2	1.5	2	77.5

Cell 4 is not displayed as it is not used in any instance.

Several cells are used very frequently and have a high utilization, while others are used only once or twice with a low utilization. Of course, this depends on the number of orders that are associated with the cells. For example, in Cell 10 only a single order must be produced in Instance 1. Therefore, planners can schedule optional orders to use remaining capacity, reschedule that order in consultation with the customer, or bring forward some orders scheduled for next week, but must ensure they can be delivered ahead of schedule or stored on site. The cells with high utilization often operate at or near the maximum intensity level, e.g., Cells 1, 3, and 5. As a result, they are particularly susceptible to disruption if a worker is absent due to illness, for example. Therefore, it is especially important to have many workers with skills for these cells available to increase flexibility and robustness. Although many workers are qualified for these cells, as shown in Fig. 3, some shifts lack potential backup workers and are critical. Therefore, some workers with skills for only one type of cell should be qualified for these cells.

Another option for planners is to instruct workers to work in multiple cells during the same shift. Hence, if the utilization of a cell is low, workers can move to another cell after they have completed all the jobs of their original cells. Again, this requires multi-skilled workers.

5 Conclusion and Future Research

In this work, we study a multi-skilled worker assignment problem in cell manufacturing with multiple shifts. The problem includes family setup times, different cell types, and time limits for processing orders. The processing time of orders depend on the number of workers assigned to process them. We introduce a 0–1 integer linear program with the objective to minimize the total number of cells opened for production in all shifts. We solve three real-world instances of five days each to optimality in less than two hours using Gurobi. We provide practical input for production planners, which can be used as planning basis or to draw attention to problems like insufficient workforce or conspicuously high cell utilization.

Future research is rich in potential. On the one hand, the problem can be extended in various ways. For example, in addition to the number of cells opened, the number of workers needed to fulfill all requirements and their required skills as well as the necessary training can be considered in more detail. Due to the trade-off between opening fewer cells by using more workers or vice versa, this can lead to multi-criteria approaches. In addition, a more detailed consideration of the individual workstations and tasks in a cell can be integrated into the model. Furthermore, incorporating setup carry-over between shifts can improve solution quality, but also leads to more complex scheduling models. On the other hand, heuristic approaches such as metaheuristics or matheuristics can be developed to speed up the solution process and to consider longer planning horizons.

Acknowledgements. We would like to thank Tony Alexander of Siemens AG for his support in elaborating the problem and obtaining the data.

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Relocation in One-Way Station-Based Car Sharing Systems: Conventional Versus Partly Autonomous Vehicles

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Abstract. Our aim with this paper is to formulate a platoon relocation model and to apply it on a large-scale one-way car sharing system. We analyze the system performance in terms of realized customer trips and relocation costs with regard to conventional, platoon or none relocation tours. We analyze the efficiency potential of platoon relocation on simplified instances that mimic demand and city structures. In these examples, the platoon approach can be up to 60% more efficient in relocating cars compared to the conventional one. We formulate a time-expanded network model for platoon based relocation in station-based one-way car sharing systems and apply it to a self-designed case study from the city of Hanover. In order to cope with runtime restrictions, we delete redundant network arcs. Our results show that in the large-scale Hanover case example, the platoon tours lead to a moderate increase of customer trips and reduced relocation costs.

Keywords: Car sharing systems · Relocation · Autonomous vehicles · Platoon

1 Introduction

Increasing population in cities, accompanied by growing mobility demand, confront the urban transportation system with new challenges in order to cope with the demand. Developing according future urban traffic systems is indispensable in order to meet mobility demand while ensuring urban and environmental compatibility. If public transport is not sufficient to satisfy customized transport requests, the sharing economy concept can be applied to individual means of transportation and resources can be used more efficiently. A large German mobility study of the Federal Ministry of Transport and Digital Infrastructure in 2017 [9] found that private cars on average are used for 45 min per day and no more than 10% of all cars are used simultaneously. Therefore, cars are suitable candidates for sharing systems. If one-way rentals are allowed, meaning that the pick up station can differ from the return station, the vehicle distribution over

U. Buscher et al. (Eds.): *Logistics Management*, LNLO, pp. 165–178, 2021.
https://doi.org/10.1007/978-3-030-85843-8_11

all stations will be affected. Performing relocation of the vehicles can readjust unwanted car allocations to meet upcoming demand.

Celsor and Millard-Ball [7] have shown that the usage of car sharing systems leads to lower car ownership rates and to lower car use among the users, a finding which is supported by the results of the German mobility study. In 14% of all households in German metropolises at least one person owns a car sharing membership. However, the traffic volume ratio of car sharing still is extremely low and leaves room for improvement. Allowing one-way rentals increases the system's flexibility and enables more customer trips to be realized.

Numerous studies address the relocation problem of station-based car sharing systems for one-way rentals, see [5,11,12] for detailed literature summaries. Especially operator-based relocation, electric vehicles and staff allocation have been studied intensively. Furthermore, the integration of fully autonomous cars in sharing systems has been considered [3,6,8,10]. Boldrini and Bruno [4] heuristically tackle a specific stackable car sharing relocation problem where up to seven cars can be physically connected and relocated collectively by one driver.

Similar to Boldrini and Bruno [4] we study a relocation process where one employee can relocate several cars at a time. Our approach is based on partly autonomous platoons, composed of a manually driven front car followed by a few autonomous cars, instead of mechanically linking the cars. In contrast to Boldrini and Bruno [4], who use heuristics to identify and match shortages and overflows to define periodic relocation tasks, we use an accurate network model and form relocation tours with regard to an objective function. The platoon relocation, as well as the stackable relocation approach, could serve as a bridge technology before fully autonomously driving cars will be market-ready in the future. Operating and safety problems, such as interactions with other traffic participants, still have to be handled. Partly autonomous platoons are not exposed to these challenges since they are manually operated and act as one traffic participant.

We compare the efficiency of conventional and partly autonomous relocation approaches in the context of station-based one-way car sharing systems. We aim to answer the question: does the platoon relocation tour model, applied to a large-scale example, live up to efficiency expectations based on theoretical deliberations? Our main contributions are as follows:

1. We formulate a time-expanded network model for platoon based relocation in station-based one-way car sharing systems.
2. We theoretically compare the relocation cost efficiency of platoon and conventional relocation tours on the basis of small artificial instances.
3. We apply our model to a self-designed realistic case study of the city of Hanover. We analyze the car sharing system's performance in terms of realized customer trips and relocation costs with regard to conventional and platoon relocation tours.

2 Relocation Process

In one-way systems the mobility demand typically leads to a disbalance of the car distribution within the city. The uneven demand patterns result for example from people commuting from living areas to working areas in the morning and vice versa in the afternoon. One-way trips in the same direction at specific times accumulate and cause a disbalanced car distribution that is not (anymore) sufficient to meet upcoming demand. To readjust the allocation, car relocation can be implemented in the system. The relocation can be operator-based or user-based, either the operator performs the relocation, or the users suitably adjust their rental behavior, for example based on financial incentives.

2.1 Problem Statement

In this work we focus on a station-based car sharing system with one-way rentals and operator-based relocation conducted with platoons. The parking lot stations of the car sharing system are located within an urban area and customers can rent available cars without reservations. The rented cars can be returned to any station with available parking lot capacity. It is assumed that the location of the stations in the car sharing system are given, as well as their inventory at the beginning of each day. For the sake of convenience we assume that customer mobility demand coincides with the locations of the stations and is only realized if a car for pick up and a free parking lot for drop off is available. The relocation is performed with manually driven front cars that can attach up to four autonomously following car sharing cars in the back. The employee driving the front car starts and ends in the depot and can easily pick up and drop off shared cars at visited stations. We consider only operator costs that are directly linked to the relocation process, namely the employee and fuel costs that are needed to conduct relocation. To model the conventional relocation approach, we assume that solitary front car trips are substituted by public transport and set the period length high enough to allow additional travel time. To prevent unwanted relative preferences for specific customer trips, we assume the operator's profit consists of an average profit generated per customer trip, independent of the trip length. Otherwise, relocation tours would only focus on a small number of long and profitable customer trips that might not occur in real-life application.

2.2 Conventional Versus Partly Autonomous Vehicles

Until now, the operator-based relocation process is performed by one worker traveling with a folding bicycle, public transport or by foot to the car sharing vehicle and then performs the relocation. This relocation process involves a zigzag course for one worker if he needs to relocate several cars from the same location to another. A recent analysis [14] found that the additional profit from realized trips due to relocation do not overcome the relocation costs for employees. In this work a relocation approach that is based on the integration of partly autonomous vehicles is proposed that can potentially overcome this drawback. The approach is based on platooning: cars closely follow each other and are driven by automatic control systems. This way the worker can manually drive a front car which is followed autonomously by car sharing cars. Therefore, one worker can transfer several cars at a time and take more efficient tours without performing a zigzag course. Furthermore there is no need to change the mode of transportation which saves additional time. This may increase the relocation capacity under given employees and hence improve the vehicle availability for customers. Under consideration of urban traffic systems the platoon length should be limited such that no further traffic congestion arises. Most likely the technical realization of platoons is sooner market-ready than completely autonomous vehicles and could serve as a bridge technology in car sharing systems.

2.3 Theoretic Efficiency Comparison

We theoretically analyze the platoon relocation efficiency potential compared to conventional relocation with small instances. The instances combine different network types with specific relocation requests and are shown in Fig. 1. For each scenario the shortest conventional and platoon tour to realize all relocation requests are depicted. We assume that for each relocation request one customer trip can be realized. The number of relocation requests per instance is denoted with Γ. As a reference value for the efficiency measurement we used the average profit per customer trip that is needed to break even with the relocation costs. The relocation costs consist of the front car costs (FCC), including employee salaries, and relocation costs of the car sharing vehicles (RC). Note that we neglect other cost factors, for example maintenance costs, which might differ for partly autonomous cars. For the efficiency comparison we assume that the front car costs are €10 per time period $t = 30\,\text{min}$ and the relocation costs $1\frac{€}{t}$. To determine the break even point for a relocation tour, we summarized all costs and calculate the average profit per customer p required to exceed those costs:

$$FCC + RC < \Gamma p. \tag{1}$$

The first instance represents a *downtown* infrastructure with equal distances between the stations and relocation requests to the city center. The respective graph in Fig. 1a visualizes the conventional relocation tour, which consists of simply picking up all cars one after another. In the conventional case we assume that the employee is using public transport to perform the solitary front car edges and that public transport costs are similar to the front car costs. In total, the employee has to travel eight edges and four relocation tasks are performed, each consisting of moving one car along one edge. Using (1) we yield the following break even point:

$$4 \times 2t \times 10\frac{€}{t} + 4 \times 1t \times 1\frac{€}{t} < 4p \Rightarrow 21€ < p. \tag{2}$$

The average profit per customer needs to be higher than €21 to allow profitable conventional relocation. The platoon relocation tour for the downtown example, visualized in Fig. 1b, consists of one continuous tour along all stations. The front car travels five edges and attached relocating cars - one additional car is added to the platoon on each black node - travel ten edges in total:

$$5t \times 10\frac{€}{t} + 10t \times 1\frac{€}{t} < 4p \Rightarrow 15€ < p. \tag{3}$$

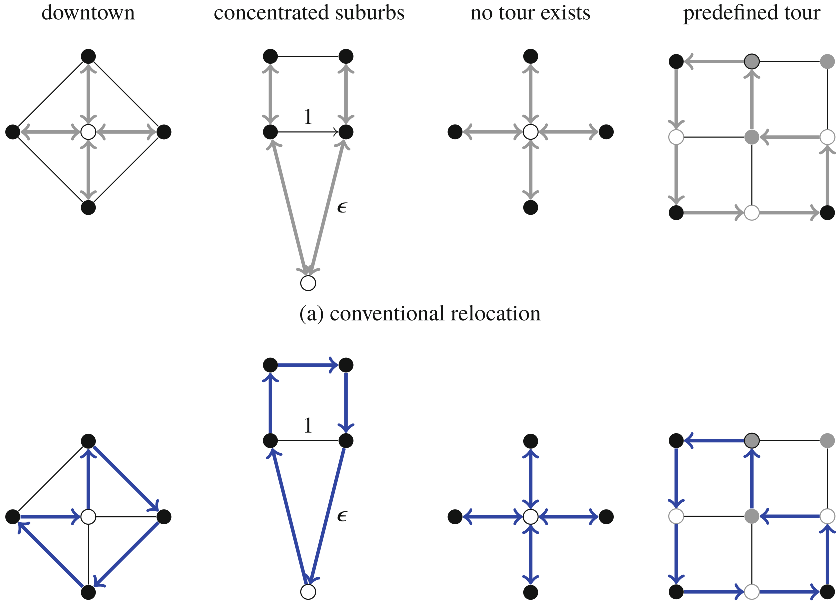

Fig. 1. Artificial instances to analyze theoretical platooning efficiency in different structures. Four different infrastructure types with relocation requests are depicted. Black nodes indicate that a vehicle needs to get picked up, at white nodes a vehicle drop off is expected. Completely gray nodes expect neither a pick up nor a drop off. One black framed white or gray node in each example marks the depot as a start and end point for the relocation tour. The relocation requests in each example are realized with the conventional (a) and the platoon (b) approach. All edges have an equal travel distance of one time period t, except the concentrated suburban instance that exhibits two edges with distance $\epsilon \geq 2$, indicating the distance between a suburb and the city center.

In the downtown example, the platoon approach exhibits a break even point of €15, which is 30% lower than the conventional break even point.

Analogously, the second instance *concentrated suburbs*, that mimics four stations located in a suburb with distance ϵ from the depot/city center, resulted in a break even point of $21\epsilon + 10.5$ for the conventional tour and $6\epsilon + 9$ for the platoon tour. The advantage of the platoon approach to only drive once to the suburb instead of four times leads to a saving of at least 60% and increases with the distance $\epsilon \geq 2$ to the city center.

The other two instances *no tour exists* and *predefined tour* visualize cases where no differences between conventional and platoon relocation tours can be observed. The first instance features a network structure where no continuous tour planning is possible. The second instance displays such specific relocation requests that no shorter platoon tour is more efficient, hence conventional and platoon tours are identical. Note that in these examples, if more than one relocation request at a station would occur, the platoon approach would become beneficial.

3 Mathematical Problem Formulation

In order to coordinate relocation decisions in time and space, a time expanded network is used to model the locations at different time periods. The total time T of a typical work- or weekend day is divided into equal periods $T = \{0, \ldots, T_{max}\}$. Let $I = \{1, \ldots, I_{max}\}$ be the set of stations where $i = 0$ in $I_0 = \{0, \ldots, I_{max}\}$ represents the depot. Every location $i \in I$ has a parking lot capacity c_i. The inventory, denoting the number of cars parked at a station, at a given time t is given by I_i^t, and the start values I_i^0 are already known. The customer demand from location i to j at time t with a trip duration until time period s is denoted with $d_{i,j}^{t,s}$, $i, j \in I$, $t, s \in T, t < s$. Note that two-way and one-way trips are allowed, hence $i = j$ is possible. The travel time l_{ij} indicates the duration for a relocation trip from i to j. The number of front cars performing relocation is given by fc and the maximum number of cars autonomously following the front car on an arc is P_{max}. The unit costs for driving the front car per time period are c_{fc}, the unit costs for relocating one car are given by c_{rep}. The average rental profit per period is determined with p.

The spatial-temporal network $G = (N, A)$ consists of the set of vertices $n_i^t \in N$, representing the different locations i at time periods $t \in T$. The set of edges with $A = A^{trip} \cup A^{tour} \cup A^{rel}$ is defined as follows:

- **trip edges** $(n_i^t, n_j^s) \in A^{trip}$ for realizing demand $d_{ij}^{t,s}$, $i, j \in I$, $t, s \in T, t < s$ for trips and individual duration. $\alpha_{ij}^{t,s}$ indicates the quantity of cars on each edge.
- **tour edges** $(n_i^t, n_j^{t+l_{ij}}) \in A^{tour}$ for $i, j \in I_0$, $t \in \{0, \ldots, T_{max} - 1\}$ that indicate the tour of the front car. The quantity of front cars traveling on each edge is denoted by $m_{ij}^{t,t+l_{ij}}$.
- **relocation edges** $(n_i^t, n_j^{t+l_{ij}}) \in A^{rel}$ for $i, j \in I, i \neq j$, $t \in \{1, \ldots, T_{max} - 1\}$ to relocate cars from station i to j in time l_{ij}. The number of relocated cars in the platoon on each edge is given by $r_{ij}^{t,t+l_{ij}}$.

In order to maximize the operator's profit using relocation tours with respect to relocation costs, the integer program (IP) based on the described network is formulated as:

$$\max_{r_{ij}^{t,t+l_{ij}}, m_{ij}^{t,t+l_{ij}}} p \sum_{\substack{i,j \in I \\ t,s \in T \\ t<s}} \alpha_{ij}^{t,s} - c_{fc} \sum_{\substack{t \in T \\ i,j \in I_0 \\ i \neq j}} m_{ij}^{t,t+l_{ij}} l_{ij} - c_{rep} \sum_{\substack{t \in T \\ i,j \in I \\ i \neq j}} r_{ij}^{t,t+l_{ij}} l_{ij} \tag{4}$$

$$\text{s.t.} \quad I_i^t \leq c_i, \forall\, i \in I,\ \forall\, t \in T \tag{5}$$

$$I_i^T = I_i^0, \forall\, i \in I \tag{6}$$

$$\sum_{\substack{j \in I \\ s \in T}} \left(\alpha_{ij}^{t,s} + r_{ij}^{t,t+l_{ij}} \right) \leq I_i^t, \forall\, i \in I,\ \forall\, t \in T \backslash \{T_{max}\} \tag{7}$$

$$\alpha_{ij}^{t,s} \leq d_{i,j}^{t,s}, \forall\, i,j \in I,\ \forall\, t,s \in T \tag{8}$$

$$I_i^t - \sum_{\substack{j \in I \\ s \in T}} \alpha_{ij}^{t,s} + \sum_{\substack{j \in I \\ s \in T}} \alpha_{ji}^{s,t+1} - \sum_{j \in I} r_{ij}^{t,t+l_{ij}} + \sum_{j \in I} r_{ji}^{t+1-l_{ji},t+1}$$

$$= I_i^{t+1}, \forall\, i \in I,\ \forall\, t \in T \backslash \{T_{max}\} \tag{9}$$

$$r_{ij}^{t,t+l_{ij}} \leq P_{max} m_{ij}^{t,t+l_{ij}}, \forall\, i,j \in I,\ \forall t \in T \tag{10}$$

$$\sum_{j \in I_0} m_{0j}^{0,l_{0j}} = fc \tag{11}$$

$$\sum_{i \in I_0} m_{i0}^{T_{max}-l_{i0},T_{max}} = fc \tag{12}$$

$$\sum_{j \in I_0} m_{ij}^{0,l_{ij}} = 0, \forall\, i \in I \tag{13}$$

$$\sum_{i \in I_0} m_{ij}^{T_{max}-l_{ij},T_{max}} = 0, \forall\, j \in I \tag{14}$$

$$\sum_{j \in I_0} m_{ji}^{t-l_{ji},t} = \sum_{j \in I_0} m_{ij}^{t,t+l_{ij}}, \forall\, i \in I_0,\ \forall\, t \in T \backslash \{0, T_{max}\} \tag{15}$$

$$I_i^t, \alpha_{ij}^{t,s}, r_{ij}^{t,t+l_{ij}}, m_{ij}^{t,t+l_{ij}} \in \mathbb{N}_0 \tag{16}$$

The objective function (4) maximizes the profit generated from customer trips minus the relocation costs. The relocation costs are divided into the master tour costs for the front car and the costs for relocating the cars between stations. Equation (5) ensures that the stations' capacities are not exceeded and (6) ensures that the inventory allocation over stations at the end of the day is equivalent to the start allocation. Equation (7) ensures that only available cars at a station can be used for relocation or customer trips. Equation (8) is the demand constraint for realized customer trips. Equation (9) depicts the flow conservation for car movements entering and leaving a station. Equation (10) ensures that the number of platooned cars on one edge does not exceed the maximum platoon length for each front car. Furthermore Eq. (10) ensures that relocation edges are only active if a master tour is using the respective edge. Equations (11)–(14) ensure that all front cars start and end their master tours in the depot. In Eq. (15) the equal inbound and outbound numbers of master tour edges at every node are ensured in order to form paths for master tours. In (16) the variables' domain is determined.

4 Computational Experiments

The aim of the computational experiment is to apply our platoon relocation model to a realistic instance. We generate a case example for the city of Hanover based on existing car sharing stations and demand model results. The model is implemented in Python 3.6, using the Gurobi Interface to access Gurobi 9.0 as the LP solver. The experiment is performed on a computer with an Intel(R) Core(TM) i7-4710MQ 2.5 GHz processor and 8 GB of random access memory operating under Microsoft Windows, version 10 Pro.

4.1 Setting Up the Case Study

We generate our case study instances for the city of Hanover based on a Hanover mobility demand forecast model and an existing car sharing operator. For the data processing of the demand model data a detailed examination of car sharing trips is necessary.

4.1.1 Suitable Trips for Car Sharing. In this section we discuss the type of mobility demand that should be realized by the car sharing system and acts as a basis for the processing of the demand model data described in the following section. We strive to support car sharing systems that serve as a complement to public transport and not as a substitute and avoid customer churn from public transport to car sharing systems, since public transport systems belong to the most efficient and environmental-friendly modes of transportation. Becker et al. [1] have carried out a survey on a station-based two-way and a free floating car sharing system in Switzerland in order to compare user groups and usage patterns. The results are that free floating systems are used more frequently for activities like commuting and serve as a substitute for public transport, whereas round-trip systems act as a complement. The same results were concluded by Vine et al. [15] who have analyzed car sharing systems in London. In order to ensure complementary usage of car sharing systems, instruments such as (dynamic) pricing or suitable establishment and management of parking lots can be useful tools.

