Public-private perspectives on supply chains of essential goods in crisis management

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Abstract

Public authorities are responsible to maintain the population's supply with essential goods like food or drugs at any