Mobility demand emerges because people want to perform different activities throughout the day at different locations. The way from one location to another is defined as a trip and several trips form a trip chain. The reasons for the performed trips can be categorized into seven main trip purposes: commute, on business, shopping, errands, leisure, company and education. Commute is the trip to the workplace and on business describes trips that are conducted during the work day, e.g. a craftsman visiting customers. Shopping can include visiting grocery or hardware stores and errands could consist of doctors appointments or visiting government offices. Leisure is any free time activity, for example sports,

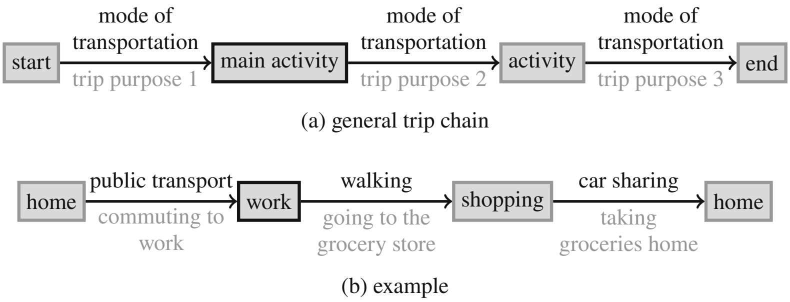

Fig. 2. Trip chains and integration of different transportation modes

and education comprises going to school, university or other educational institutions. The trip purpose company stands for accompanying persons, for example bringing kids to school or elderly people to the doctor. Those defined trip purposes can be extended with specific characteristics of trip attributes such as carrying goods or persons, travel time, flexibility, reliability and weatherproof. Especially trips where goods or persons need to be transported, time needs to be flexible and the transport mode should be weatherproof, seem to be suitable candidates for car sharing trips. We assume that from the seven main trip purposes shopping, errands, leisure and company commonly show those characteristics and are therefore appropriate trip purposes that could be realized by car sharing. This assumption is in accordance with the findings of the German mobility study [9] where 156.000 households were surveyed and car sharing has mostly been used for the trip purposes mentioned above. If only one preferably short activity is performed and the trip chain only consists of an outbound and inbound trip with the same start and endpoint, a two-way car sharing trip is suitable to realize this trip chain, if the car is the favored mode of transportation. If more than one trip purposes are chronologically linked together to a trip chain linking several activities, as shown in Fig. 2a, one activity is defined as the main activity. For example, working could be the main activity and other activities, such as bringing kids to school or grocery shopping, are added before or after it. A trip chain has an internal dependency between the choice of transport mode for each single trip. Most likely the choice of transport mode is determined through the activity with the least freedom of choice. For example, if for one trip within a trip chain goods need to be transported or the activity location is only accessible via car, the private car would be chosen as the mode of transport for the whole trip chain. The one-way car sharing system would be the ideal mode of transport extension for such trip chains, since the crucial trips can be conducted by car while other trips can be executed with different transportation modes, see Fig. 2b for an example. This fosters a higher flexibility in the choice of transportation mode within a trip chain and creates the potential to reduce private car use.

4.1.2 Generating Instances. The car sharing company *Stadtmobil* operated a two-way system with 120 stations in Hanover. Their publicly available locations of stations and inventory levels are used as the car sharing infrastructure, although our model is assumed to operate as a one-way system. To include spare parking spaces, the stations' additional parking lot capacities are manually approximated by means of satellite pictures. The depot is assumed to be located downtown near the central station. A driving street network from OpenStreetMaps is integrated into the model and travel durations from one station to another are determined through shortest paths and speed limits on the respective routes. We assume a workday length of 16 h starting at 6:00 a.m. The time periods are 30 min long and we assume that the car pick up and drop off process can be conducted in those time intervals. The previously described infrastructure and time definition form our time-expanded network. The relocation tours are executed by one employee, $fc = 1$, we assume the same cost structure as in Sect. 2.3 and an average profit per customer trip of €10. We assume a maximal platoon length $P_{Max} = 4$ and set the solver's optimality gap to 5%.

The mobility demand forecast model by Bienzeisler et al. [2] is an agent-based model that creates day schedules for Hanover's inhabitants based on mobility survey results. Those schedules with associated mobility demand are realized by suitable modes of transportation with regard to trip purposes. The output of the model is a detailed list with trips of each agent including start and end point, departure and travel time, trip purpose and other characteristics. We engage a forecast result for 10% of Hanover's inhabitants and considered trips that are conducted by car between 6:00 a.m. and 10:00 p.m. As discussed in Sect. 4.1.1, we assume that shopping, company or leisure are suitable trip purposes for car sharing trips. We further define a distinction between one-way and two-way trips. If a trip from home to a location is followed directly by the return trip, a two-way trip is identified. Some of the remaining trips are linked to multi-trips, if the time difference between departure times within a trip chain is less than 90 min. It is assumed that connected multi-trips are either executed with one nonstop rental or only the first or last trip of the multi-trip chain is conducted by car. If the start and end point of multi-trips are at the same location, the multi-trip chain is considered as a two-way trip. Otherwise it is considered as a one-way trip with multiple stops. The remaining not categorized trips are assumed to be single one-way trips. The start and end locations of all suitable trips is mapped into the car sharing network infrastructure and if car sharing stations are within a 500 m range, the demand is assumed to be satisfied by the car sharing system. The total number of demand requests generated from this data processing is too large for the given car sharing infrastructure, hence we randomly picked 20% of the generated demand requests and merged them into one demand instance.

4.2 Reduction Techniques to Increase Algorithmic Efficiency

To reduce the runtime of the solver, we implement the *arc deletion* procedure proposed by Raviv et al. [13]. In another pre-processing step ahead of the optimization, this procedure deletes redundant edges inside the spatial network that are never used because shorter paths exist. For every station i the set δ_i contains all stations j where the edge from i to j is the shortest path that does not include any other station:

$$\delta_i = \{j \in I_0 : \ l_{ij} < l_{ik} + l_{kj} \quad \forall\, k \in I_0, k \neq j\} \qquad \forall\, i \in I_0. \tag{17}$$

Subsequently the master tour edges and relocation edges are only created for pairs i and $j \in \delta_i$, customer trip edges remain unchanged since car sharing rentals are not based on shortest paths. Equations (4)–(16) in the IP are updated consequently in order to exclude deleted edges from the constraints. Obviously the arc deletion method does not affect the optimality of the IP solution.

Solving the IP with the arc reduction technique and previously described instances in a standard solver still results in a not manageable runtime. Therefore a smaller set of stations is selected to reduce the runtime. All 122 stations clustered into groups if all stations within a group are less than 500 m apart, result in a new set with 62 locations. Furthermore, we relax our model constraint 6 that ensures that we have equal inventory levels in the beginning and end of the day. Instead, a 40% deviation of the inventory levels at the end of the day is allowed, which is equivalent to a difference of maximal two cars.

5 Results

The results for conventional and platoon relocation tours in the Hanover case study are shown in Fig. 3. To determine the no relocation scenario in our model the front car number is set to zero and in the conventional relocation scenario the maximal platoon length is limited to one. The platoon relocation approach enables one employee to relocate four cars at the same time. If no relocation is executed in the Hanover instance, 419 customer trips are realized. A conventional relocation tour realizes 441 customer trips and the platoon relocation tour increase this number to 462. Even though the additional number of realized customer trips when changing from no relocation to conventional relocation is identical when changing from conventional to platoon relocation, the profit increases by 1.3% in the first case and by 2.5% in the second case. This effect is visualized by a steeper profit line, it can be explained by reduced relocation costs, and proves the increased efficiency of the platoon relocation approach. The model runtime of the platoon relocation approach is 467 min, 18 min for the conventional relocation approach and 10 min for the no relocation scenario.

6 Discussion

The theoretical analysis in Sect. 2.3 has demonstrated two scenarios where platoon relocation tours are 30% to 60% more efficient compared to conventional tours. Two additional unusual scenarios have shown a possible destruction of the advantages of platoon tours. The Hanover case study results show a moderate positive effect when platoon tours instead of conventional tours are used.

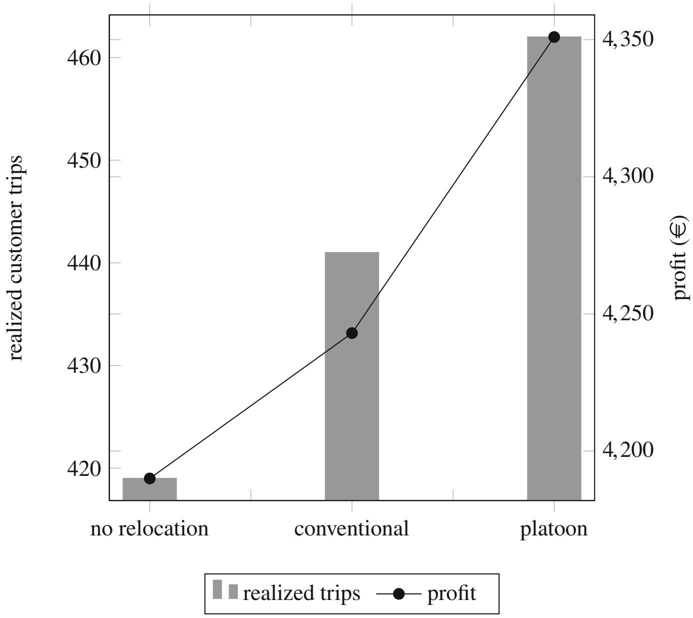

Fig. 3. Hanover case study efficiency analysis of conventional and platoon relocation. Model results for the case study described in Sect. 4 are visualized for three different relocation approaches. The left y-axis illustrates the number of realized customer trips that the car sharing system realized throughout the planning period of 16 h. The relocation costs subtracted from the summed up profit from all realized customer trips yield the operator's profit, plotted on the right y-axis.

Although the platoon efficiency effect is observable, it is lower than we expected based on our theoretical analysis. The reason may be that the Hanover case exhibits unfavorable infrastructure and demand requests as pictured in Fig. 1.

Boldrini and Bruno [4] find that their heuristic relocation algorithm applied to car sharing demand in Lyon achieves a relocation performance close to that of autonomous vehicles, if 30 employees perform relocation tours, and significantly improves over the conventional relocation approach. We believe that the divergence to our case study results are caused by different demand instances. Whereas several stations in Boldrini's case study have a daily inflow and outflow gap above 100 cars, our case study has a maximum inflow/outflow gap of 12 cars, leaving less options for efficient large-scale relocation.

7 Conclusion

We are able to apply our time-expanded network relocation model for one-way car sharing systems to our self-designed case study from the city of Hanover. We observe a moderate improvement of realized customer trips and relocation costs in the car sharing system performance with the platoon relocation approach compared to the conventional relocation method. The absence of stronger improvements, that we initially expected based on theoretical deliberations, is presumably caused by the specific characteristics of the Hanover demand instance and infrastructure. We have made several simplifications in order to cope with runtime restrictions. The twenty-six times longer runtime for the platoon relocation approach in contrast to the conventional relocation approach clearly emphasizes the complexity of the platoon problem structure. In order to solve larger instances, a solution methodology for the IP, potentially with a matheuristic and iterative solving, is necessary. This could lead to further improved solutions, for example the period length could be reduced and more stations could be served within a day.

Acknowledgements. Funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) - 227198829/GRK1931.

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Sustainable Supply Chain Management

Reverse Logistics Challenges in the Textile Industry in the Year 2035

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Abstract. This paper presents three explorative scenarios for reverse logistics in the textile and apparel industry in Germany for the year 2035. The scenarios build upon six key factors which represent technological, legal, societal, and sustainable perspectives. Scenario "Sustainable policies" refers to companies in the textile and apparel industry changing their production philosophy towards sustainability and producer responsibility due to stricter legal recycling regulations. Scenario "Consumer awakening" assumes a rise in backward flows of recyclable apparel due to consumers demanding sustainable fashion and recycled apparel. The third scenario "Profit over humanity" is negative in its basic tone and describes a profit driven production philosophy where sustainable aspects such as recycling-oriented product development are not considered at all by society.

1 Problem Background and Research Questions

Since the turn of the millennium, the textile and apparel (T&A thereafter) industry has experienced a strong increase in global production and sales volumes. Sales increased by almost 800 billion US dollars between 2002 and 2015. This development is supported by increased consumerism and shortened wearing time of individual apparel (Greenpeace 2017). The corporate strategy known as fast fashion favours the increasing demand for apparel by minimising processes associated with the purchase cycle. New apparel is also intended to be introduced for sale in a timely manner by shortening delivery times so that consumer demand can be met at its peak (Barnes and Lea-Greenwood 2006).

In online retail, the apparel sector recorded sales of €14.3 billion in Germany in 2019, surpassing the sales figures of other product groups such as electronic goods and telecommunications (Furchheim et al. 2020). A survey by PostNord showed that apparel is also the front runner in terms of the five most frequently returned products as more than 67 million consumers reported to have returned products in this category (PostNord 2019). Significant factors for a purchase or return of apparel are the size, fit and product quality. Hereby, product fit often depends on brands and manufacturers. This uncertainty in turn advocates multi-brand ordering and high return rates (Deges 2017). In the case of slim fit fashion for young consumers, the return rate is even 70%. But, for a firm to compete in such a fierce business sector, it is necessary to integrate return policies as part of their everyday business. Otherwise, consumer would not buy the apparel online

U. Buscher et al. (Eds.): *Logistics Management*, LNLO, pp. 181–193, 2021.
https://doi.org/10.1007/978-3-030-85843-8_12

(Urbanke 2009). However, a study by the Ellen MacArthur Foundation revealed that less than 1% of clothes manufactured worldwide is recycled and reused in the T&A industry. This fact considers both, the recycling of pre-consumer as well as post-consumer waste. The rate of recycling could be below 0.1% when just regarding post-consumer waste (Ellen Macarthur Foundation 2017).

There are several dynamic factors in the T&A industry, which are complex and difficult to predict. As the modern T&A has overly complex features, there are also numerous challenges such as short life cycles or superior product quality that needs to be addressed in the upcoming period (Das 2013). Companies can survive and sustain when they consider decisions with foresight and gear them accordingly to the future (Kosow et al. 2008). Scenario analysis offers an opportunity to foresee positive as well as negative developments in the T&A industry based on the identification of general framework conditions. Based on these, various situations or scenarios can be generated which describe these developments and provide options for actions (Gausemeier et al. 1996; Mietzner 2009; Rose 2017). Hence, this endeavour will create explorative future scenarios, focussing on reverse logistics (RL) in the T&A industry and state business implications. Thus, the following research question arises:

To what extent is reverse logistics able to address the challenges in the textile industry in the future?

The remainder of the paper is as following: After a brief introduction, we present a short description of RL and the T&A industry. Subsequently, the methodology of scenario generation is presented, and three explorative scenarios are developed and critically assessed. The paper concludes with a contribution and business implications chapter and ends with a conclusion and the need for further research.

2 What is Reverse Logistics?

RL is a vital element of sustainable logistics and supply chain management (SCM) (Dowlatshahi 2000). According to Rogers and Tibben-Lembke (1999) RL addresses all necessary processes and activities that deal with the reverse flow of goods and related information with the purpose to either recapture value or to properly dispose the returned goods. RL processes in the T&A industry comprise the sourcing of old or returned apparel from consumers or retailers, the gathering of old apparel at central points, the sorting of old apparel according to specific measures and the final distribution to matching stages in the textile supply chain for the purpose of recycling, remanufacturing, reutilisation, or repair (Agrawal et al. 2015).

Backward logistics flows differ to a large extent from the associated forward flows as they are much more reactive and less visible. All business activities related to RL depend on consumers behaviour, thus, RL is rather a reactive than a conscious proactive business decision (Rogers et al. 2012).

Interest in RL has risen recently due to the decreasing use of raw materials, the creation of value through restoration or even the reduction of disposal costs (Rahman 2016). Besides direct economic benefits, RL also offers indirect marketing benefits.

These include but are not limited to differentiation from the competitors, image improvement, improved customer and supplier relations (de Brito and Dekker 2003). Furthermore, regulations and legislation are among the incentives for the introduction of RL. The Recycling Management Act regulates the product responsibility of producers. Even after their products have been used, producers must take back and recycle the resulting waste. Thus, a strong motivation for RL is already given during production stages. Depending on the type of product, there are various regulations that define the scope of a company's product responsibility (Umweltbundesamt 2013).

Ecological aspects have become mandatory for many manufacturers due to public concern about sustainable development. On the one hand, the successful integration of RL can assist companies following environmental law and restrictions. On the other hand, it creates the opportunity for companies in the T&A industry to present themselves from a sustainable point of view (Rahman 2016).

Overall, we consider RL as a necessary part to implement and control an efficient and sustainable material backward flow and an important issue for the T&A industry. So far, research in the area of RL, recycling economy and its sustainable impact on the T&A industry deserves more attention than it is currently arousing (Cullinane et al. 2017).

3 Textile and Apparel Industry

3.1 Description and Challenges of the Industry

Both, the textile and apparel (T&A) industry represent typical global supply chains and stand out as key contributors to the global economy (MacCarthy and Jayarathne 2012; Singh et al. 2016). Production in both industries is globally dispersed and globally organised by division of labour, which means that manufacturing is mainly located in low-cost countries. Consequently, transport distances are very long as it takes several individual processing steps in various countries to complete apparel. But sales prices do not reflect these distances at all (Stamm et al. 2019; Umweltbundesamt 2016). Furthermore, the T&A industry accounts for around 10% of total CO_2 emissions which makes it the second most polluting sector worldwide (Echeverria et al. 2019). Taking the case of Germany, approximately 90% of all apparel is imported mainly from China, Bangladesh, or Turkey.

Another ecological challenge of the T&A industry is the sustainable and environmental friendly processing of used textiles. More than one million tonnes of used apparel were collected in Germany in 2018 (Bundesverband Sekundärrohstoffe und Entsorgung e.V. 2020), and only a fraction of this is needed by institutions for needy or crisis areas (Böschen 2018; Bundesverband Sekundärrohstoffe und Entsorgung e.V. 2015). Also, the recycling of textile waste is currently still a difficult process, as most fabrics consist of a mixture of different types of fibres, such as cotton and polyester (Franco 2017).

3.2 Textile Waste Streams

The textile waste streams can be divided into pre-consumer waste, such as offcuts that are still generated in production, post-consumer waste and industrial waste (Echeverria et al. 2019). Pre-consumer waste is generated by the producer and never reaches the consumer. In contrast, post-consumer waste comes directly from the consumer, while industrial waste is generated during the textile manufacturing process and accounts for approximately 15% of fibre waste (Beitch 2015; Leonas 2017). In the European Union (EU), nearly 6 million tonnes of post-consumer waste are generated every year, of which about a quarter of the total is recycled into low-value products or recycled through thermal recovery. However, this still leaves three quarters of waste that is eventually disposed of in landfills. The post-consumer waste streams originate either from municipal solid waste or from trading and retail industry (Echeverria et al. 2019). For further analysis, the post-consumer waste stream will be considered, as it accounts for a large part of the overall waste generated.

3.3 Circular Economy and Innovation Opportunities

The current view of the economy is evident in the limitations of the T&A industry. However, the EU has recognised the relevance of the necessary transition towards a circular more sustainable economy (Koszewska 2018). Circular economy mainly consists on the principles of waste reduction, product reutilisation and recycling (Su et al. 2013; Zhijun and Nailing 2007).

Jia et al. (2020) conducted a systematic literature review on this topic and establish a conceptual model which contains drivers, barriers, practices, and sustainable performance indicators for a circular economy in the T&A industry. According to Jia et al. (2020) main barriers for implementing a circular economy in the T&A industry are lack of technology systems for recycling, lack of stakeholder cooperation, and most of all lack of supportive policy making. Among other factors, customer awareness and community pressure represent drivers for the conversion of the current T&A industry into a circular economy.

Regarding various innovation opportunities, the European Technology Platform for the Future of Textiles and Apparel identifies opportunities to address the multiple challenges of the textile sector. Smart and high-performance materials, advanced digitalised manufacturing, circular economy and resource efficiency and solutions with high added value for attractive growth markets are some selected strategic topics on impactful innovations (European Technology Platform for the Future of Textiles and Apparel 2016).

4 Methodological Considerations

In this paper, we use a narrative and qualitative approach by applying the methodological approach by Gausemeier et al. (1996) for creating possible explorative scenarios. Table 1 summarises our methodological steps. The procedure of scenario analysis in this work is based on a narrative and qualitative approach.

The influencing factors were identified by the authors of this work and are based on the systematic literature review that covers the field of RL and the T&A industry regarding the process of developing future scenarios. Thereby, we followed the suggestions for analysing qualitative data by Creswell (2009) as well as Krippendorff (2004). We

Table 1. Four scenario steps and their implications for this work

Methodological steps	Characterisation for the present study
Step 1: Scenario preparation	We focus on the RL processes in Germany for the T&A industry needed in 2035
Step 2: Scenario field analysis (considered key factors for further analysis in bold)	Identification of 12 influencing factors based on a systematic literature review by the authors who are experts in the field of logistics: **(1) Chemical and mechanical recycling technology**, **(2) Extended producer responsibility**, **(3) Collecting processes**, (4) Sorting process, **(5) Recycling-oriented product development**, (6) RFID, **(7) Law**, **(8) Environmental awareness of consumer**, (9) Reverse logistics cost, (10) Willingness to cooperate, (11) Supply chain transparency and (12) Use of resources Next, 132 influencing factor relationships were assessed by the authors to determine six key factors with the highest influencing factor relationship for the scenario field
Step 3: Scenario forecast	Then, possible key factor projections were developed by describing every key factor in its current state. Based on this, possible projections for the year 2035 were then developed for each key factor which resulted in six general descriptions and twelve developed projections for the T&A industry
Step 4: Scenario development	The key factor projections were linked to 126 possible combinations of key factor projections by using a consistency matrix with values from 1 (weak) to 5 (strong) in order to determine their tolerability in a scenario

included the influencing factor "law" because legal changes have a strong influence on the RL activities (see e.g. the "Waste Electrical and Electronic Equipment" regulation, which has led essential changes for collecting, sorting and recycling of electronic waste (Walther and Spengler 2005)).

Based on the evaluation of the mutual tolerability of possible key factor projections, three different and consistent explorative scenarios were elaborated which are shown subsequently. The occurring codes at the end of the sentences in the following chapters point to the projections in the respective scenario illustrations. Where A indicates a positive development (also a green illustration frame) and B indicates a negative development (also a red illustration frame) towards sustainability. Table 2 shows the six key factors (in bold) and key factor projections with their respective projection codes (indicated by the respective key factor number and capital letter), which are subsequently used for the scenarios.

Table 2. Overview of the six key factors (in bold) and the twelve developed projections

(1) Recycling technologies	(2) Extended producer responsibility	(3) Collecting processes	(5) Recycling-oriented design	(7) Law	(8) Environmental awareness of consumer
(1A) Expansion	(2A) Expansion	(3A) Expansion	(5A) Expansion	(7A) Tightening	(8A) Increasing
(1B) Stagnation	(2B) Stagnation	(3B) Stagnation	(5B) Stagnation	(7B) Loosening	(8B) Decreasing

5 Results of the Scenario Analysis

5.1 Scenario Management

The scenario management approach revealed twelve factors influencing the environment of RL in the T&A industry. The key factor "law" is the most important influencing factor for the T&A industry and thus has a high impact on the design of RL processes in Germany. A loosening of the legal framework would probably not lead to an expansion of recycling-oriented product development. Hence, no expansion of RL processes would occur.

Recycling technologies can also be part of the economic incentives in the T&A industry if the legal framework is expanded. Nevertheless, with a tightening of the legal framework, companies in the T&A industry must evaluate between additional costs of non-compliance and investment costs for recycling technologies.

5.2 Influence Analysis

The influence analysis also indicates that there are preconditions for the performance of RL. The collection and sorting processes are most strongly influenced by all other factors from the scenario field. Hence, the collecting and sorting of used and old apparel is easily executed, when a high consumer awareness leads to optimal pre-sorting. Likewise, if the T&A industry includes consumer incentives for the correct return at take-back locations for used and old apparel the recycling process as a whole accelerates.

Overall, the use of recycled resources, the transparency of the manufacturing process and the willingness to cooperate between all stakeholders in the T&A supply chain are important factors influencing the performance of the entire RL.

Scenario 1: Sustainable policies
General description
Figure 1 gives an overview and illustrates the used key factor projections.

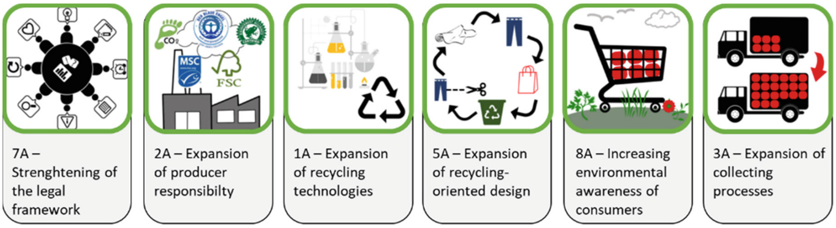

Fig. 1. Scenario 1: sustainable policies

This scenario assumes that legal framework conditions regarding the disposal and recycling of old apparel will be tightened (7A). In this case an expansion of producer responsibility is highly likely (2A). As a chance to meet these new strict laws on disposal and recycling, companies in the T&A industry start investing in technologies which enable recycling of old T&A (1A). Advanced technologies can make it easier for companies to integrate recycled fibres and reduce production and sourcing costs. For this reason, recycling-oriented product development is also highly likely (5A). With the increased supply of recycling-oriented clothing, it is likely that consumers will develop a sustainable consumption behaviour (8A). At the same time, there is a need to facilitate return of used T&A into the T&A supply chains, as they become a valuable resource. Accordingly, the returning and collecting of used apparel is standardised and improved (3A).

Critical Assessment
In case of the first scenario, legal restrictions demand companies to address the reverse material flow of old textiles and support an increase in resource reusability. Otherwise, companies could find themselves liable or will be denied entry to certain markets. Thus, legislation acts as a driver to lead companies to invest into recycling-oriented design and change production philosophy. As a positive side effect, companies are able to advertise sustainable fashion and make consumers feel environmentally conscious. Furthermore, consumers get the impression of supporting progressive and sustainable business models.

In the first scenario companies in the T&A industry change their production philosophy towards sustainability and producer responsibility due to stricter legal regulation in terms of recycling. Thus, a higher and steady backward flow of old or returned apparel opens the possibility of standardised RL processes. Due to rising volumes of backward flowing recyclable apparel, RL becomes predictable, visible, less reactive and expanding central collection points could achieve profitability due to economies of scale in further stages of RL processes.

Scenario 2: Consumer awakening
General description
Figure 2 gives an overview and illustrates the used key factor projections.

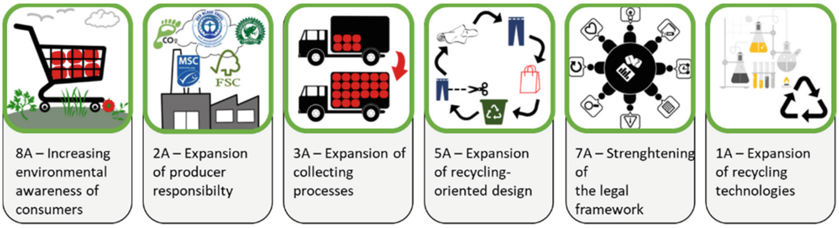

Fig. 2. Scenario 2: consumer awakening

This scenario considers an increased environmental awareness of consumers (8A). The changed consumption and purchasing behaviour results in the expansion of producer responsibility (2A). The awakening of consumers is also visible in the return logistics activities, as textiles are increasingly being handed in at collection and recycling points. Consequently, T&A industry offer more and diverse collection points, where old apparel is dropped off and sorted by the consumer (3A). Apparel that is neither recycled nor recyclable is considered unsustainable and become shelf warmers. Producers are responding to the change in consumer buying behaviour by expanding recycling-oriented apparel design (5A). To preserve resources and fulfil consumer needs, producers continuously try to integrate smart and recycled materials into apparel design. As both, consumers, and producers, demand stricter framework conditions politicians pass new laws, which tighten up the legislation on the disposal and recycling of used apparel (7A). To meet the new legal requirements, technological progress in recycling technologies is supported (1A).

Critical Assessment
The second scenario assumes high ecological consumer standards which may lead to an increased consumer demand for sustainable and recycled apparel. This, in turn, offers producers with a steady demand for sustainable fashion and incentives to change into a sustainable production philosophy. This scenario also assumes high return rates of used apparel for further recycling processes which may at first result in higher handling costs but in the long run may lead to customer loyalty and resource efficiency. The high waste percentage of apparel that is no longer needed, as described above, gives way to the responsible use of old apparel as a valuable resource.

Likewise, the second scenario assumes a rise in backward flow of recyclable apparel. However, in contrast to a law induced sustainable production change, in the second scenario it is the consumer who demand sustainable fashion and recycled apparel . Companies need to rethink their image and increase resource efficiency. As consumers adopt a greener lifestyle, consumerism gives way to a sustainable use of apparel. Consumers tend to buy fewer clothes and wear them more often.

Scenario 3: Profit over humanity
General description
Figure 3 gives an overview and illustrates the used key factor projections.

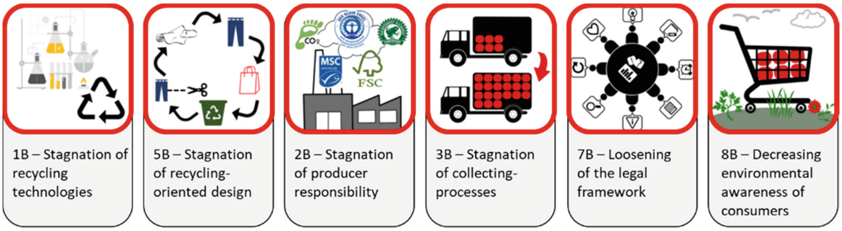

Fig. 3. Scenario 3: profit over humanity

This scenario assumes that future research and further development of recycling technologies will stagnate (1B). The cost-intensive development as well as low investments in this field will lead to a standstill in textile recycling. Accordingly, recycling-oriented apparel design also stagnates (5B), as there is no incentive for producers to change their behaviour.

As there are no incentives, producers do not feel obliged to change their current production philosophy. Producer responsibility is rarely seen (2B) and other factors such as increasing profits remain in focus. The lack of incentives to rethink sustainability measures in the production stages leads to decreased attention for collection processes of returned apparel (3B).

Additional loosening of the legal framework (7B) strengthens the producers in their irresponsible behaviour to the disadvantage of sustainable production philosophy in the T&A industry. In this context, consumers continue buying cheap apparel and not paying attention to environmental negative side effects (8B).

Critical Assessment
While the first and second scenario offer the T&A industry high potential for sustainable development, the third scenario assumes negative trends in the production philosophy as well as in consumer behaviour. Recycling rates remain low which hinders the development of recycling-oriented apparel and the understanding for the necessity of recycling technologies. Since production philosophy and consumerism prevails, low quality is more cost-effective than high-performance materials. As consumers do not demand sustainable apparel, in this scenario, legal intervention to raise ecological awareness solely among producers would result in legal disputes between government and the T&A industry.

The third scenario is characterised by a negative development towards a profit driven production philosophy. Neither consumers nor the government do see a necessity in sustainable production measures. This way RL processes keep being reactive and hard to predict. There is no recycling-oriented product development nor a recycling-oriented industry or any presentable progress in recycling technologies. This way, no expansion of RL process capacity is necessary. The only way of doing profitable business with recycled apparel is through purchasers of recycled fibres. However, since new fibres are cheaper, there will be no incentive to expand the RL processes.

6 Contribution and Business Implication

Based on the key factors, three consistent and plausible explorative scenarios described possible future development for RL in the T&A industry. Thereby, both scenarios "Sustainable policies" and "Consumer awakening" foresee changes towards sustainable production and high return rates of old apparel. However, the third scenario "Profit over humanity" assumes no change in current behaviour.

The contribution of these scenarios lies in the revelation of possible development of the T&A industry due to different framework conditions. Table 3 sums up the framework condition, the main development and business implication for RL.

Table 3. Framework conditions, main development and business implications for RL

Framework condition	Main development	Business implication for RL
Scenario 1: Tightening of legal restriction determines companies' behaviour	• Higher and more predictable amounts of old apparel • T&A industry is forced to rethink their production philosophy	• Standardization of apparel take-back in all shops • Implementation of warehouses with corresponding recycling zones and integrated automatic sorting machines • Establishment of a recycling industry with the purpose of pre-processing and distribution of recycled apparel to the corresponding stages in the supply chain (recycle, remanufacture, reuse, repair)
Scenario 2: Consumer behaviour changes towards environmental awareness	• Consumers' change their mind towards environmental awareness • RL processes become visible and plannable	• Provision of advanced recycling bins for the purpose of consumer driven pre-sorting • Expansion of collection infrastructure and placement of more recycling bins • Optimisation of pick-up processes at collection points • Improvement of recycling bins by adding sensors for detecting and sending the fill levels
Scenario 3: No research progress towards recycling technologies	• Development towards a profit driven production philosophy • RL processes keep being reactive and hard to predict	• No expansion of RL processes is necessary

7 Conclusion

The aim of this work was to create explorative future scenarios, focussing on RL in the T&A industry. As a second goal, based on these scenarios, we stated business implications for RL processes to answer the research question:

To what extent is reverse logistics able to address the challenges in the textile industry in the future?

RL is able to address a certain part of the challenges in the T&A industry in the future under certain conditions such as the tightening of legal framework conditions or the development of high ecological standards on the part of consumers. One specific challenge is the short life cycle of textiles that could be addressed by RL. By closing the loop and extending the life cycle of textiles, RL improves the use of resources because it utilizes old textiles by assigning a new value to them through RL processes such as collecting, sorting and recycling. A precondition that is needed for an optimal operating RL is for example the recycling-oriented design. Without regarding the condition of the textiles arriving in the reverse supply chain it becomes very difficult to keep the textiles circular. However, RL processes depend moreover on factors such as consumers' willingness to change as well as, from a producer's perspective, the willingness to change the production philosophy towards sustainability and preservation of used resources. The third scenario shows – opposed to the first two scenarios – that RL processes cannot solve future challenges in the T&A industry. This is mainly due to unpredictable volumes of returned apparel and the lack of producers' and consumers' eco-friendliness. In this case campaigns for sustainable clothing could be launched to strengthen the sustainability awareness of consumers to trigger a rethinking among producers.

Overall, the possibility of returning used apparel must be simplified. This could be achieved for instance with a standardization of apparel take-back in all shops and an establishment of a recycling industry. This way RL processes can profit at all stages by a predictable and visible return flow of used apparel to meet consumer demand for a sustainable use of resources.

As the scenarios were developed on an "intuitive logic" base, we suggest as further research to confirm or contradict the scenarios with empirical evidence from other world regions. The results elicited in relation to RL relate to the geographical area of the German T&A industry. Accordingly, the influencing factors affect the German T&A industry. However, this is a limitation of the current scenario analysis. Future research could focus and broadening the geographical scope and implement the European Union's perspective in that matter.

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Characteristics and Environmental Orientation of Modality Concepts

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Abstract. Different modality concepts for freight transportation have been developed over the past decades. One inherent emission reduction strategy they all include, by definition, is the strategy of modal shift. Several literature reviews are made to identify main characteristics of multi-, inter-, co- and synchromodality with a special focus on the most current concept of synchromodal transportation. The analysis further focuses on the environmental orientation (sustainability, emission reduction and modal shift) of the concepts. The emission reduction importance for modality concepts is analysed, to determine if they can be used by different actors in the transportation chain to reach emission reduction and to ascertain if courses of action for low-emission transportation planning can be deducted. The differences between the modality concepts are not very distinct, emission-reduction is expected to be achieved by using these concepts and courses of action are usually developed in form of methods or tools for specific problems and users. They are difficult to access or transfer onto other cases or user. A standardized process usable for different Logistic Service Provider is needed.

1 Introduction

Freight transportation is the only economic sector in which green-house-gas (GHG)-emission is expected to rise is the future (UBA 2019). Caused by the increasing need for freight transportation which is expected to rise by 60% until 2050 (EC 2019). One of the main strategies, to reduce emission in transportation, targeted by the European commission, is the modal shift strategy. Instead of mainly using road transportation, the aim is to shift goods on transportation modes which emit less GHG-emission like railways, inland waterways or sea transportation (UBA 2019). The avoidance of transportation strategy includes measures like bundling or avoiding less than full truck load transportations. The strategy of technological improvements leads to a reduction of the energy consumption and/or fuel use through new propulsion technology like electrical engines (Centobelli et al. 2020; Walnum and Aall 2016). The modal shift strategy is connected to modality concepts in transportation (Bouchery and Fransoo 2015). In the following, basic definitions of these concepts are given, to derive a first interpretation of the characteristics of modality concepts and their environmental orientation.

For freight transportation, especially over long distances, different concepts of modalities have been defined including multimodality, intermodality, co-modality and

U. Buscher et al. (Eds.): *Logistics Management*, LNLO, pp. 194–212, 2021.
https://doi.org/10.1007/978-3-030-85843-8_13

synchromodality (Rossi 2012). The basic definitions of multi- and intermodality were given by the "economic commission for Europe" UN/ECE (2001):

– Multimodal transportation includes at least one mode change.
– Intermodal transportation includes at least one mode change and the goods are transported in the same loading unit or vehicle, without the handling of the goods themselves.

COM (2006) reviewed and updated the white paper from 2001 and introduced co-modality as "the efficient use of different modes on their own and in combination" and stated that this "will result in an optimal and sustainable utilization, of resources.".

No fixed definition of synchromodality exists (Giusti et al. 2019b), instead various approaches to find a definition have been taken. According to (van der Burgh 2012) "the core of the concept" was defined in a TNO report Gorris et al. (2011): "The continual synchronization of chains of goods, chains of transport and infrastructure in such a way that the best modal choice can be made at any moment for the aggregated demand for transport.". By Balázs et al. (2016) it is described as a business-driven concept which includes "the optimization, of logistic chains through the efficient combination of transport modes, the allocation of freight to various modes according to available capacities, possible time and cost savings, including the re-planning of the transport and the booking of alternative capacities/modes in case of events, while alerting electronically supply chain partners about the changes".

Co-modality is the first description of these concepts which includes the phrase sustainable, while the EC definition of the most recent concept synchromodality does not include environmental considerations. Each of the defined modalities is meant to have its own characteristics and significance which is challenged by Rossi (2012) and Reis (2015). Reis (2015) criticizes, that: the concepts overlap each other and are not entirely differentiable from each other which could lead to "misinterpretations of research efforts and hampers the coherent development of theory, regulations and policies." Not only the concepts overlap but there are various definitions used in research for each modality concept.

The aim of this paper is to answer the following three research questions:

– RQ1: Which main characteristics can be assigned to the different modality concepts? With a special focus on synchromodality.
– RQ2: Which modality concepts support environmental oriented planning?
– RQ3: Can different courses of action be derived for emission-low planning of transportation chains for different users?

RQ1 and RQ2 are processed in Sect. 2, based on an extensive literature analysis. For RQ1 by showing the variety of characteristics which are assigned to the modality concepts in research, with a special focus on environmental-oriented characteristics for RQ2. In Sect. 3 the emission importance in the reviewed articles is determined to finalize the answer for RQ2 and to lay a foundation for processing RQ3, which is investigated in Sect. 4. In Sect. 5 the answer to the research questions is discussed. A conclusion for the implications of the study for further research directions is drawn in Sect. 6.

2 Characteristics of Modality Concepts

In this chapter the characteristics which are assigned to the different modality concepts, with a special focus on the environmental orientation, are identified using several existing literature reviews. For co-modal and synchromodal transportation additional literature reviews are conducted to take into consideration the novelty of the models in comparison to multi- and intermodal transportation.

2.1 Multi- and Intermodality

For the concepts of multimodality and intermodality a lot of research has been done in which the basic definition of UN/ECE (2001) is used and extended. The following analysis of the definitions is based on existing literature reviews. The findings of the literature reviews of Rossi (2012), Giusti et al. (2019b), Reis (2015), Pleszko (2012) and SteadieSeifi et al. (2014) are combined to list and interpret the main characteristics assigned to multi- and intermodal transportation in research. The literature review in Lößer and Sackmann (2020) is used as additional orientation for environmental concerns.

The studies mentioned above are in sync with the given definition by UN/ECE (2001) and characterize multimodality as the transportation of goods using at least two different modes. Lößer and Sackmann (2020) identify four articles including emission-reduction concerns into multimodal planning problems.

Intermodality is a more restricted concept than multimodality and assigned characteristics are not as perceivable. All the studies mentioned above agree that intermodality is a further development of multimodality, meaning it includes at least two modes. They all see the use of only on transportation unit (loading unit or vehicle) as second characteristic. Furthermore, two studies state that intermodal transportation can be seen as a door-to-door concept (Giusti et al. 2019b; SteadieSeifi et al. 2014). As for the environmental orientation of the mentioned literature reviews only Rossi (2012) concludes that intermodal transport is a method to reduce GHG-emission. Looking into the studies included in the literature reviews, of 20 studies included in Reis (2015), only three mention sustainability as key element. Lößer and Sackmann (2020) identify three studies mentioning sustainability and two that mention the reduction of GHG-emissions in the definition of intermodality.

2.2 Co-modality and Synchromodality

Co-modal and synchromodal transportation are the youngest concepts. Therefor not as many literature reviews and research exist in comparison to multi- and intermodal transportation. Additional reviews are conducted to extend or support the characteristics found in existing literature reviews.

2.2.1 Co-modality

As mentioned before the basic definition of co-modality is the only one including sustainability. The research on co-modal transportation is rather limited. To define the main characteristics a short literature review was done. No hits with the "co-modality" title search in ScienceDirect have been achieved, so google.scholar has been used for a more extensive search. In addition to the introduced articles, five more articles giving definitions for co-modality could be found they are listed in Table 1 in bold print. Based on these ten studies the different characteristics assigned to co-modal transportation are identified.

Table 1. Characteristics of Co-modal transportation

Authors	Efficient transport/mode use	More than one mode	Sustainability	Modal shift	Optimize resource utilization	Cooperation
Rossi (2012)	x	x	x	x		
Giusti et al. (2019b)	x	x	x		x	
Reis (2015)	x	x			x	
Pleszko (2012)	x	x				
SteadieSeifi et al. (2014)	x	x	x	x		x
Jarzembowski (2007)	x	x				x
Giannopoulos (2008)	x	x				
Kalantari (2011)	x	x		x		
Ambroziak et al. (2013)	x	x	x	x		x
Żak et al. (2013)	x	x	x	x	x	
Sum	10	10	5	5	3	3

Only the characteristics which were mentioned more than two times are represented. The x represents that the characteristic has been termed with this word or phrase and the (x) represents that the characteristic has not been named exactly but has been described. Efficient transport or mode use and the use of at least two modes are agreed on as characteristics in all articles.

Sustainability and modal shift are mentioned by five articles as one of the main characteristics. Other possible characteristics are only mentioned by one or two authors, which makes it difficult to determine if they can be interpreted as main characteristic of co-modality. Only the environmental-oriented are discussed. Jarzembowski (2007) sees the need for the optimization of each mode in addition to modal shift to reach an environmental-friendly transportation. Emission reduction and the need to reach the aims of the Paris agreement is only mentioned by Rossi (2012).

2.2.2 Synchromodality

An unified definition of synchromodality does not exist, various definitions have been used in research. Figure 1 shows that synchromodality is often mentioned as a further development of existing modality concepts. 58% describe it as a progression of inter-modality. This description also includes one characteristic that all authors again agree on, the use of at least two modes.

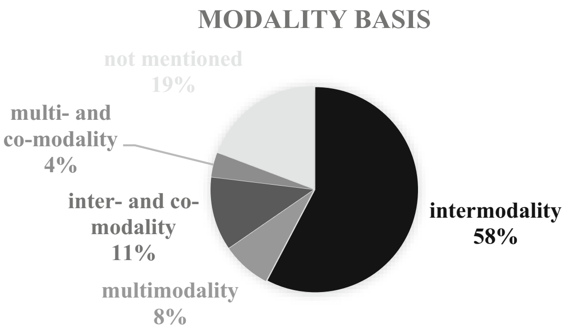

Fig. 1. Modality basis for synchromodal transportation

The disunity in definitions also leads to a broad range of characteristics. Four articles Rossi (2012), van der Burgh (2012), Fan (2013), Solvay et al. (2019) have compared different definitions to identify core characteristics in their studies. An overview of all four studies and the identified core characteristics is shown in Table 2. In addition to the use of more than one mode two other characteristics on which all articles agree on can be found. The mode free/a-modal booking and the need for cooperation. Sustainability is mentioned three times, twice in connection with the development of sustainable modes and once as target.

In addition to these reviews a new literature review was conducted to show an up-to-date overview and determine if sustainability or low-emission considerations are part of the characteristics by now. This analysis, represented in Table 3 and 4, is also meant to examine if the characteristics named by only one or two of the former studies can be supported. For the additional literature review the databases ‘ScienceDirect’ and ‘Scopus’ were used, searching for synchromodality and synchromodal transportation. Overall, 78 articles have been reviewed. Articles were excluded if they do not focus on synchromodality, if they are not looking into logistic or freight transport planning, if they mainly focus on urban logistics. 26 articles have been chosen for the analysis of their synchromodality definitions. They are listed in Table 3. The use of at least two modes is again inherent and not listed anymore.

Comparing the characteristics found in the former literature reviews (table two) with the characteristics listed in Table 3, most of them can be confirmed. Not part of the findings anymore is centralized planning although it could be argued that the use of a LSP also signifies the need for central planning. Additionally there are changes in the importance of the mentioned characteristics, now real-time planning seems to be the most important one and the optimization of network and transport utilization not

Table 2. Characteristics of synchromodal transportation in existing literature-reviews

Characteristics/Articles	Rossi (2012)	van der Burgh (2012)	Fan (2013)	Solvay et al. (2019)
Use of at least two modes	x	x	x	x
Mode free/a-modal booking[a]	(x)	x	x	x
Cooperation	x	(x)	x	x
Optimize network utilisation		(x)	x	x
Real-time mode switching[b]		(x)	x	x
Sustainability	x		x	x
Dynamic planning of transportation	x		x	
Bundling/Aggregation/Consolidation		x	x	
LSP	x			
Centralized planning	x			
Information availability and visibility			x	
Tactical SND and operational real-time optimization				x

[a]Shippers do not decide the used transport modes, they only book the transport volume. The service provider or forwarder makes the final decision. Solvay et al. (2019).
[b]If disturbances occure the route can be changed on short notice.

as important as before. Furthermore 3 new characteristics could be identified, they are emphasized using bold print.

Integration is a hypernym for different descriptions of "mode integration" and "horizontal integration". Parallel mode use means that goods from the same shipper could be transported via different types of modes at the same time (Dong et al. 2018). Of the new-found characteristics a special focus will be set on the pre-defined Key Performance Indicators (KPI's) by the shipper. To realize a mode-free and meet the service expectations of the shipper a framework, in which decisions can be made, is needed. This framework could be provided by determining KPI's.

Table 4 shows properties which can be interpreted as characteristics of synchromodality and at the same time be used as defined KPI's. From 26 articles 18 mention flexibility as an important characteristic. This is not surprising, for dynamic and real-time planning of transportation flows and modalities a very flexible transportation planning is needed. Low delivery times and costs are still the focus of the mathematical optimization problems in research and possibly the focus of the shipper. Also, reliability and efficiency are mentioned, the shippers and the customer who receives the goods need to be able to relay on the fulfilment of the agreed terms to the best possible conditions.

Three different environment-oriented characteristics were mentioned or described. Modal shift was included 11 times in the definition of synchromodal transportation also sustainability and even emission reduction were named. Which hints into the direction,

Table 3. Identified characteristics of synchromodal transportation part 1

Author	Real-time mode-switching	a-modal booking	Integration	Cooperation	Dynamic	Parallel mode use	Opt. utilization	LSP	Predefined KPI's	Information	Consolidation
SteadieSeifi et al. (2014)	x	(x)			X	(x)	x				
Agbo and Zhang (2017)	x		x	x		x		x		x	
Ambra et al. (2019)	x	x		x	X						
Behdani et al. (2016)			x	x			x			x	
Bauer et al. (2010)	x	x						x	x	x	
Dong et al. (2018)		x	x			x		x	x		
Farahani et al. (2018)						x					
Giusti et al. (2019a)				x			x			x	
Guo et al. (2018)	x				X						

(*continued*)

Table 3. (*continued*)

Author	Real-time mode-switching	a-modal booking	Integration	Cooperation	Dynamic	Parallel mode use	Opt. utilization	LSP	Predefined KPI's	Information	Consolidation
Guo et al. (2020)	x	x	(x)	x	X		x				
Kapetanis et al. (2016)	x		(x)			x	x	x		x	
Kourounioti et al. (2018)			x		X						x
Le Li et al. (2017)	x	x			(x)	(x)		x		x	
Lemmens et al. (2019)	x	x			X	x			x		x
Mes and Iacob (2016)	x	x	(x)	(x)	X			x	x		
Oonk (2016)		x	(x)							x	
Pleszko (2012)	x	(x)	(x)	x			x		x		x
Prandtstetter et al. (2016)		(x)				(x)		x			x
Qu et al. (2016)	x	(x)		x			x		x		

(*continued*)

Table 3. (*continued*)

Author	Real-time mode-switching	a-modal booking	Integration	Cooperation	Dynamic	Parallel mode use	Opt. utilization	LSP	Predefined KPI's	Information	Consolidation
Reis (2015)	x	x		x	(x)	(x)				x	
Resat and Turkay (2019)	x	x							x		
Šakalys et al. (2019)	x	x	(x)	x				x	x		
Tavasszy et al. (2015)					X		x	x		x	
Wang et al. (2019)	x		(x)	x			x		x		x
Yee et al. (2019)	(x)					(x)					
Zhang and Pel (2016)		(x)	x		X						x
	17	16	12	11	11	10	9	9	9	9	6

Table 4. Identified characteristics of synchromodal transportation part 2 and possible KPI's

KPI's	Number of articles
Flexibility	18
On-time delivery/time reduction	10
Modal shift	11
Sustainability	8
Cost reduction	8
Reliability	6
Efficiency	4
Emission reduction	4

that environmental considerations could be one of the main parts or characteristics of this modality concept.

3 Importance of Emission-Reduction

How defining and important is the environmental orientation for different modality concepts? This will be discussed in this chapter. The importance of emission-reduction in the reviewed articles will be the basis for decision-making. A categorization of emission-importance was introduced by Lößer and Sackmann (2020) including four categories.[1] They defined emission importance for multi- and intermodality research articles. For Co- and synchromodality the 26 articles in Table 3 are categorized into the four emission-importance categories. Only the articles in category 3 and 4 are considered for further investigation.

3.1 Multi- and Intermodality

In Lößer and Sackmann (2020) only two articles are assigned to category 4, Bauer et al. (2010) make emission reduction the main objective of their mathematical model and Wang et al. (2019) develop a green index. Hrušovský et al. (2018) and Macharis et al. (2012) are rated in category 3 offering the option to determine the emission importance.

3.2 Co-modality

Co-modal transportation is the only transportation concept in which sustainability was already included in the basic definition. In Sect. 2 only 5 articles focused on co-modality problems. The identified characteristics show that sustainability and modal shift are mentioned in 50% of the identified papers, but not one of them calculates

[1] Category 1: low priority, Category 2: medium priority, Category 3: possibility to decide the priority and Category 4: high priority of emission reduction concerns.

or presents any emission, environmental-cost or modal share/shift-figures. They are assigned to the emission-importance categories one or two and thereby excluded from further investigations.

3.3 Synchromodality

Before the emission-importance analysis is made, some conclusions from Sect. 2 are drawn. 42% of the 26 articles do not make any remark on sustainability, low emission or modal shift. The phrase emission-reduction is mentioned in 22% of the articles and always in combination with the phrases: sustainability and modal shift. For the analysis of the emission-importance and the identification of possible courses of actions the 26 articles are further circumscribed. Only articles which focus on synchromodality and calculate, or present, environmental cost, emission or modal shift figures are included. 16 papers were identified as fitting for the analysis and the emission-importance categorization based on Lößer and Sackmann (2020) is depicted in Fig. 2.

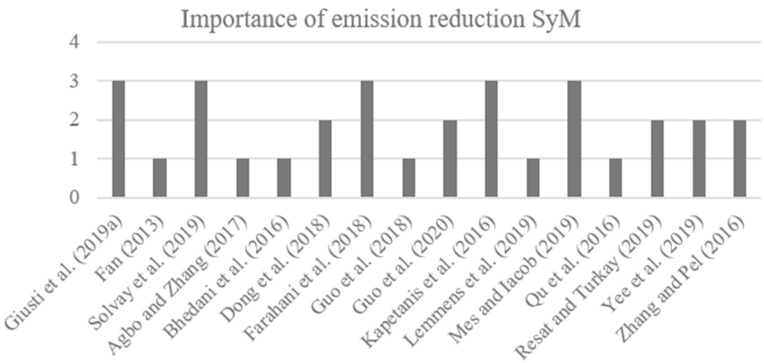

Fig. 2. Importance of emission reduction in synchromodal transportation

11 paper are rated in the low and medium importance category. Not one is rated in the high priority category. But 5 articles can be assigned to category 3.

4 Usability of Emission-Reduction Approaches and Tools

In this chapter the multimodal, intermodal and synchromodal transportation articles assigned to emission-reduction importance category 3 or 4 are analyzed, to determine their usability for solving transportation planning problems by different users. The nine articles and findings are represented in Table 5.

The table is sectioned in two levels, firstly after the addressed modality concepts and secondly after the question if a usable tool is developed or not. The second column shows the planning horizons, strategic (s), tactical (t), operational (o) and (for synchromodal transportation) real-time (rt) planning and the modes which are consider in the according paper, road (RO), rail (RA), inland waterway (IWW), maritime (M) and air (A).

Table 5. Methods and tools for emission-low transportation planning

Article	Time-horizon/Modes	Named actors/Users	Planning problem	Tool	Utilizable	Limitation
Multimodal transportation						
Wang et al. (2019)	t, o RO, RA, IWW, M	Government, MM transport operator and shipper	SND, R	(No)	MTEE-Framework	Adaptability, Usability
Intermodal transportation						
Bauer et al. (2010)	t, o RO, RA	Carriers, shippers, 3PL's	SND + FP	No	Green index	Adaptability, Usability
Hrušovský et al. (2018)	o RO, RA, IWW	Decision maker	TP	No		Adaptability, Usability
Macharis et al. (2012)	t RO, RA, IWW	Governments, communes	ND + NFP	Yes	Interactive modal shift website tool (LAMBIT)	Accessibility, Focusses on certain modes
Synchromodal transportation						
Mes and Iacob (2016)	s, o, rt RA, IWW	4th LSP	R	No	Synchromodal planning algorithm, ABCO2 for emission calculation	Adaptability
Solvay et al. (2019)	t, o, rt RO, RA, IWW	LSP 1,2,3,4 and forwarder	SND	No	Programming code	Adaptability, Usability
Farahani et al. (2018)	s, o RO, RA, IWW, M, A	Supply chain manager	SCD	Yes	SySCEA – based on Excel	Accessibility, small network
Giusti et al. (2019a)	s, o, rt RO, RA, IWW, M	Logistic operators, Firms, Public authorities, Port authorities, Research institutions, Trade associations	SCD, (Re)-R	Yes	SynchroNet-Online Tool	Accessibility, Predefined network
Kapetanis et al. (2016)	s, o, rt RO, RA, M	Shipper, LSP's, Port authorities	SND + CFP	Yes	Open architecture software	Accessibility, Availability, Parameters

Most of the models are developed to be used by different actors in the transportation or supply chain. Mainly some sort of Logistic Service Provider is named as targeted user. Now the question is for which planning problems the models and tools are developed and if and how the models or tools can be used by different actors. The utilizable column shows the part of the model or the tool which might be usable by various actors.

In the last column the limitations of the model or tool to be used by various actors are given. For example, if a membership or a high payment and is needed to get access to the tool the accessibility for different users is limited. If the access is possible the next question is if the tool can be used in its form or if it is easily adapted to the needs of the user. If not, for example if high programming skills, or a certain knowledge is needed which is not easily accessible, the usability is seen as limited. Further limitations could be linked to the kinds of problems that could be worked on with the tool. If the tool is only meant for very small networks and so on.

4.1 Articles Without Usable Tools

Five articles develop emission-oriented planning models but no usable tool, they will be shortly described in this sub-section. For all of them the adaptability and usability for various actors is limited. Most of the models would need a high level of expertise to be adapted and used for real-life planning problems.

The study of Wang et al. (2019), is the only study based on a multimodal network. It addresses a Service Network Design (SND) problem and a Transport routing (TR) problem. No real Tool is developed but the multimodal transport efficiency evaluation framework (MTEE) is depicted and might be transferable for other users, which is represented by the vague no in brackets.

Two articles concerned with intermodal planning problems can be listed. Bauer et al. (2010) include the minimization of green-house-gas emission as a main objective into the formulation of a SND problem with fleet planning (FP). They also develop a green index which could be an orientation basis for other users. Hrušovský et al. (2018) combine an optimization and simulation model to create transportation plans (TP) for a decision maker. Even though the model is tested in a case study using a real-life network, it does not present a usable tool for any other decision maker.

Two of the articles concerned with synchromodal transportation also fit into this sub-section. In Solvay et al. (2019) synchromodal services are created, for synchromodal transport planning on an intermodal freight transport network. Three optimization models are developed. The emissions are integrated into the objective function as external costs, to create efficient synchromodal transportation chains in a real-time environment. The model is based on an offline algorithm, part of the code is given which provides a better position for the model to be used by someone else. Mes and Iacob (2016) propose a multi-objective k-shortest network and an online algorithm to provide multimode k paths as options for the 4th LSP to choose from. The CO_2 emission is calculated via ABCO2, an external cloud based, carbon management system. The different models pose an obstacle for other users.

4.2 Articles with Usable Tools?

The following articles all develop tools for transport planning problems which are designed to be used by different actors in the transportation or supply chain. A limitation they all share is the question of accessibility for different actors.

One intermodal tool could be identified. To make it possible to check if intermodal transport is an economic option for shippers and other interested parties Macharis et al. (2012) develop a web-based tool which builds upon the Location Analysis Model for Belgian Intermodal terminals (LAMBIT). The user gets different options of intermodal transport with the connected costs and emissions to choose from. Limitations are that the website can not be found anymore and the focus on certain mode connections, either RO and RA or RO and IWW.

Three synchromodal planning tools were found. Farahani et al. (2018) develops a low-cost decision support tool for supply chain managers based on Excel. The "Synchromodal Supply Chain Energy Analysis (SySCEA) tool, is oriented on lowering energy consumption in the supply chain. A wide range of parameters can be adapted to the needs of the user. The main limitation is, that the network is restricted to a network of six nodes so far, but it is stated that it is easily extendable for larger networks. Giusti et al. (2019a) summerize the developments for the Horizon 2020 European research project SYNCHRO-NET and its scientific contribution. The integrated and cloud-based eco-system includes optimization and simulation software modules for a SCD and a routing problem. Synchromodality and slow/smart steaming are meant to lead to an environmental and cost oriented planning. When using the Online-Tool the starting and final destination can be chosen and the importance of different KPI's (time, distance, emission) and KRI's (safety, flexibility, cost and time reliability) can be determined by the user. Based on these choices different routing options can be compared. The only additional limitation which can be named is the fixed underlying network. Kapetanis et al. (2016) tackle a SND problem and a container flow planning (CFP) problem. A calculation tool based on mathematical modelling is used to calculate and compare cost, time and emission of different transportation options. It is the only tool also considering and presenting emission figures other than Co_2 or CO_2e. Here the availability is also unclear and Giusti et al. (2019a) criticize the limited number and adaptability of the parameters.

4.3 EU-Projects and Usable Tools?

Considering that the modality concept definitions are made by the European Union and the efforts taken to achieve emission reduction by the very same, it is not surprising that several projects concerned with transportation and emission have been or are done. In this article only one of these projects (SYNCHRO-NET) was explicitly included in the evaluation in Sect. 4, based on the fact, that the article research focused on scientific articles and conference contributions. To ensure that no important tools are overlooked a third and final literature review was conducted searching the EU TRIMIS (Transport Research and Innovation Monitoring and Information System) database. Filtering all projects concerned with freight transport and multimodal transportation and extending the research by further investigation into the Horizon 2020 program.

Overall 48 projects concerning multimodal, Co-modal and synchromodal, transportation as well as transshipment were found. After reviewing 108 white paper, reports and working packages and excluding all projects not concerned with freight transportation planning, more than one modality type and calculating or presenting sustainability, modal shift or emission-reduction figures. In the end two projects and one tool are added in addition to Giusti et al. (2019a) to answer RQ3.

The focus on planning low-emission multi-modal transportation chains is only inherent in some projects one of them is the development of the Global Logistics Emission Council (GLEC) framework. It offers a step-by-step description for emission accounting for different kinds of companies. Dividing the calculation of emission into 3 Scopes. All scopes combined lead to the overall GHG-emission. Some companies are already orienting their emission accounting on the GLEC-Framework. (GLEC 2019).

Mostly it is an orientation for emission accounting and an approach for reaching a standardised method of emission accounting in supply and transportation chains. GLEC builds on existing standards used for emission calculation in transportation like the GHG-protocol (Greenhouse Gas Protocol 2021) or the DIN EN16258 (Schmied and Knörr 2013) standard. Davydenko et al. (2014) pushed the development of a global standard, the ISO 14083 which is currently in the preparatory stage of development (ISO). The limitation of GLEC lies in the missing descriptions for the usability for low-emission planning. The possibility to use the accounting method as basis for planning decisions is recommended and described. The development of tools or frameworks is listed as further research area (GLEC 2019).

As a real tool for emission calculation the EcoTransIT is to be named which is based on the GLEC-Framework. (EcoTransIT world 2021). A main concentration of EU projects on emission reduction seems to be on the development of emission calculation tools. A detailed overview about these calculation tools has been made and published from the Smart Freight Centre (2019) as part of the LEARN-Project. It lists 7 emission calculation tools for freight transportation, freight transportation and warehousing or transshipment and warehousing. LogEC, TK'Blue and VGP are only available for members, BigMile, Green Router, Reff Assessment Tool and EcoTransIT are available for customers based on a contract with the development company. Only a simple version of EcoTransIT is available on an open access Website (EcoTransIT world 2021) which limits the usability.

5 Discussion

Three questions are to be answered in this research. First the answer to RQ1: "Which main characteristics can be assigned to the different modality concepts? With a special focus on synchromodality." is discussed. The first conclusion to be drawn from the identified characteristics is, that all studies are based on the same concept of multimodality which makes the shift of goods between different vehicles a key characteristic of all concepts. This is consistent with the findings of SteadieSeifi et al. (2014) who state that all modality concepts could be defined as multimodality concepts and extended with new characteristics. Additional key characteristics for intermodality are the use of one loading unit and door-to-door transportation. Co-Modality is more difficult to define. Efficient mode use and environmental orientation (as combination of sustainability concerns and modal shift) can be assigned as key characteristics.

A more extensive research was made for the latest concept synchormodality. In the definitions of synchromodality the number of mentioned characteristics is vast. Therefor the main characteristics of synchromodlity are difficult to determine. This could be due to the fact, that synchromodality is the only concept not developed in research but as business concept. Some of the characteristics in Table 2, 3 and 4 are now further aggregated. Cooperation also encloses the need for a LSP or/and the definition of pre-defined KPI's. Environmental orientation is seen as a combination of sustainability, modal shift and emission reduction. With parallel mode use, a-modal booking and flexibility 5 additional characteristics could be circumscribed.

The answer to RQ1 is the groundwork for RQ2: "Which modality concepts support environmental oriented planning?" Overall, it can be concluded that recent articles show a higher orientation on modal shift and emission reduction for all modality concepts. For the concepts of multimodality and intermodality, articles concerned with emission reduction exist, as can be seen in Table 5, but still it could not be identified as a main characteristic in Sect. 2. For Co-Modality the question is more difficult to answer. It is the only concept in which the basic definition of EC already includes the aim of sustainability and environmental orientation. But the research in this area is rather limited and no article could be found focusing on emission-reduction, so even though emission reduction is part of the definition no defined statement can be made. Synchromodal transportation is the only concept where the assigned characteristics and a great part of the research is concerned with environmental oriented planning. It is therefore declared as the only concept which designed for environmental oriented planning.

Sections 3 and 4 are the basis to answer RQ3: "Can different courses of action be derived for emission-low planning of transportation chains for different users?" First of all, most of the time modal shift was mentioned as strategy for environmental protective planning in the articles, but often without a course of action, meaning without a detailed description on how to achieve a modal shift. Just naming the strategy and focusing on just one strategy will not be enough to realize low-emission transportation chains. But maybe helpful tools for different planning problems and actors exist which can offer courses of action for low emission transportation chain planning.

The number of identified models and tools with the aim of low emissions transportation planning was rather narrow and as discussed most of them have limitations which are difficult to overcome. A helpful framework on a non-operational level can be found in the GLEC-framework which then would need to be adapted to a planning tool or the like. The most promising tools are developed by EcoTransIT world (2021), Farahani et al. (2018) and Giusti et al. (2019a). EcoTransIT world (2021) offers an available tool for emission accounting in a multi-mode transportation chain, but no automatically comparison is possible. EcoTransIT and similar tools can be important parts of overall low emission planning tools on an operational basis but do not offer planning options or courses of action on their own. Farahani et al. (2018) and Giusti et al. (2019a) are two options to solve an emission oriented SCD problem. SynchroNet also solves routing and re-routing problems. For various planning problems also concerned with transportation like SND or FP no available, accessible or usable methods or tools exist. Further research is needed to identify different courses of action for emission reduction strategies which can be used by different actors and address different planning problems.

6 Conclusion

Modality concepts can be difficult to distinguish at times, based on the fact, that they all built upon the basic concept of multimodality. Still distinct key characteristics for inter-co- and synchromodality could be identified. These key characteristics are an orientation for managers which concept fits their planning intention best, it has also been shown that every concept can be extended with additional characteristics by the user if needed to solve a specific transportation planning problem.

All concepts focus on the strategy of modal shift for environmental oriented planning, the environmental benefits are therefore similar and further steps need to be taken. Emission-reduction should be one of the key features of all planning in transportation for the future. As mentioned before an emission-oriented direction is already visible in research. The connection from research to practice needs to be brought in focus. It should be easier to get access to information, methods and tools for the user especially for emission-oriented planning. For RQ1 and RQ 2 it can be concluded that the key characteristics of the concepts give an orientation for the right concept to solve the problem but especially for low emission planning the vital decision is not which concept is chosen but how the concept is used.

Further research directions include the definition of standardises courses of action to implement emission reduction strategies like the modal shift strategy but also further strategies. These courses of action need to be useable for different decision makers. Additionally, an overview about these courses of action as well as low-emission planning processes, methods and tools should be on hand for decision makers in transportation chains. This could be provided in a standardised, open access and adaptable way by developing a reference model serving as a handbook for low-emission decision making in transportation chain planning.

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Towards Sustainable Freight Transportation - A Risk Framework Application to Truck Platooning

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Abstract. National and international authorities, specifically the European Commission, have set challenging targets for the reduction of carbon emissions. Transportation is an important lever for emission reduction due to the share of over one quarter of the total emissions in Europe. In particular, road transportation, which accounts for 75% of the transported goods, offers saving potential. The improvement of traffic flows has been identified as a field for prospective energy consumption reduction, among others, by automation, especially platooning. Truck platooning has been discussed from a technical perspective, as well as with a focus on advantages. Risks have so far been included by some authors but not examined holistically. To close this research gap, a case study was conducted in this article to investigate the risks associated with platooning. For this purpose, eight semi-structured interviews were conducted with experts from logistics service providers and truck manufacturers. Eighteen risks were identified and classified into six dimensions (economic, social, legal, IT-related, technical, and ecological), resulting in a risk framework. The results extend the research on truck platooning by clarifying the risk perspective of this concept and provide a starting point for a discussion on the feasibility.

1 Introduction

In recent years, governments and international authorities have set challenging targets for the reduction of carbon emissions; in particular, the European Union has established a goal of reducing carbon emissions by 60% until 2050 (European Commission 2011). The transport sector is considered as an important lever, as it accounts for a large share of greenhouse gas emissions of approximately one quarter in Europe, and this proportion has increased continuously over the past decades (European Environment Agency 2020). With more than 75% of the transported goods volume in Europe and nearly 80% in Germany, road transport has a central role in freight transportation (Eurostat 2020) and therefore also in the sustainable development of the carbon emissions of the entire union. In addition to vehicle improvement measures, the improvement of traffic flows has been identified as a field for potential energy consumption reduction, among others, by smoothing speed and avoiding stops as well as automation, especially platooning (Krause et al. 2020). To align with these targets, the automotive industry

U. Buscher et al. (Eds.): *Logistics Management*, LNLO, pp. 213–228, 2021.
https://doi.org/10.1007/978-3-030-85843-8_14

has undergone considerable change in recent decades. Automated driving systems have developed rapidly, with automation technology being capable of influencing not only profitability (for example, through improved fuel efficiency; Turri et al. 2017) but also traffic flow efficiency (Ghandriz et al. 2020).

Commercial vehicles contribute to these innovative developments. Truck platooning (TRP), the so-called electronic drawbar, could revolutionize the future of transportation (Zhang et al. 2020). Platooning describes a vehicle system that provides the coupling of up to three trucks through internal vehicle communication, whereby the direction and speed are determined by the leading vehicle (Ihlow 2019). The potential of this technology is to increase the efficiency of the vehicles through the resulting slipstream effect and to effectively use the available space in the transport infrastructure (Ihlow 2019).

Individual scientific areas have already been researched independently. These scientific areas include automation technology with its levels of automation (Pütz et al. 2019), as well as autonomous driving in general (Maurer et al. 2015). Castritius et al. (2020) considered the public acceptance of semi-automated truck platoon driving. Thus far, platooning has only been explored to a limited extent in the existing literature due to its novelty, and it is mainly associated with benefits such as increased road safety and the potential to reduce fuel consumption and CO_2 emissions (Aki et al. 2014; Le Wang et al. 2014; Martínez-Díaz and Soriguera 2018).

However, the higher levels of assistance systems also increase the challenges of automated vehicles, which may entail significant risks (Elgharbawy et al. 2019). A few studies have already investigated TRP, taking into account the risk aspects. For example, Hardy and Fenner (2015) explained the risks from a technical perspective, focusing on autonomous vehicle technologies. Rahman et al. (2018) analyzed the improvement of traffic systems and the reduction of crash risk through connected vehicles with and without platooning. In another study, Rahman and Abdel-Aty (2018) examined the risk indicators for safety evaluation. Sheehan et al. (2019) developed a cyber risk classification framework for connected and autonomous vehicles, but one that is not focused on platooning.

To the best of the authors' knowledge, research that provides a comprehensive overview of the risks of TRP is lacking. Hence, this article aims to identify and subsequently evaluate the risks associated with TRP to close this research gap. For this purpose, a multiple case study is conducted, including semi-structured interviews with eight experts from the commercial vehicle industry and the logistics sector; furthermore, numerous secondary materials are utilized.

The study is organized into several sections. Section 2 includes the theoretical background, introducing platooning, and risks for TRP. Section 3 is focused on the methodological approach. In Sect. 4, the results of the expert interviews are subsequently presented and classified into six risk categories. The most relevant results are then listed and discussed in Sect. 5. In the final section, the conclusion ispresented.

2 Theoretical Background

2.1 Platooning

Platooning pertains to the automatic train formation of trucks, whereby highly automated vehicles follow one another within very short intervals at high speeds (Martínez-Díaz and Soriguera 2018). The first attempts at platooning were already made during the Partners for Advanced Transit and Highways (PATH) program in 1997 (Martínez-Díaz and Soriguera 2018). In various tests in 2009 and 2010 at a speed of up to 80 km/h, distances of 10–15 m between vehicles have already been achieved (Aki et al. 2014).

In contrast to cooperative adaptive cruise control systems, platooning automates both longitudinal and lateral control, that is, "*the separation between vehicles remains constant and does not vary with vehicle speed*" (Nowakowski et al. p. 5). If an obstacle appears in front of the lead vehicle, the control algorithm is activated by sensors (Aki et al. 2014). These systems carry out a control to initiate a lane change or other evasive maneuvers, whereas "*the goal of longitudinal platoon control is to ensure that all the vehicles move in the same lane at the same speed with desired inter-vehicle distances*" (Le Wang et al. 2014, p. 606).

According to Martínez-Díaz and Soriguera (2018), the focus of TRP is on driver safety and comfort but its aim is to also improve the overall efficiency through environmentally friendly driving. However, many doubts about this technology persist, especially regarding a mixed-traffic environment. Additionally, platoons must share the highway with conventional vehicles, which has a negative impact on the infrastructure. Finally, the need for highly automated vehicles is to ensure protection and security and, at the same time, the use of data for all without opening the interface to hackers or terrorists (Martínez-Díaz and Soriguera 2018).

2.2 Risks of Truck Platooning

From an economic point of view, one of the main risks with vehicle automation is that consumer markets will continue to grow (Pająk and Cyplik 2020). This increase has resulted in the expansion of road freight transport, which puts pressure on logistics service providers (Pająk and Cyplik 2020). The most problematic issue is probably the social level because automation technology is expected to change the profession of the drivers (Sheehan et al. 2019). In this context, professional drivers could be at a disadvantage compared to this promising technology, as automation can induce drivers to feel under-challenged (Hjälmdahl et al. 2017). Furthermore, the risk that the driving task will generally be oversimplified is present, "*resulting in boredom, cognitive underload, and eventually increased drowsiness and loss of situation awareness*" (Hjälmdahl et al. 2017, p. 2). This scenario can ultimately increase the risk of the truck driver's ability to recover (Hjälmdahl et al. 2017). In addition, the gradual decoupling of humans from the actual driving task can have serious consequences (Pütz et al. 2019). In particular, the system may return the responsibility of driving in potentially risky and urgent situations to the individual (Pütz et al. 2019). As vehicles communicate via wireless connections, high technical demands are placed on them (Kaur and Rampersad 2018). Any failure of components or sensors can have devastating consequences and, in the worst case, cause a collision or even a fatal accident (Kaur and Rampersad 2018). The risk of traffic disruptions and interruptions is also present (Kaur and Rampersad 2018). In the area of information technology, highly automated vehicles entail above all the risk of software-related security flaws, which become apparent, for example, through "*car hacking, remote access, remote control of the vehicle, computer virus's malware*" (Kaur and Rampersad 2018, p. 89). According to Pütz et al. (2019), the undertaking of cyberattacks on-road vehicles is not yet commonplace, but the interfaces in the vehicles can be targets for attack. In this case, wireless connections, whether short or long range, can serve as access points for external cyberattacks. The consequences of external interventions can make themselves felt, for example, in the form of business interruptions, which can have financial consequences for the affected company (Pütz et al. 2019).

Networked driving also presents manufacturers with legal challenges, for example, the potential risk from the obligation to monitor products, which results from the implementation of safety-relevant actions by the system (Pütz et al. 2019). Consequently, the algorithms must be adapted by the vehicle manufacturer based on input data to meet the legal requirements (Pütz et al. 2019).

3 Research Method

The aim of the study is to identify the risks involved in the operation of TRP. As this field of knowledge has not been studied extensively thus far (Larsen et al. 2019), case study research was conducted (Yin 2018). At a high level, the study followed the risk framework concept proposed by Birkel et al. (2019); at a micro level, it theorized in a grounded inductive approach (Birks 2013). Several measures were applied to ensure validity and reliability during the research process (Yin 2018).

In the current study, a multi-stage sampling approach was used for selecting the cases. TRP is a novel phenomenon from a management perspective; thus, adopting a broad approach was important to capture the multiplicity of how TRP is associated with risks. To deepen the understanding of the potential risks, initially the key players in TRP were identified, namely logistics service providers and the commercial vehicle industry. Subsequently, the potential companies in these two sectors were determined. In selecting the companies, attention was paid to heterogeneity to include as many perspectives as possible. In addition, the focus was on companies headquartered in Germany.

Theoretical sampling was used for the selection and analysis of cases (Yin 2018). Therefore, eight semi-structured interviews were conducted between June 2020 and July 2020. Table 1 gives an overview of the firms and their sizes, as well as the interviewee's position. The selection of the companies themselves was based on their specialization in automation or road freight transportation.

Semi-structured interviews were used as the primary data source. Interviews were conducted in person, by telephone, or via an online meeting tool, and they lasted between 30 and 45 min. The interviews were guideline-based and the questions were asked variably. These interview guidelines included a brief thematic introduction based on the scientific literature. The interview was divided into three parts. The first part consisted of personal information such as the current position and the general state of knowledge on the research topic. In the second part, the research context underpinning this paper was

Table 1. Overview of interviewees

#	Interviewee	Perspective[a]	Employees[b]
1	Head of Autonomous Driving	(1)	10,000–100,000
2	Development Manager Automated Driving Functions	(2)	10,000–100,000
3	Managing Director	(1)	<100
4	Head of Import, Export and Customs	(1)	<100
5	Product Manager Alternative Fuels and Sustainable Transportation Solutions	(2)	10,000–100,000
6	Managing Director	(1)	<100
7	Project Manager Automated Driving	(2)	10,000–100,000
8	Press Officer Truck	(2)	10,000–100,000

[a]Classification as (1) logistics service provider or (2) truck manufacturer
[b]For reasons of confidentiality, a range and not an exact number is provided.

explained to the experts: (1) Germany as the geographical object of consideration; (2) long-distance traffic on highways; (3) fully automated platoon (i.e., drivers are present in leading truck and following trucks, but they intervene only in case of emergency) (Hartwig et al. 2020); and (4) organizational form of a coordinated platoon (i.e., different subsystems possible in the platoon) (Hartwig et al. 2020). Finally, in the third part of the interview, the respondents were asked to give their detailed opinion on the risks they would expect to face in connection with TRP. All the interviews were tape-recorded, transcribed, and returned to interviewees for amendments and corrections. In addition, various secondary data sources were used for triangulation and validation.

The analysis started after the data collection was completed, and it consisted of two main steps. The within-case analysis allowed for understanding each company's approach in detail, whereas the across-case analysis served to identify common patterns between cases. A systematic coding procedure was used for data analysis, in which the collected primary and secondary data were analyzed by two researchers in three consecutive coding cycles (Corbin and Strauss 2015). In the open coding cycle, all the interview transcripts were independently assessed and coded line-by-line with the support of MAXQDA qualitative data analysis software. In keeping with the constant comparative method, new occurrences in coding subsequent interviews were regularly cross-checked against occurrences in earlier interviews (Corbin and Strauss 2015). Codes were then consolidated into a common coding scheme. Both researchers conducted this process iteratively, discussing and further adjusting the codes until a complete consensus was reached. Axial coding was then applied, which is characterized by an alternating inductive and deductive reasoning pattern. By comparing and identifying relationships between codes, the aim was to understand the underlying phenomenon (Corbin and Strauss 2015). Although an improved understanding was gained with each iteration, the interview material was repeatedly returned to match and verify new findings. The final step was to use selective coding to link the categories to our research question. The goal was to identify core categories to which the categories identified in axial coding were systematically linked (Corbin and Strauss 2015).

4 Results

The study revealed six risk dimensions: *economic* risks, *social* risks, *legal* risks, *IT-related* risks, *technical* risks, and *ecological* risks. The risks dimensions are classified into 18 sub-categories that are involved in the operation of TRP.

4.1 Economic Risks

Finance

The experts considered the financial aspects to be the major risk in the economic dimension. They emphasized that the development of platooning is associated with high costs, whereby the market launch prices, in particular, must be considered. The resulting high purchase prices represent an obstacle that cannot be compensated for even by aerodynamics or alternative drives, causing difficulty for freight forwarders to achieve efficient cost savings. State subsidies could be a solution, but the experts were unsure about the specific benefits that the state would expect and whether the state would indeed support TRP financially. Additional costs are also an increased risk (e.g., due to detours, expensive interface programming, system failures, defects, or damage).

Deployment of Truck Platooning

The experts also identified the implementation of TRP as a possible risk. According to the interviewees, platooning leads to higher economic costs for the carriers, as the issue of whether and how platooning can be used sensibly is presently unclear. In addition, the experts believed that platooning was only used on straight routes and far away from highways, and that the truck driver must intervene.

Vehicles

The vehicles themselves also influence platooning by their equipment, load, and speeds. As the vehicle equipment of each manufacturer is different, the problem may arise that the vehicles forming the platoon are not designed for this configuration. The decisive factor in this situation is engine power because an underpowered leading truck will slow down the following vehicles, or underpowered trailing vehicles will be incapable of maintaining the speed. In these cases, the efficiency of the entire platoon is reduced. The loading similarly affects the platoon because a large difference in load also implies different speeds on uphill and downhill gradients. This situation results in break-up maneuvers, as the speeds in the train can no longer be maintained.

Ambient Traffic

The impact on the surrounding traffic is difficult to assess, whereby the volume of traffic and the length of the platoon are decisive. The problem with excessive traffic with many heavy goods vehicles is evident in some regions of Europe. An equally problematic matter is the length of the highway sections on which platooning is to transpire, as these highway sections are considerably shorter in Central Europe than in Northern European countries. These aspects result in the limitation of the platoons to a few vehicles, as already one column of three trucks is nearly 100 m long. Platoons become problematic for surrounding traffic if they block entrances or exits. For this purpose and for reasons of efficiency, no more than three vehicles should form a platoon so that it is not disturbed by other traffic participants. Other vehicles that nevertheless thwart the platoon may result in the technical systems being switched off, thus reducing the efficiency. Another economic risk is the proliferation of truck convoys. In the worst case, no basic fleet of vehicles is capable of platooning, which hinders the formation of platoons and leads to this technology being forgotten.

Road Infrastructure

A further economic risk highlighted by the interviewees is the lack of road infrastructure for TRP. The issue of whether a dedicated infrastructure (i.e., a dedicated road lane) for platoons will become available remains unclear thus far. In this case, the platoons and surrounding traffic could run without interference; however, the implementation in Europe is complicated. Consequently, platooning cannot be fully developed ecologically and economically due to the lack of independent infrastructure. In addition, highway bridges are characterized by a static design, as they are only designed for specific payloads. The short distances between trucks in the platoon could overload the bridges and increase the risk of collapse.

4.2 Social Risks

Technology Acceptance

The deployment of platooning must also consider social aspects, particularly the acceptance of the technology by professional drivers and society in general. Although the respondents stated that such systems only serve as support, they also emphasize that drivers feel patronized by the technology and thus resist it. The public may also have concerns about the concept, as they will have to directly interact with the platoons as traffic participants when TRP is introduced. A unique role is given to the driver in the leading truck. He has the highest responsibility, as he must initiate maneuvers and pay attention to the traffic. Nonetheless, the drivers in the following vehicles must also trust this individual and the technology, as they have no chance to intervene when the distances are so short.

Changing Job Profiles

Platooning will also change the driver's job description, whereby the change will start from an active job and lead to a supervisory one. The matter of whether a driver will sit at a control panel for up to 10 h to monitor driving activity is uncertain, as only intervention in an emergency reduces the attractiveness of the profession. Moreover, the distribution of roles would change, as the driver in the lead vehicle would be active, whereas the other drivers would only be passive in road traffic.

Unemployment

People can be displaced by technological advances, as technology is often faster, cheaper, and possibly also faultless. According to statements, platooning can result in a reduction in jobs, especially on long-distance routes. The main problem is the shortage of skilled workers in the logistics sector in the area of professional drivers, whereby the challenge consists of finding and retaining qualified personnel. Introducing partially and fully automated platoons will be possible in the long term to replace the driver with technical systems.

Remuneration of Professional Drivers

The remuneration of professional drivers is also essential, as platooning will primarily increase the responsibility of drivers in the lead vehicle. An assessment must also be made about how profitable the drivers in the following vehicles are; similarly in this case, the technology must be remunerated accordingly. The matter becomes problematic if long distances are reduced or eliminated, thus minimizing the salaries of the personnel in the distribution. Another effect of increasing automation may be that expense rates cannot be paid in full.

Accidents

Road accidents are mainly caused by fatigue, crashing vehicles, or negligence, the latter being the consequence of turning errors. The risk of an accident to truck drivers is increased by long monotonous stretches of road, making them either unfocused or careless. In the platoon, the damage potential increases many times over, and automation results in the loss of the actual driving task and to drivers being distracted. Highly automated driving systems also encourage negligent behavior and reduce reaction awareness, because of which drivers no longer intervene appropriately. Other traffic participants also influence truck traffic, as they often move into the TRP, causing accidents. The damage potential increases if the driver or system does not react appropriately. Highway exits are also hazardous, where traffic participants force their way between the platoons, which in the worst case leads to uncontrollable braking maneuvers, and the vehicles are involved in an accident.

4.3 Legal Risks

Legal Framework

Regarding the legal risks, the experts highlighted the general lack of a legal framework for platooning that is also internationally valid. They noted that the difficulty is developing a universally valid legal framework so that the implementation of this technology can occur soon. The legal framework referred to must also have international validity. Some industrialized nations are currently testing TRP independently, resulting in different technological approaches and various government regulations. This matter is also associated with the problem that pilot projects have only been conducted with special permits, and the legal aspects have been neglected. In addition to a basic legal framework, detailed aspects must be defined, such as regulating minimum distances within the platoon. Current distances in platooning projects are usually far below the prescribed minimum distance. The uncertain situation regarding the conclusion of a unified legal framework also increases the time that needs to be invested in it. This process must be initiated at the political level, and such effort may take several years, depending on its scope. At the European level, the process may even take between eight and 10 years.

Liability

Liability is another aspect that must be considered in road freight transportation, as certain legal requirements stipulate that the goods must be packaged safely for transport. In practice, however, this packaging cannot be guaranteed, as the goods are often damaged. In road freight transport, personal injury can also occur as a result of an accident. At best, platoons are made up of vehicles from different companies and cargoes, with the latter being supplemented by diverse cargo systems with quality differences in terms of composition and packaging. A legal provision on liability for damage is likewise necessary once the vehicles are on the train, as this stipulation has been completely lacking. Jurisprudence must determine how the insurance companies decide in the case of accidents involving platoons and how the course of the accident can be traced.

4.4 IT-Related Risks

Network and Data Transmission

With regard to IT-related risks, the experts considered the network and data exchange as a potential risk. The establishment of a network infrastructure is particularly important because platoons are coupled by a local network connection. The networks generally cover a wide area, but the interviewees expressed concern that dead spots or similar issues have a negative impact on the networks and that the probabilities of network failure or the stability of the system cannot be accurately assessed thus far. In addition, some experts observe problems not only with the networks but also with the transmission of sensitive data. In particular, data protection (i.e., data transmitted on the air interface) must be encrypted and signed. The end-user must be guaranteed that the data are secured multiple times and that the information from the network connection is matched and verified with the information collected by sensors. Furthermore, information exchanged between vehicles on the air interface must be safeguarded by a security mechanism.

Cyberattacks

Experts identified a second IT risk in cyberattacks, as highly and fully automated systems are popular targets for hackers. The risk is that the number of cyberattacks will increase with the proliferation of automated vehicles. The more platoons that will be on the road, the higher the risk of attacks from outside. Similarly, platoons open an interface via the vehicle's port that could allow hackers to penetrate the system. The vehicles are equipped with a local WLAN network installed around the trucks, making them an ideal target for attacks to pursue commercial interests. The economic damage in the event of an attack would affect both logistics service providers and the entire supply chain. The time during which the vehicles are blocked is crucial, resulting in supply bottlenecks that would have a macroeconomic impact.

4.5 Technical Risks

Automated Systems

Automated systems are primarily intended to increase safety, but a higher degree of automation also increases the risk of malfunctions. Due to technical errors, these systems could, for example, steer a train in the wrong direction, which would also endanger other road users. The interviewees stated that the vehicles often simultaneously display error messages, which can also unsettle the driver. Even small things can have a negative impact on technical functions and cause major system failures. Professional drivers are required to intervene at the accident level, which is impossible with platooning due to the small distances involved. If the systems fail here and, for example, the vehicle in front brakes accordingly, these situations can no longer be controlled by the driver.

Cross-manufacturer Functions

With the large number of heavy-duty vehicles from different manufacturers, they must be able to form a platoon. In this respect, logistics service providers expressed concerns, as they fear that this approach is not possible. In the previous tests, trucks of the same manufacturer, which were technically identically equipped, formed a platoon. Carriers are concerned that the implementation in a mixed fleet will be too costly and that platoons will not occur without the unity of vehicles that are capable of platooning.

Weather-related Disruptions

Vehicle systems are also adversely affected by the effects of the seasons. Accidents on slippery or wet roads are more frequent, but as soon as drivers rely on the technical components in these situations, the severity of accidents can increase many times over. According to current statements, the platooning systems are switched off in case of poor weather, as the functionality of the network connection is negatively affected. Furthermore, the global positioning system or the vehicle's sensors can be compromised, causing accidents resulting from altered braking distances.

4.6 Ecological Risks

Exploiting Potential

Respondents expressed some concerns about potential ecological risks. However, one concern is that, according to current studies, platooning does not come within the scope that developers expected at the beginning of the test phase in terms of fuel reduction efficiency. Furthermore, one interviewee recognized the difficulty of, for example, not being able to properly recycle the disposal of accumulators, batteries, and the like that could be used for these systems. As mentioned in one of the previous sections, a unified road network for the trains is lacking; thus, the system is currently not as efficient as it could be. Energy is needed accordingly to build a new network. The result is that the energy balance for the creation is higher than the benefit to be obtained in the end.

5 Discussion

The results of the study lead to a risk framework consisting of six dimensions and 18 sub-categories. The multiple aspects, including *economic*, *social*, *legal*, *IT-related*, *technical*, and *ecological* risks, are illustrated in Fig. 1. The further breakdown of the dimensions into sub-categories highlights the wide variety of risks related to TRP. In the next section, the case study results are reflected and discussed with the existing literature.

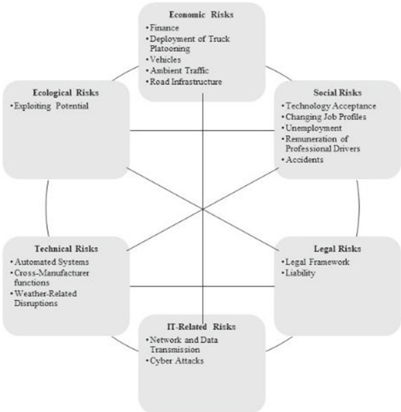

Fig. 1. Risk framework to truck platooning

With the introduction of a new technological concept, such as TRP, the cost factor is assumed to be an essential aspect. TRP can reduce costs due to reduced fuel consumption (Bhoopalam et al. 2018) and labor costs (Pająk and Cyplik 2020); however, it is countered by high acquisition costs, costs for retrofitting the existing fleet, and additional costs such as expensive interface programming and system failures. In addition to the aspect that the carrier's fleet must be designed for this technology, consideration should be given to how platooning can generally be implemented in the logistics process of a service provider. In the literature, reference is made here to platooning service provider (Janssen et al. 2015), which creates schedules based on the trip data of various vehicles (Bhoopalam et al. 2018). The conditions under which platooning can be used sensibly should be considered as well, as the concept can currently only be implemented on straight highway routes. As Duerr (2019) underscores, highly automated trucks will initially only operate between predefined areas or junctions.

Another challenge is the interaction with other traffic participants. The increasing traffic volume, which is mentioned by Pająk and Cyplik (2020) because of the rising consumer markets, will have a major influence on the platoons. The efficiency of TRP will only increase the longer the vehicles can run in the appropriate mode, but the potential savings will decrease as soon as other traffic participants cross the platoon and the system shuts down. Furthermore, Wang et al. (2019) believe that problems caused by other traffic participants will mainly occur at entrances and exits. This aspect is also associated with the formation of platoons, which is recognized as a challenge both by the experts and in the literature (Bergenheim et al. 2010). The possible problems with other traffic participants can be solved by adapting the road infrastructure. However, further costs are to be expected in this case (Janssen et al. 2015). In addition, this infrastructural adaptation has certain limitations, including on- and off-ramps of the highways and the design of bridges (Seidenova et al. 2020), for which solutions are currently unavailable.

A further problem is the structure of the platoon. A leading truck is typically at the first position of the platoon, followed by other trucks (Bhoopalam et al. 2018). Given some disadvantages for the leading vehicle, such as less fuel savings, no freight forwarder will voluntarily accept this role. This matter also raises the question of which trucks are involved and in which order (Bhoopalam et al. 2018).

From a social perspective, society's acceptance of new technologies is imperative, and in the case of platooning, a distinction must be made between two social categories: on the one hand, the drivers, whose job is to be simplified by platooning, and on the other hand, society in general, which is mainly confronted with it in road traffic. Another essential step is to communicate to the public that a technological innovation such as TRP can contribute to the overall safety and environmental protection, as this matter is primarily the predominant problem on highways (Seidenova et al. 2020). Therefore, vehicles must be equipped with appropriate software that is mechanically and electrically reliable (Maurer et al. 2015). Elgharbawy et al. (2019) also agree with the statement that the human driver is not displaced by automated driving systems, as the driver can recognize and assess unclear driving situations better than technical systems. In the long term, the changes are also likely to pose a problem for truck drivers. Automation fundamentally changes the job profile of drivers and brings implications not only to their pay but also to their future professional practice. Pütz et al. (2019) already argued that the decoupling of humans from their driving tasks could have serious consequences. Hjälmdahl et al. (2017) similarly noted that the impact on the professional driver can be far greater and can be felt, for example, through underutilization. Most drivers are passionate about their profession; however, the experts were also skeptical about whether drivers would feel more comfortable in a supervisory role than in the task of actively intervening in road traffic. Another prevailing opinion is that technology could gradually displace humans from the workplace and take their place (Kilcarr 2016). Although TRP will reduce the number of human errors (Bhoopalam et al. 2018), a questionable issue is whether the technology will be as reliable as initially assumed, as technical systems can be disrupted by external influences. Even if many traffic accidents are due to human error (Duerr 2019), the problem remains that the more technology is installed in a vehicle, the more potential for error is existent. According to Bhoopalam et al. (2018), technologies will instead increase the comfort of truck drivers.

One of the major problems related to TRP is the legal situation, as previous studies could only occur under special permits. According to the experts, a generally applicable legal framework for this technology is still completely lacking. The legal framework must contain general provisions such as infrastructure, minimum distances, and liability in the event of damage and should have international validity. Additionally, the unclear legal situation is repeatedly mentioned in the literature (see, e.g., Janssen et al. (2015), Bhoopalam et al. (2018), or Bridgelall et al. (2020)) and is in line with the findings of the case study. From a legal standpoint, however, liability in the event of damage also plays a significant role, whereby both personal injury and body damage, as well as property damage, must be considered. Maurer et al. (2015) similarly believe in the importance of clarifying who is liable in the event of damage to goods or vehicles.

Another vital aspect of platooning is data security; as platoons become more widespread, they could be the potential targets of cyberattacks, and sensitive data could be filtered out. This factor is mainly due to software-related security vulnerabilities (Kaur and Rampersad 2018) resulting from the interfaces of vehicles (Pütz et al. 2019). The objective must be to build a secure network system that is resistant to any type of attack. In addition, platooning needs to ensure data transmission reliability, as radio interference is common in more rural or mountainous areas.

From a technical perspective, the risks are mainly related to the technology's failure and the associated risk of accidents. According to the experts, this case can manifest itself primarily through the failure of technical systems and the vehicle turning into surrounding traffic, which is also confirmed by Kaur and Rampersad (2018). Furthermore, the experts clarify on fail-safety in the face of external influences such as weather conditions and the need for technical interfaces to connect vehicles from different manufacturers in the platoon.

The analysis of the interviews also revealed that the lowest risks come from the ecological dimension. As mentioned in the introduction, TRP can positively impact the problem of global warming and environmental pollution. In particular, the slipstream effect can save fuel and CO_2 (Gungor et al. 2020). However, the matter of whether the desired effect will occur in practice is impossible to accurately estimate (Duerr 2019). As tests have mostly transpired under defined and optimized conditions, the issue of whether the anticipated fuel savings will be achieved under normal conditions is thus questionable (Pająk and Cyplik 2020).

6 Conclusion

Automation technology has the potential to influence road freight transportation in the long term (Krause et al. 2020). In this context, TRP has an important role. Platoons primarily offer advantages in terms of fuel and CO_2 savings, and they can also make a positive contribution to environmental protection (Gungor et al. 2020). In addition, TRP can help to increase safety on the roads further (Aki et al. 2014). However, consideration for only the opportunities of a technology is insufficient, as holistic feasibility can only be made if the risks are also taken into account. For this purpose, a case study was applied in which eight semi-structured interviews were conducted with experts from logistics service providers and truck manufacturers.

The results show that TRP is associated with risks in the *economic*, *social*, *legal*, *IT-related*, *technical*, and *ecological* dimensions. The individual risks identified for each dimension illustrate that many weak points still prevail before platooning can be deployed. The *economic* dimension reveals a significant risk potential, especially from the viewpoint of the logistics service provider. The economic feasibility of this technology should be principally mentioned in this regard. It essentially includes enormous acquisition as well as additional costs. According to the carriers, another problem is that no uniform, manufacturer-independent system has yet been developed, which is indispensable for a mixed fleet. Furthermore, the realization or implementation of the concept into the already existing road infrastructure proves to be complicated. From a *legal* perspective, logistics service providers and manufacturers agree that platooning only makes sense if a corresponding international legal decision has been made. The general acceptance of platooning among the public and the consequences for truckers are the substantial risks in the *social* dimension. This situation entails boosting people's awareness because many accidents are still caused by trucks. However, TRP will not pose a threat to professional drivers in the near future, as this technology's replacement of drivers in time is not foreseeable, which is why TRP will instead be a supporting function. Regarding *IT-related* risks, cyberattacks and a robust network for data transmission were considered as the most critical. In the *technical* dimension, the results confirmed that the reliance on an automated system is still an uncertain issue, requiring the driver for emergencies due to unpredictable ambient conditions such as the weather and other traffic participants. From an *ecological* perspective, the study confirms some uncertainty about whether the fuel savings found in field studies can be achieved under normal conditions.

The results of this study are intended to provide a baseline for further research in TRP; however, the study has some limitations. The expert sample included eight participants from logistics service providers and commercial vehicle manufacturers for a first insight into the topic. To conduct a comprehensive analysis, future studies should increase the number of experts, involve more stakeholders of TRP (e.g., policymakers, mobility solution providers, truck drivers, and research institutes), and adopt a more global perspective, given the different technologies and approaches to TRP internationally as well as other infrastructural prerequisites. Furthermore, this study only focuses on risks that are directly related to TRP. The ensuing risks arising from the use of TRP, such as the impact on traffic or the consequences for road infrastructure, are not considered and should be analyzed in further studies.

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Supply Chain Risk Management

Towards Resilient Supply Chain Structures

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Abstract. Disruptions pose a significant threat to supply chains, as their impact may have devastating consequences. As a result, the research in supply chain resilience has increased immensely over the last years. This growing research's particular focus is the kind of disruptions supply chains have to face and consequently what capabilities supply chains should inherit to be more resilient. This article focuses on the supply chain structure and investigates how resilience depends on it. Thus, a LR was conducted to identify the vulnerabilities the supply chain structure is exposed to and the strategies that exist to counteract these vulnerabilities and increase supply chain resilience. Findings show that vulnerabilities are manifold and that there is no strategy that in itself leads to supply chain resilience. It is especially crucial first to examine the supply chain structure, identify the specific vulnerabilities to the supply chain and subsequently choose an appropriate strategy.

1 Introduction

In the last decades, driven by competition and innovation, supply chains grew to global spanning networks. Outsourcing and offshoring of manufacturing and R&D activities and reducing inventories increased the interrelation between companies and the complexity of the supply chain [1, 2], which finally made these global supply chains more susceptible to disruptions [3–5]. To overcome these disruptions, supply chains need to be more resilient.

The principle of supply chain resilience (SCRES) is based on the assumption that not all disruptions can be prevented [6] what makes it necessary for supply chains to be better prepared to face disruptions and gather skills to react appropriately [7]. A supply chain disruption can manifest itself in manifold ways and rarely affects the whole supply chain, but a single or a small number of its entities. Due to the supply chain's complex relationships and interdependencies, the negative consequences then propagate through the supply chain and possibly hamper many of the supply chain's entities. For example, a supplier that is no more capable of delivering its products may damage all manufacturers that rely on its supplies, and a disconnected transportation route is qualified to bring fabrication to a complete halt. Due to these interdependencies, the severity of disruptions depends on the relation between supply chain entities and their respective flows [8–10]. Therefore, a broad branch of literature considers it crucial to adapt structure of a supply chain to increase its resilience [3, 4, 9, 11, 12].

Despite this growing research, the literature still lacks specific advice on how to change the structure to improve the supply chain's resilience. Some publications urge to

U. Buscher et al. (Eds.): *Logistics Management*, LNLO, pp. 231–245, 2021.
https://doi.org/10.1007/978-3-030-85843-8_15

re-engineer supply chains [4, 13] or highlight the relation between the number of nodes and flows and supply chain resilience [8]. Others identify capabilities supply chains should inherit to be resilient [6, 14]. However, they are rather conceptual and lack clear recommendations on how the supply chain structure can specifically be altered to be more resilient. For example. Kochan and Nowicki [14] mention the need to change the supply chain in terms of agility, visibility and redundancy. However, they do not mention in how far this can be achieved.

We here build on the concept of supply chain vulnerability which is, that apart from the impact of the specific disruption, certain characteristics of the supply chain influence how severe the whole supply chain is finally affected [2, 6, 15]. Furthermore, we focus on the supply chain structure, as the structure describes how the supply chain entities depend and relate to each other. Therefore, the paper's objectives are to (I) identify the vulnerabilities and strategies most addressed by scholars working on supply chain resilience structures and (II) study how far the found strategies attenuate the identified vulnerabilities.

The paper is organized as follows: Sect. 2 presents a short introduction to supply chain resilience and supply chain structure. Section 3 offers our research process. Section 4 contains the results towards the identified vulnerabilities, strategies, and the matching between those. Section 5 reflects how far our research could answer the research objectives, and, finally, Sect. 6 gives a short conclusion.

2 Theoretical Background

Supply chains are exposed to all kinds of risks, where risk is defined as the probability and impact of unexpected, adverse events [16]. A disruption is an event that finally leads to the realization of risk [2], as it is then observable how significant the impact is. However, the specific loss of supply chains to disruptions also depends on supply chains' susceptibility to specific disruptions, which is the concept of supply chain vulnerability [17]. The premise of supply chain vulnerability is that certain characteristics influence the impact and likelihood of disruptions [15]. For example, the loss to a supplier's failure is less severe if there is another supplier, which is unaffected by the specific disruption.

Although there is no comprehensive definition, SCRES is built on the ability to minimize the impact of disruptions [18] and refers to the supply chains ability to either lower supply chain risks or to reduce supply chain vulnerability [5]. To enhance SCRES, there are specific capabilities a supply chain should have to be prepared for disruptions, have the ability to resist disruptions, and finally react in a way to minimize the consequences [3].

A supply chain consists of different entities involved in producing, warehousing and transporting goods to fulfill customer demand. These entities are connected by the flow of materials, information, and finance. Differences in the number and kind of nodes and differences in the pattern of flows lead to different supply chain structures. For example, outsourcing production to another manufacturer or changing the sourcing from a single supplier to multiple suppliers change the flows coming from and leading to specific entities, therefore changing the whole supply chain structure. In case of a disruption, the severity depends on these dependencies as they determine which and how many other entities are affected.

In general, supply chains are designed to be cost-effective and, at the same time, increase performance to satisfy customer demands [7]. The increase in efficiency and decrease in costs leads to vulnerabilities such as a reduction in assets (supply base, manufacturing) and buffers. However, as there are risks inherent in supply chains, the structure needs to be adapted accordingly to reduce supply chain vulnerabilities and finally increase supply chain resilience. Kim et al. [9] compare different supply chain structures and conclude that they differ in how the continuity of supply chain flows is affected by disruptions. Furthermore, Scholten et al. [11] claims the importance of the subject as by altering the supply chain structure, the impacts of disruption can be lessened or prevented at all.

To increase SCRES by altering the supply chain structure, it is now crucial to first examine what specific vulnerabilities are inherit in a supply chain, as these vulnerabilities then need to be reduced. For this, it is then necessary to identify strategies that exist in the supply chain context and furthermore link certain strategies as being able to reduce certain supply chain vulnerabilities.

3 Methodology

To avoid bias and guarantee rigor, we conducted a literature research following [19] to review existing literature on supply chain structure. To cover interdisciplinary literature from different types of sources and disciplines, this study considered the databases Scopus and Web of Science. We furthermore incorporated both contributions from journals and conferences to even widen the range of sources. We limited our search to publications written in English.

To select appropriate literature, we defined relevant keywords as search criteria. As we focus on the supply chain structure and entities and flows are elements of the supply chain design, we incorporated both structure and design in the search term. Also, re-engineering is a term often used in relation to changing the supply chain structure. Therefore, the key phrase we used was: *"supply chain*" and "resilien*" and (*structur* or *design* or *engineer*).* After deleting duplicates, we finally identified 1258 publications. We subsequently first examined title, abstract, and the publications' defined keywords to determine whether the publication addresses the stated research's focus. As a result, this finally led to 88 papers and additionally 11 papers found through forward and backward search. The total 99 publications were read to identify, on the one hand, the most mentioned vulnerabilities and, on the other hand, the most applied strategies to improve supply chain resilience by altering the supply chain structure.

After identifying the vulnerabilities and strategies mentioned in each of the identified 99 papers, we categorized them into different groups and investigated how far the vulnerabilities influence the supply chain structure in case a disruption occurs. Furthermore, we analyzed how strategies change supply chain structure to lower the negative consequences disruptions have on the supply chain. Finally, we revise if there is a match between vulnerabilities and strategies and if, based on the structure, strategies can be deduced.

4 Results

As depicted in Fig. 1, the number of publications continuously grows from the beginning of 2004, with a stronger increase from 2014. Furthermore, the number of publications in this area nearly doubled from 2019 to 2020. For one part, this is due to the challenges arising from Covid-19. On the other hand, this visualizes a clear trend in research and underlines the importance of this research area.

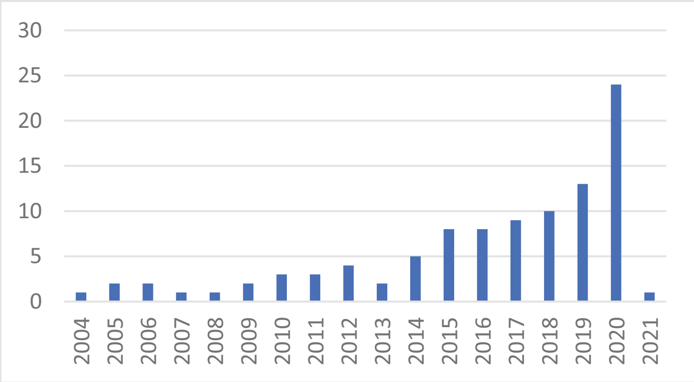

Fig. 1. Distribution of publications over the years

We next divided the literature based on the focus they have: vulnerabilities, Table 1, and strategies, Table 2. Of the 99 papers we considered, 55 articles mentioned vulnerabilities, and 90 considered strategies—finally, 44 of those considered both vulnerabilities and strategies to counteract them.

We then grouped the articles in more detail, subject to the kinds of vulnerabilities and strategies mentioned.

4.1 Vulnerabilities

Table 1 subsumes the collected vulnerabilities found in the identified publications, sorted from highest to lowest mentioned. The vulnerabilities target either single nodes (critical node), single connections (interruption of transportation), the overall topology of the supply chain structure (high redundancy, high regionalization, lack of information) or properties of the nodes, connections (extended lead times, geographical risks, lack of stock), which can be analyzed structurally by using weighted nodes and links.

The most named vulnerability (40 out of 99) is the dependence on a *critical node*. Here a node is deemed critical when it either is a *bottleneck* [20], an *important node* in terms of production volume [8, 21] or the number of connections [22, 23], or a *single supplier* [24–26] or *single customer* [15, 27]. This can be explained by considering that in case of failure, a critical node will affect a large number of other nodes: a supplier all entities downstream that depend on the suppliers' resources; a single customer harms the entities upstream financially. Lastly, in the case of a highly connected entity, the

Table 1. Vulnerabilities and publications they are mentioned in

Vulnerability	Counts	Publications
Critical node	40	[1–3, 8, 15, 20–28, 31, 34, 37, 40, 41, 44, 57, 60, 68, 71–87]
Interruption of transportation	17	[1, 2, 20, 23, 27–31, 35, 40, 74, 78, 83, 84, 88, 89]
High regionalization	14	[2, 8, 26, 30, 32, 34, 35, 37, 41, 62, 78, 82, 86, 90]
Lack of information	13	[2, 3, 12, 25, 38, 40, 57, 64, 71, 78, 79, 85, 87]
High redundancy	12	[1–3, 8, 15, 26, 34–37, 78, 84]
Extended lead-times	7	[2, 3, 32, 40, 41, 84, 87]
Geographical risks	5	[1, 21, 26, 40, 42]
Lack of stock	4	[26, 30, 39, 90]

failure probably spreads to a large part of the system. A similar vulnerability is the *interruption of transportation*, which, contrary to the disruption of nodes above, describes the interruption of links. The interruption of transportation hinders the movement of the material and (semi-) finished goods-flow from one entity to another [20, 28–31], and leads to a lack of resources at subsequent nodes. For both the critical node and interruption of transportation, the damage is more severe the more upstream the damage occurs [32, 33], as there are possibly more companies downstream that might be affected.

Other often mentioned vulnerabilities are *high regionalization*, a *lack of information* and *high redundancy* of the supply chain structure.

A regionalized supply chain describes a supply chain for which the value-creating entities are concentrated in a small geographical area [8, 34]. The lack of information encompasses the lack of knowledge of damaged suppliers [25, 38], and available resources [25]. A supply chain with high redundancy, on the other hand, is one with an increased number of entities and an increased number of connections between these entities (either upstream, downstream, or within-tier) [8, 35–37]. The theory is that increased redundancy leads to a higher chance of any entity failing; furthermore, it increases the system's final failure size as more entities are affected by a failure.

To a lower extent, the literature also mentions *extended lead times*, which is especially noted as a problem concerning global sourcing [40, 41], *geographical risks* like earthquakes and floods [42] as vulnerabilities and a *lack of stock*, both in terms of warehouses [30] and safety stock [39].

4.2 Strategies

Table 2 shows the found strategies to increase resilience and the respective publications they were mentioned in, ordered from highest frequency to lowest. As with the vulnerabilities, strategies target both single nodes and links (e.g. backup supplier, multi sourcing), the overall structure (multi sourcing, multiple rerouting, domesticity) as well as properties of nodes (safety stock) and the overall structure (visibility, understanding of the network) which might be analyzed structurally by introducing additional flows.

The most popular strategy to improve resilience, mentioned 73 times, is to *increase redundancy* by the duplication or increasing of resources [6, 36, 43]. Some publications consider more specific strategies like *multi-sourcing* [3, 44], *backup suppliers* [45, 46], *safety stock* [47, 48], and placing *strategic stock* in additional warehouses to be shared by multiple partners [49]. Apart from adding additional nodes, *alternate routing* is a widely accepted strategy, where the latter encompasses additional routes [26], not relying on limited infrastructure like ports [50], using multiple transportation modes [49], and explicitly making use of *lateral transshipment* [51–53].

Another widely accepted strategy to improve the resilience of the supply chain structure is to improve its *visibility.* Here, under visibility, we encompass *information sharing* [60, 61] *warnings* between entities about, for example, affected areas or impact on operations [8, 36, 62] and, finally, the capability to know all processes and products from source to customer [22, 63]. The premise behind this is that increased visibility results in better preparation for those entities that, depending on their relations to channel partners, might be affected by a disruption. This then allows applying appropriate activities to lower the disruption's negative consequences, for example, by conducting lateral transshipment.

Additionally, some strategies target the regionalization of the supply chain structure. More specifically, quite a high number of publications propose to *reduce regionalization* [57, 58], that is, geographically largen the network.

A widely accepted step in the literature that is related to strategies is the *understanding of the network* [12, 64, 65] and especially the *identification of critical nodes* [23, 66–68]. The terms encompass on the one side the need to identify dependencies between nodes and on the other side important nodes, that is, critical nodes, the failure of which would lead to a high number of other nodes to fail.

Interestingly, both in the subject of redundancy and regionalization there are some contradictions: Opposed to increasing redundancy, some publications propose to *reduce redundancy*, for example, by reducing the number of suppliers or warehouses, to increase resilience [37, 54, 55]. A more specific strategy with the same goal is to use *cross-docking* [31, 56].

In the same way, contrary to reducing regionalization, a different branch proposes to *increase regionalization* [6, 20], that is, reducing the distance between entities, to finally *reduce lead times* [59].

4.3 Matching of Vulnerabilities and Strategies

After identifying the most mentioned vulnerabilities the supply chain structure inherits and most applied strategies to change the supply chain structure to increase resilience, we here investigate if there is, depending on vulnerabilities, a recommended strategy to apply to increase supply chain resilience.

First of all, there is a match between vulnerabilities and strategies: For the dependence on critical nodes, the interruption of transportation, and a lack of stock, the strategy to

Table 2. Strategies and publications they are mentioned in

Strategies	Count	Specification		Publications
Increase redundancy	73	Nodes and flows		[6, 23, 33, 34, 36, 43, 48, 55–59, 76, 80, 83, 87, 91–96]
		Flows	Multiple routing	[1, 8, 22, 26, 31, 36, 37, 40, 43, 47, 49, 50, 54–61, 65, 74, 77, 87, 89, 93, 95, 97–100]
			Lateral transshipment	[22, 25, 31, 46, 49, 51–53, 56, 62, 99]
		Nodes	Backup supplier	[3, 22, 26, 39, 45–47, 56, 59, 66, 76, 77, 86, 101]
			Multi sourcing	[1, 3, 6, 8, 12, 20, 23, 25, 27, 33, 37–39, 41, 43, 44, 56, 58, 59, 61, 62, 64–66, 72, 79, 82, 97, 101–105]
			Backup DC	[3, 22, 23, 26, 39, 42, 45, 49, 59, 65, 66, 74, 76, 77, 79, 106]
			Safety stock	[1, 12, 25, 28, 41, 44–48, 51, 57–59, 61, 62, 76, 89, 90, 94, 97, 99, 102]
Visibility	39			[1, 3, 6, 8, 20–22, 25–27, 33, 38, 44, 48, 59–63, 65, 66, 72, 78, 79, 83–85, 87, 88, 92, 97, 102, 106–112]
Reduce regionalization	24			[3, 26, 29, 33, 37, 41, 47, 53, 55, 57, 58, 63, 65, 67, 82, 88, 90, 95, 96, 102–104, 112, 113]
Understanding of network	18			[1, 12, 23, 34, 50, 55, 64–68, 77, 95, 96, 98, 100, 111, 113]
Increase regionalization	12	Domesticity		[6, 20, 26, 44, 62, 88, 99, 106]
		Reduced lead-times		[3, 40, 49, 59]
Decrease redundancy	11	Reduce redundancy		[34, 37, 54, 55, 68, 77, 91, 108, 113]
		Cross docking		[31, 56]

increase redundancy can be applied. The vulnerability arising with too many entities and connections is counteracted by the strategy to reduce redundancy. For highly regionalized supply chains, there is a strategy to increase the space between entities. For supply chains with extended lead times, there exist strategies to regionalize supply chains or increase redundancy. Finally, for supply chains that lack information-sharing, there exists the strategy to increase visibility.

However, some strategies are contradicting: In the case of redundancy, there are two strategies; one argues for increasing redundancy by adding nodes and flows, the other proposes the opposite. This is, in fact, highly discussed in the literature. [69], for example, argue that supply chain redundancy triggers negative events, as with an increased number of entities and flows in a supply chain, there is a higher chance of any of them being hit by a disruption. On the other side Birkie et al. [70] conclude that redundancy reduces the harmful effect disruptions have on performance. Others, like Falasca et al. [34], subsume that there are arguments for both strategies: a disruption in a less redundant supply chain affects fewer nodes, but on the other side, a more redundant supply chain has an additional buffer. Birkie et al. [33] discuss both strategies and derive the importance of adding redundancies specifically at critical nodes, especially at critical upstream tiers. This helps to restrain a disruption locally and reduces the probability of it affecting other entities and flows.

The latter underpins the importance of identifying critical nodes/flows, which helps to identify further the supply chain parts where additional redundancy helps increase resilience.

Additionally, there is a contradiction between the two strategies targeting the regionalization of supply chains: One proposes to regionalize supply chains, which means to reduce the distance between entities of the supply chain, the other the opposite. However, this hypothetical contradiction can be resolved by considering the focus of the different publications: Brown and Daswon [58] and Haraguchi and Lall [57], both arguing to increase space between supply chain entities, focus on the impacts of flooding. This disruption targets a specific geographical area; therefore, all entities close to this area are likely to be affected by the initial disruption itself or channel partners' failure. Whereas Jütner and Maklan [6] and van Remko [20], which focus on global disruptions like the financial crisis and Covid-19, where especially supply chains that traverse multiple regions are disrupted, propose to move entities closer together.

5 Discussion

Tables 1 and 2 list the vulnerabilities supply chain structures have and strategies that, applied to supply chain structures, increase resilience. Comparing the quantity the different vulnerabilities, respectively strategies are mentioned, we see that there is appropriately a matching between the number the specific vulnerability and the counteracting strategy are mentioned. Furthermore, the different numbers suggest, that certain vulnerabilities are more severe and/or for a higher percentage of supply chains, and that certain strategies are applied more often.

However, there is a peculiarity with the vulnerabilities and strategies related to visibility. The lack of information sharing and missing warnings is not often mentioned (13 times) as a vulnerability. Interestingly, enhancing information sharing and enhancing the warning capability, both strategies related to the information flow, are often mentioned (39 times) as increasing supply chain resilience. This can possibly be explained by considering that little information exchange itself is not considered as critical as, for example, the dependence on a single supplier as disruptions in the information flow propagate less far through the supply chain and have little influence on the material flow. On the other hand, increasing visibility might be an established strategy, as it helps supply chain entities be better prepared for disruptions and increases collaboration. It, therefore, counteracts vulnerabilities that are otherwise only reduced by increasing redundancy [33].

Finally, we found two characteristics of the supply chain structure that strongly influence resilience: Regionalization and redundancy. For both of them exists no clear the more, the better-strategy. In this sense, it is important to consider circumstances and investigate the supply chain structure to deduce whether more or less redundancy or regionalization is increasing resilience. Regionalizing makes supply chains more vulnerable to disruptions that have a high impact on the area where the supply chains are located. On the other side, supply chains that are less localized are more prone to a disruption happening at all, as channel partners along the supply chain are situated in different regions and therefore prone to different risks. Redundancy increases the number of nodes and flows and therefore increases the chance of any entity or flow being disrupted. Also, as an entity has, in general, several connections to other entities, a failure in an entity may affect a higher number of subsequent entities. On the other side, reducing redundancy increases the impact of a disruption as there is less additional buffer to compensate for a failure in an entity or flow.

For regionalization, of course, geographical risks are an important factor for determining whether global or local vulnerabilities are predominant. For redundancy, we found that, above all, redundancy should be increased more upstream where the failure of critical nodes or flows has a higher chance to affect a high number of entities.

Generally, we can deduce that it is highly important to investigate the supply chain structure and apply appropriate strategies depending on these findings.

6 Conclusion

In this paper, building on the literature, we identified vulnerabilities the supply chain structure is exposed to and strategies that exist to extenuate the vulnerabilities and increase the resilience of the supply chain structure. For this purpose, we identified 99 papers, consisting of case studies, literature reviews, and journal and conference articles. Overall, we find that altering supply chains' structure to increase resilience is a growing research field. However, literature still lacks insights into how resilience depends on regionalization and redundancy.

We found that supply chains face all kinds of different vulnerabilities ranging from a lack of storage and information sharing to high redundancy, regionalization, and, foremost, the dependence on specific entities and connections between entities.

On the other side, for all of the above vulnerabilities, there exist appropriate strategies. Moreover, some strategies, those counteracting the most found vulnerabilities, are mentioned in a higher number and therefore seem to be applied more often.

However, we found no one-size-fits-all path to alter the supply chain structure to increase resilience. That is, some strategies are contradicting, proposing to either increase or decrease redundancy, respectively regionalization. The latter highlights the need to investigate the supply chain structure to identify specific vulnerabilities before choosing a strategy.

Finally, we find that supply chains' structure needs to be more thoroughly investigated to deduce factors that influence resilience. There is little knowledge of how redundancy and regionalization influence the propagation of a disruption in the supply chain structure. And, following, in how far resilience and regionalization specifically influence resilience. Especially, it should be analyzed if it is possible to increase resilience by increasing redundancy/regionalization in one part and reducing redundancy/regionalization in another part of the supply chain structure.

For practitioners, we provide a catalog of vulnerabilities that need to be considered. Furthermore, we derive that strategies like multi-sourcing or multiple suppliers do not necessarily lead to increased resilience.

Of course, there are limitations to our research. We followed a simple search structure and, furthermore, did not validate our findings with interviews or by conducting case studies.

Recently, there is a branch of literature, that focuses on disruptions, that have long-lasting effects, like it is in the case of Covid-19 [114]. In case of disruptions like these, the pre-disruption state wouldn't be considered as a suitable state to come back to, as possible changed business environments require completely new business models and an adaptation to new regularities and customer needs. In this regard, a supply chain, that is highly resilient to the disruption itself, might be unable to cope with the aftermath of it.

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Risk Indicators and Data Analytics in Supply Chain Risk Monitoring

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Abstract. This paper seeks to complement the supply chain risk monitoring literature by identifying analytics methods and the risk indicators being monitored for this purpose. This includes the underlying supply chain data used for short-term or even real-time monitoring of risks in supply chain risk management. A systematic literature review is carried out in order to identify risk types and underlying factors considered in the context of risk monitoring. Furthermore, the monitored risk indicators and the data analytics methods applied in their generation, monitoring or prediction, as well as the underlying risk data are examined. The identified works focus mainly on micro risks, where supply and transport risks are the most prevalent. A variety of risk indicators is found to be used including both, qualitative and quantitative, which are often used jointly. Identified data sources range from operational databases to IoT and sensor networks. Moreover, first approaches utilizing predictive analytics methods to anticipate risks are identified. The findings are used to derive promising research topics to further explore this largely underrepresented field within supply chain risk management and pave the way for data-driven risk monitoring.

1 Introduction

Compared to the supply chain risk management (SCRM) phases of risk identification, assessment and mitigation, risk monitoring has received only little attention in research (Fan and Stevenson 2018; Ho et al. 2015) and few address IT-support for risk monitoring (Fischer-Preßler et al. 2020). This is despite the fact that in practice, several examples of advanced monitoring systems exist and have existed for years (e.g. Intel, Cisco, DHLResilience, Ericsson, Blackhurst et al. 2008). Still, even among practitioners less than half utilize some sort of technology to record, monitor, measure and predict supply chain disruptions (BCI 2019). The incorporation of automatically collected data for monitoring and early warning-systems has the potential for a significant time advantage as opposed to relying solely on traditional risk assessment techniques. These usually depend on qualitative data collected in time-consuming processes involving many experts (Marhavilas et al. 2011). To capture the level of risks in supply chains, the choice of relevant risk indicators is of utmost importance in order to monitor and predict changes in risk-relevant conditions (Scarlat and Bradea 2011; Schlüter et al. 2017). These may rely on a multitude of data from different sources and aid in the monitoring of different types of risks and underlying factors which are relevant for the supply chain, ranging from

U. Buscher et al. (Eds.): *Logistics Management*, LNLO, pp. 246–263, 2021.
https://doi.org/10.1007/978-3-030-85843-8_16

demand, to transport and supply risks (Baryannis et al. 2019a; Diedrich and Klingebiel 2020; Zhang et al. 2020), and therefore constitute a valuable risk management tool. The potential of supplementing advanced monitoring with real-time business intelligence capabilities to discover or predict risks has been pointed out (Schlüter et al. 2017) and therefore raises the question of how data analytics methods can utilized for this purpose.

With proceeding digitalization and technological advancements, a greater data basis than ever before is available for supply chain decision-makers (Rozados and Tjahjono 2014). This in conjunction with data analytics tools allows for new risk indicators to be calculated and underlying data to be gathered at a higher speed; however, data-driven approaches are still rarely reported in the SCRM literature (Baryannis et al. 2019b). These approaches carry great potential for automated risk identification, improved risk assessment and advanced warning-systems (Schlüter et al. 2017). Data-based approaches are regarded as more suitable for real-time application (Poschmann et al. 2019) as opposed to relying solely on survey-based risk assessment, disregarding the advantages of a model-based risk score derived from the supply chain database (Li et al. 2016). So far, the literature has approached this topic mostly conceptually (Fu and Chien 2019; He et al. 2014; Radanliev et al. 2020), indicating the need for a more application and method-focused research approach.

The utilization of real-time data thus enables short-term, even live risk monitoring in supply chain operations, which this work seeks to explore. Despite the numerous studies (Ho et al. 2015; Rao and Goldsby 2009; Tummala et al. 2011) examining different types of risk, e.g. demand risk, and their underlying factors such as inaccurate forecasts, at the time of writing, to the best of the authors' knowledge, no dedicated synthesis of risk monitoring and prediction, and the considered risk indicators in the SCRM-phase of risk monitoring exists. By carrying out a systematic literature review, this work seeks to address this issue by answering the following three research questions:

1. Which risk types and factors are considered in supply chain risk monitoring?
2. What are suitable risk indicators to monitor these risk factors?
3. How can data analytics methods and supply chain data be used in the analysis, prediction and monitoring of these risk indicators?

The remainder of this work is organized as follows: First, a background on supply chain risks and their measurement is given and previous works on the potential of supply chain risk monitoring are reviewed. Next, the methodology for the systematic literature review is laid out. Afterwards, the results are presented and discussed. Promising research topics are presented to conclude the work.

2 Theoretical Background on Risk Factors, Indicators and Data Analytics in Supply Chain Risk Management

In the SCRM literature a distinction is generally made between risk types and risk factors. Risks types can be categorized in many ways. Ho et al. (2015) divide them into macro- and micro-risks where macro risks can be natural or man-made and micro-risks, which can refer to supply, demand, manufacturing, and infrastructure risks. The latter can be further divided into information, transportation and financial risks. Risk factors on the other hand comprise "events and situations that drive a specific risk type" (Ho et al. 2015, 7), and are therefore very case-specific and will also influence the possibility of monitoring and predicting the occurrence of different types of risks. Monitoring performance indicators and risks themselves is made possible thanks to real-time data from a variety of internal (sensors, IT systems) and external (SC partners, web) sources and enables warning-systems that not only provide information the moment a risk is manifested but may even predict this ahead of time (Schlüter et al. 2017). To monitor supply chains, indicators are used which may be considered "key" if they describe particularly relevant properties. While key performance indicators (KPIs) are used to evaluate a supply chain's performance and tend to rely on lagging indicators, key risk indicators (KRIs) show the level of risk and rely on forward-looking indicators (Chadha and Rodriguez 2016). Similarly, key control indicators (KCIs) are used to monitor the controls applied in the risk treatment phase (Chadha and Rodriguez 2016). As the focus of this work lies on the risk monitoring phase, KRIs are of primary interest. The relationship between data, risk indicators and key risk indicators can thus be structured as follows (Chadha and Rodriguez 2016):

- SCRM data: all available internal and external data relevant to SCRM including risks
- Risk indicator: SCRM-relevant data or calculated value from SCRM-relevant data that indicates level of risk on a regular, short-term basis
- Key risk indicator (KRI): chosen risk indicator to be "key" to risk management

Technological advances driven by Industry 4.0 surrounding advanced sensor networks, cloud computing or cyber physical systems have led to greater data availability, potentially in real-time (Schroeder et al. 2014). Also, the potential and challenges of utilizing big data and advanced analytics in supply chain management (Rozados and Tjahjono 2014; Waller and Fawcett 2013) and later SCRM (Choi et al. 2017; Kache and Seuring 2017; Schlüter et al. 2017) have been a subject in the scientific literature for some years now. He et al. (2014) developed a conceptual framework on the monitoring of supply risks and proposed the usage of a variety of data sources ranging from traditional data regarding supplier capability, deliver history, and quality and new, external data sources including weather and social media. An example for dealing with demand-side risks is a data-driven demand forecast framework proposed by Fu and Chien (2019) that includes several methods such as time series and machine learning. Radanliev et al. (2020) evaluate the potential of artificial intelligence and machine learning to combat cyber risks, which can be positioned in information risks. These works approach monitoring of risks in supply chain management primarily conceptually. A synthesis of concrete applications, utilized risk indicators and analytics methods is yet missing. Thus, the work at hand seeks to fill this gap by complementing the existing body of research by identifying monitored risk factors, utilized risk indicators, concrete analytics methods and data that enable short-term or even real-time risk monitoring.

3 Research Approach

Risk analysis methods and risk indicators used for monitoring and prediction in SCRM are identified through a systematic literature review. The methodology relies on the five-step approach of Vom Brocke et al. (2009). The goal of the review is to identify which risk types and factors are considered in risk monitoring, to identify suitable risk indicators and how data analytics methods can be used to support risk monitoring. The search string consists of "supply chain" as a central term and then "risk", which is combined with various expressions often used synonymous with "indicator". Additionally, "risk" is combined with "analytics", "monitoring" and "prediction", motivated by a greater availability of supply chain data as an enabling factor. Given the focus on applications and the scope of the research questions, the literature is expected to include most if not all information relevant to answer all three research questions and is therefore searched using a single query. Works identified in the initial scoping review are included, too. To explore this sub-field of SCRM, a representative sample typifying similar works must be analyzed (Cooper 1988). Scopus and Web of Science were seen fit for this purpose due to their size and range of publications.

Search string (title-abstract-keyword):

> "supply chain" AND ("risk index" OR "risk score" OR "risk indicator" OR "risk value" OR "risk analytics" OR "risk monitoring" OR "risk prediction")

Similar to how key performance indicators can be selected from all available performance indicators (Neely et al. 1995), such a relationship between key risk indicators and regular risk indicators can be assumed, which is generally not mentioned explicitly in the literature. It is instead documented if a central risk indicator is constructed from several risk indicators. The identified works are then classified according to risk types, which are determined using the framework by Ho et al. (2015) encompassing different types of risks within the categories of macro and micro risks. This ensures statements about the coverage of risk types and factors in the literature can be made regarding research question one. Furthermore, risk indicators are identified to answer research question two and utilized data and analytics methods are documented to answer research question three.

In order to be included, a work must utilize some sort of risk indicator capable of monitoring on the short term or even in real-time, or some sort of data analytics method for (near) real-time risk monitoring in order to follow the indication of potential of such approached pointed out in the previous chapter (Choi et al. 2017; Kache and Seuring 2017; Schlüter et al. 2017). In order to determine if a work complies with the inclusion criterion concerning data analytics methods, a taxonomy of big data analytics in SCM is used encompassing data discovery, reduction, deduction, quantification and visualization, as well as predictive, event-oriented and statistical-inference methods (Chehbi-Gamoura et al. 2019), where the latter four are expected to be most suitable for the purpose of risk monitoring on the short-term. As the focus of this paper lies on methods and actual applications in contrast to the various existing theoretical approaches, purely conceptual works are excluded, and the results are limited to journal and conference articles. Furthermore, the work must deal with managing risks in the supply chain context and not solely rely on qualitative risk assessment methods to quantify the probability and likelihood in a way not suited for regular monitoring and quick responses, e.g. via annual expert interviews which take weeks to complete.

From the 259 results, 239 were articles and conference papers from which 52 duplicates were removed. Of the remaining 187, 101 works have been selected through title and abstract reading and were then filtered further through content screening. The remaining eleven papers were used for forward and backward search which yielded an additional seven papers, which combined with the three found in the initial scoping review make for a final set of 21 papers.

4 Risk Indicators and Data Analytics in Supply Chain Risk Monitoring

Many of the works in the query result rely solely on data gathered from interviews, surveys etc., which are then used in conjunction with traditional analytic hierarchy process (AHP), analytic network process (ANP), fuzzy logic for risk identification, assessment and prioritization. Due to the limited suitability of this type of data collection for monitoring, these works were therefore discarded unless they elaborate on how exactly the results can be used for monitoring at regular intervals. Through title and abstract reading, 63 works and through full text reading further 56 were discarded due to limited monitoring suitability. The finally selected works are the few that either implicitly – through their use of methods and data – or explicitly state how their respective models and methods can be used on a regular basis to monitor supply chain risks. Many of them go into surprising detail when it comes to analytics methods and data, in theory, their application or both.

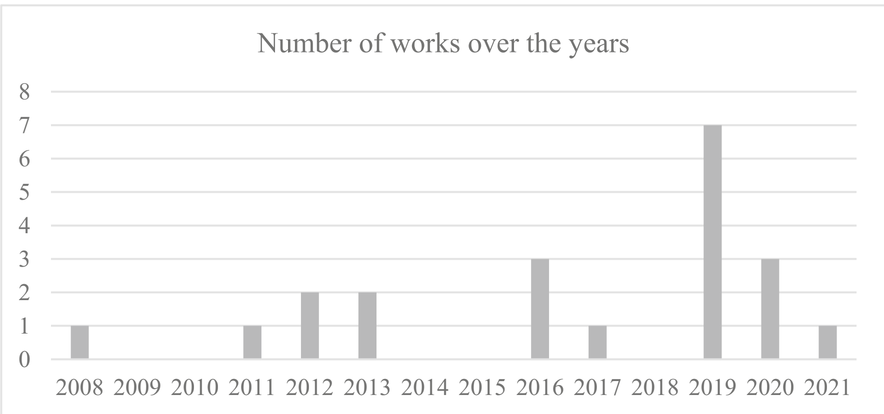

Fig. 1. Distribution across time of analyzed papers

Most of the works were published during the last 5 years which may be an indicator of progressing supply chain digitalization, increased interest in data-driven methods and corresponding research revealing the necessity of developing risk early-warning capabilities (see Fig. 1). In the following, the result set is thematically analyzed in accordance with the research objectives of this paper.

4.1 Risk Factors and Indicators

The risk factors and indicators considered in the literature are categorized according to their associated risk type in Table 1 using the framework by Ho et al. (2015). The occurrence of all risk types encountered in the result set are shown in Fig. 2. The most prominent risk types are transportation risks considered in five works (Bains et al. 2016; Kim et al. 2016; Poschmann et al. 2019; Shin et al. 2012; Zhang et al. 2020) and supply risks in five (Baryannis et al. 2019a; Blackhurst et al. 2008; Er Kara et al. 2020; Hosseini and Khaled 2019; Li et al. 2016). This might be due to the data availability of transport data, which can be collected easily, both, for the actual transport itself and the transported goods, using localization technology like GPS and various types of sensors. Similarly, data on suppliers might be collected from publicly available sources and complemented by company experts working together with the suppliers. There are only two works considering demand risks (Beheshti-Kashi et al. 2019; Diedrich and Klingebiel 2020) and one work considering social (man-made) risks (Mani et al. 2017). Further five works consider multiple risks where one regards different risks according to different performance attributes (Curbelo et al. 2019) and the other focusses on enabling supply chain risk visualization capabilities and therefore does not make any restrictions in terms of risk types (Goh et al. 2013).

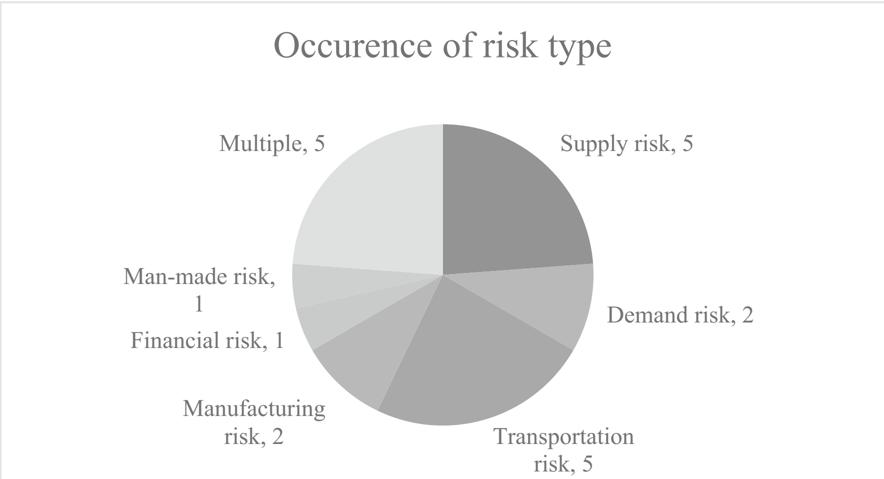

Fig. 2. Occurrence of risk types in analyzed papers

Apart from the rather focused consideration of risk types, different industries ranging from manufacturing in automotive, aero-space, steel and telecommunication to fashion and dairy produce are present. Modes of transportation include road, air, railway and maritime, showing that transportation risks are deemed highly relevant irrespective of the mode of transportation, and also that transportation data for all of them are available.

Almost half of the works utilize a risk indicator directly based on SCRM data to monitor risks while the other half calculates and, in some cases, predicts a key risk indicator in order to support the risk managers with one central value. For example, supply chain data such as the temperature and humidity of products in transport are used directly in cold chain scenarios (Kim et al. 2016; Lam et al. 2013) while various technological and biological indicators can be aggregated into a central transportation risk indicator (Zhang et al. 2020). Even within one risk type, there is a great variety of indicators that can be utilized for specific risks. This is illustrated for example with supply risk. Here, choices for indicators are supply quality and disruption-related ones such as labor availability and disputes (Blackhurst et al. 2008), whether deliveries are delayed or on time (Baryannis et al. 2019a), rather traditional indicators such as cost, quality and time (Hosseini and Khaled 2019) or the questions if a product will stop being produced as indicated by its price, lead time, cycle time and throughput, as well as further secondary indicators (Li et al. 2016). It can be observed that not just data associated with supply chain risks, but the likelihood of risk events can be utilized as an indicator (Baryannis et al. 2019a). The choice of risk indicators is generally described in great detail, which emphasizes the importance of understanding the organization's specific context and risks which threaten it. However, which supply chain member should use which indicators is not explained further. In summary, it is not entirely possible to answer the question of which risk factors and indicators can be used in supply chain risk monitoring since the identified factors and indicators vary greatly with different industries and risk types. However, this can be seen as a great indication of the need for guidance when establishing risk monitoring beyond specific use cases as is the case for the studies analyzed here.

Almost half of the works utilize a risk indicator directly based on SCRM data to monitor risks while the other half calculates and, in some cases, predicts a key risk indicator in order to support the risk managers with one central value. For example, supply chain data such as the temperature and humidity of products in transport are used directly in cold chain scenarios (Kim et al. 2016; Lam et al. 2013) while various technological and biological indicators can be aggregated into a central transportation risk indicator (Zhang et al. 2020). Even within one risk type, there is a great variety of indicators that can be utilized for specific risks. This is illustrated for example with supply risk. Here, choices for indicators are supply quality and disruption-related ones such as labor availability and disputes (Blackhurst et al. 2008), whether deliveries are delayed or on time (Baryannis et al. 2019a), rather traditional indicators such as cost, quality and time (Hosseini and Khaled 2019) or the questions if a product will stop being produced as indicated by its price, lead time, cycle time and throughput, as well as further secondary indicators (Li et al. 2016). It can be observed that not just data associated with supply chain risks, but the likelihood of risk events can be utilized as an indicator (Baryannis et al. 2019a). The choice of risk indicators is generally described in great detail, which emphasizes the importance of understanding the organization's specific context and risks which threaten it. However, which supply chain member should use which indicators is not explained further. In summary, it is not entirely possible to answer the question of which risk factors and indicators can be used in supply chain risk monitoring since

Table 1. Risk factors and indicators identified in the literature

Author	Risk factors	Key risk indicators and indicators
Supply risks		
Blackhurst et al. (2008)	Supply risk (different risks per supplier and per part in automotive industry)	Risk indicator based on different quality and disruption-based indicators for part and supplier
Li et al. (2016)	Supply risk (end-of-supply risk for a maintenance and repair organization (MRO))	Risk indicators calculated from data – price, lead time, cycle time, throughput – summed up in survival probability of respective part as central indicator
Baryannis et al. (2019)	Supply risk (order fulfilment and late delivery in multi-tier aerospace manufacturing supply chain)	Risk classification whether delivery in time or too late
Hosseini and Khaled (2019)	Supply risks (supplier risk in sewage pipe manufacturing)	Supplier resilience value as central index, primary indicators cost, quality, lead time, response rate and several secondary indicators
Er Kara et al. (2020)	Supply risks (supplier risk)	Numerous qualitative and quantitative indicators of supplier risks used in final selection
Demand risks		
Beheshti-Kashi et al. (2019)	Demand risk (forecasting risk in fashion industry)	Use correlation between textual and sales data as indicator for forecasting risk
Diedrich and Klingebiel (2020)	Demand risk (inaccurate demand planning of automobile manufacturer)	Theory: Early warning risk indicator Case: spread of risk, risk impact on the KPI for the security of supply of the OEM
Transportation risks		
Shin et al. (2012)	Transportation risk	Use cost of transportation and costs caused by machine malfunctioning and delay of manufacturing or delivery as indicators

(continued)

Table 1. (*continued*)

Author	Risk factors	Key risk indicators and indicators
Bains et al. (2016)	Transportation risk (global airline logistics)	Risk indicator based on weighted ubiquity score per part and geopolitical score per supplier to determine high-risk supply chain nodes
Kim et al. (2016)	Transportation risk (cold supply chain)	Risk indicator given specific rules and contexts, e.g. temperature and humidity
Poschmann et al. (2019)	Transportation risk (maritime supply chain)	Expected time of arrival as central risk indicator
Zhang et al. (2020)	Transportation risk (cold supply chain, case of strawberry supply chain)	Aggregated transportation risk indicator based on various indicators ranging from technological to biological (hypothetical case)
Manufacturing risks		
Zhang et al. (2011)	Production risks (food supply chain, case of pork industry)	Three level indicator system considering water, pig farms and pork quality (physical and chemical)
Lam et al. (2013)	Storage risks (food supply chain, case of wine industry	Storage temperature and humidity range, fluctuation
Financial risks		
Lyu and Zhao (2019)	Financial risks (internet supply chain finance)	Indicators referring to solvency, profitability, operations and products, network technology and environment, among others
Man-made risks		
Mani et al. (2017)	Man-made risks (social risks in milk production and 3PL provider)	Monitor drivers and vehicles for personal safety, unethical or illegal behavior and environmental concerns
Multiple risks		
Zhang and Lu 2012	Multiple (supply chain risk level in steel industry w.r.t finances, business processes, customer service, development)	E.g. net sales and growth, supply chain response time, on-time delivery and order fulfilment, market share

(*continued*)

Table 1. (*continued*)

Author	Risk factors	Key risk indicators and indicators
Goh et al. (2013)	Multiple (supply chain risk level)	Logistics-related, inventory, order-related indicators
Curbelo et al. (2019)	Multiple (supply chain risk level w.r.t different performance attributes, case in telecommunications industry)	Aggregated risk indicators for different objectives
Yang and Xie (2019)	Multiple (supply, technology, docking and external risks in agricultural supply chain)	E.g. unfulfilled demand, overproduction, delivery delay, organizational efficiency, public opinion, severe weather, among others
Han and Zhang (2020)	Multiple (supply chain risk level, case of food producing company)	Three-level indicator system, including suppliers, demand and consumers, logistics costs and processes, technology and information sharing, environmental indicators, among others

the identified factors and indicators vary greatly with different industries and risk types. However, this can be seen as a great indication of the need for guidance when establishing risk monitoring beyond specific use cases as is the case for the studies analyzed here.

4.2 Methods and SCRM Data

Analysis methods and data related to the various risk indicators used in each work are summarized in Table 2. Different machine learning methods are utilized to predict future risk levels and approximate experts' estimates. For example, support vector machines (SVMs) are compared with decisions trees in order to illustrate how the choice of methods can impact the risk manager's ability to interpret the prediction result when using delayed deliveries as an indicator (Baryannis et al. 2019a). SVMs are also utilized to predict an aggregated risk indicator for transportation risks in the case of cold chains (Zhang et al. 2020). Another tool utilized is supply chain visualization which is realized using dashboards (Goh et al. 2013), to include geopolitical risk indicators (Bains et al. 2016) or drivers' routes and associated vehicle activities as risk indicators (Mani et al. 2017). Er Kara et al. (2020) suggest the creation of a risk data warehouse and further utilize k-means clustering to cluster suppliers into groups. The risk level within each cluster varies given different risk indicators related to sales performance (e.g. failure rate), production planning and control (e.g. number of delayed orders) or logistics (e.g. inaccurate deliveries). Bayesian Belief Networks are used to model interdependencies between risks and their associated location along the supply chain and thus go beyond monitoring single KRIs on their own (Shin et al. 2012; Yang and Xie 2019). Also, artificial neural networks find their uses when trained based on experts' judgements of risk levels, thus enabling ongoing, automated risk level estimations (Han and Zhang 2020; Zhang et al. 2011; Zhang and Lu 2012).

Hosseini and Khaled (2019) combine several methods such as decisions trees and artificial neural networks with an ensemble approach to predict the supplier risk using indicators such as cost, quality, lead time, response rate and qualitative resilience criteria. This illustrates how predictive methods can be used in conjunction with an AHP approach based on data generated from questionnaires. Curbelo et al. (2019) and Lyu and Zhao (2019) show how approaches relying on qualitative data can be extended with quantitative data to warrant monitoring at regular intervals. Quantitative and qualitative data can thus be used jointly, the latter mostly with expert involvement where the bounds of the risk levels of different indicators are initially determined through forms or interviews. Furthermore, the range of different methods and underlying data illustrate how various approaches could be incorporated into one integrated approach. Apart from the potential of integrating internal and external data, which only few of the works incorporate, the approaches range from the acquisition of quantitative and qualitative risk data, their integration into risk databases, their processing and preparation for further analysis, the application of analysis methods with the goals of monitoring risk levels associated with supply chain members, actors or products, or their classification or clustering into different groups, each associated with different risks, as well as modelling their interdependencies. Finally, automatic handling of minor exceptions might be implemented, based directly on the data and method outputs used for monitoring.

Some of the works even give details on how they introduced their specific approach in the case company. One work (Diedrich and Klingebiel 2020) relied on a proven methodology in the form of CRISP-DM. Others describe the creation of risk management tool (Li et al. 2016), integration into existing risk management tools or prototype development (Poschmann et al. 2019), while many did not reflect upon the integration into any system. This also means that the supply chain perspective has not been elaborated on in detail. Not only discrepancies in function and location of supply chain members, but also those regarding the definition and sharing of data may result in problems (Zhang et al. 2011). It may be necessary to involve all members in order to collect the necessary data and understand each supply chain actor's role (Poschmann et al. 2019), as well as involving experts with different backgrounds, including risk management, domain, IT and those with knowledge in the applied methods (Er Kara et al. 2020). In most of the identified cases, the data was collected with a certain goal determined beforehand, indicating that different monitoring goals come with different data requirements. Also, it has been pointed out that data availability and the communication between experts in supply chain risks and data-driven methods largely influence the success of such efforts (Baryannis et al. 2019a). All of this might indicate certain specifics in the application and introduction of data analytics and monitoring systems in supply chain risk management and the need for a more detailed analysis on how to conduct and introduce data-driven risk monitoring in organizations.

In summary, as for research question three, identified approaches include data visualization, discovery, deduction and quantification, mostly predictive machine learning

Table 2. Analytics methods and SCRM data identified in the literature

Author	Methods	SCRM data
Bains et al. (2016)	Dashboard with geographic display	Component data of airplane models, geopolitical information
Blackhurst et al. (2008)	Define maximum percentage change in risk and control limits for risk score and monitor trends	Quantitative data for calculated measures (e.g. defects per million) supplemented by qualitative ratings
Baryannis et al. (2019)	Support-vector machine (grid search for parameters), decision tree with and without limited number of leaves	Around 500.000 product deliveries from tier 2 to the tier 1 supplier over six-year period (2011–2016), two sets of around 30 features in two models based on product-, order- and delivery-related data
Beheshti-Kashi et al. (2019)	Natural language processing	Textual data from blogs relevant to the industry, sales data
Curbelo et al. (2019)	Mathematical model with fuzzy inference system	Define list of control objects for different risk events with different data each
Diedrich and Klingebiel (2020)	Several machine learning methods	Over seven million values, over 90 calculated for each part number and demand date
Er Kara et al. (2020)	Risk data warehouse, k-means to group suppliers, best-worst for weights	Quantitative and qualitative data associated with the indicators, not further specified
Goh et al. (2013)	Dashboard with geographic display, risk alerts, determine vulnerabity using optimization and simulation	Internal operational data (logistics, inventory, order fulfilment, …) and external (public map services, OSINT, twitter)
Han and Zhang (2020)	Artificial neural network	Data gathered via questionnaires from enterprises and universities to determine risk levels
Hosseini and Khaled (2019)	Logistic regression, decision tree (CART), artificial neural network in ensemble	Data for primary criteria, qualitative data for resilience-related attributes, complemented by web-data

(*continued*)

Table 2. (*continued*)

Author	Methods	SCRM data
Kim et al. 2016	Ontology and dynamic rule creation engine for risk detection & response	RFID data (temperature, humidity, …) and other sensors
Lam et al. 2013	Statistical analysis, genetic algorithm for case handling	RFID data (temperature, humidity) and product data (quantity, value…)
Li et al. (2016)	Proportional hazard model (PHM)	MRO's purchase history (date, part, price, quantity, supplier, delivery)
Lyu and Zhao (2019)	Big Data-drive gray assessment	Financial risk scored by group of experts from case company, financial statement data
Mani et al. (2017)	Dashboard with geographic displays for vehicles, routes	Quantitative logistics data from 3PL provider (fleet-management, live-tracking, IoT sensors) with millions of data points combined with qualitative data from interviews
Poschmann et al. (2019)	Estimation of importance and maturity of available information, propose array of artificial intelligence methods	Transport data (planned and actual times, disruption information)
Shin et al. (2012)	Bayesian belief networks	Not specified
Yang and Xie (2019)	Bayesian belief networks	Probabilities gathered from field research and questionnaires
Zhang et al. (2011)	Artificial neural network and statistical analysis for anomaly detection	Pre-warning rules defined by the case company's experts, integrated data from supply chain members
Zhang and Lu (2012)	Artificial neural network	Integrated historic and surveyed data over two years corresponding to the various indicators

(*continued*)

Table 2. (*continued*)

Author	Methods	SCRM data
Zhang et al. (2020)	Support-vector machine	350 values across 30 different features surrounding logistics and fresh-keeping technology, product, packaging, equipment effectiveness, biological, sustainability, environmental and emergency

methods for regression and classification as well as clustering, and furthermore data management itself, which means almost all categories as defined by Chehbi-Gamoura et al. (2019) could be identified by this study.

5 Future Research for Data-Driven Supply Chain Risk Monitoring

The analyzed works reveal several promising topics for future research. As we learn from research question one, for instance, the analysis of risk factors must go beyond hierarchical relationships and instead incorporate risk agents and their interaction (Curbelo et al. 2019). The progressing digitalization is mentioned as a further driver for the expansion to more supply chain risks (Diedrich and Klingebiel 2020). Another common topic is the application of the respective methodologies and methods in different industries, e.g. the manufacturing of different vehicles (Bains et al. 2016), different OEMs (Diedrich and Klingebiel 2020) or just generally more case studies for validation purposes and to advance theory (Curbelo et al. 2019; Er Kara et al. 2020; Mani et al. 2017; Shin et al. 2012). Monitoring different products and extending proposed methodologies from e.g. transportation to storage and production are proposed as well (Zhang et al. 2020). This resonates with the highly heterogenous set of application areas identified in this paper, indicating the need for an evaluation of methods across different domains.

In terms of risk indicators considered in research question two, apart from using supply chain data as a risk indicator or to calculate one, the duration of risk events may be an important indicator (Curbelo et al. 2019), just as the dynamics of disruptions themselves (Hosseini and Khaled 2019). In the case of supplier risks, their resilience level could be used as an indicator to determine the risk level of the entire supply chain (Hosseini and Khaled 2019). Most of the works analyzed in this paper focus on micro-risks and consequently primarily internal data sources are used, with a few exceptions. This raises the question of how to determine suitable macro risk indicators and their underlying data.

As for research question three, a common theme is the application of more data, both in volume and variety (Curbelo et al. 2019) and period of storage (Diedrich and Klingebiel 2020), as well as extending risk monitoring to the entire supply chain in order to support the decision making for exceptional case management (Kim et al. 2016). This holds the potential for more accurately portrayed risks and additional risk indicators (Bains et al. 2016) and to improve prediction performance by adding more features (Baryannis et al. 2019a). On the side of data analytics methods, the application of a larger set of machine learning techniques (Curbelo et al. 2019; Kim et al. 2016), also for risk prediction (Baryannis et al. 2019a), as well as combining data-driven and knowledge-based artificial intelligence approaches (Baryannis et al. 2019a; Diedrich and Klingebiel 2020) are mentioned. This indicates that future research may be required, eliciting concrete data and IT-infrastructure requirements to enable data-driven risk monitoring. A transfer of general big data analytics literature in the context of supply chain management as a whole may constitute a first step in such an endeavor. Finally, integrating data-driven and knowledge-based approaches makes for a promising topic for future research, in particular in the area of artificial intelligence.

The impact and integration of the identified methods into SCRM phases, specifically risk monitoring processes, may reveal interesting results. Here, the development of data-driven risk monitoring methodologies may be supported by examining the willingness of stakeholders to adopt them (Blackhurst et al. 2008). Also, the implications for other phases such as risk mitigation with regard to assisting in decisions making and automation are mentioned (Diedrich and Klingebiel 2020), just like the usage for risk identification (Goh et al. 2013) and integration of further assessment methods (Li et al. 2016). This raises the question of what barriers there are to introducing risk monitoring into organizations and how to overcome them, as well as methodologies for the creation of risk monitoring systems and continuous control of the adequacy of chosen risk indicators in a specific context.

6 Conclusions and Outlook

In this work, risk factors, monitored risk indicators and the usage of data analytics to generate, monitor and predict risk in the field of supply chain risk monitoring were explored through a systematic literature review. The results where synthesized along the dimensions of risk types, and corresponding application of risk indicators. Analytics methods and data were identified, revealing foci and gaps in the literature. The findings were discussed and potential reasons for them outlined. Following the discussion, propositions for future research were derived. A trend towards more data-driven monitoring approaches and analytics methods was revealed, yet there are still many more risk types and factors that need to be explored in future research. Also, the introduction of supply chain risk monitoring with its wide array of potential data sources and analytics methods into organizations requires particular attention.

The main limitations for this work result from the choice of databases and keywords. Even though the small result set may be explained by the current lack of research in supply chain risk monitoring, the discussion and implications for future research were based on a limited set of results and are therefore insufficient to provide the full picture. Second, the focus lies on KRIs as opposed to KPIs or KCIs, which may warrant research of their own, but may require an entirely different research approach. As a lesson from the current effects of the Covid-19 pandemic onto global supply chains and their ever-increasing complexity as well as changing environments, the need for advanced monitoring capabilities will continue to rise. This paper established the first overview of supply chain risk monitoring and derived future research topics, giving both researchers and practitioners a starting point for further exploration and investigation in this endeavor.

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U. Buscher et al. (Eds.): *Logistics Management*, LNLO, p. 265, 2021.
https://doi.org/10.1007/978-3-030-85843-8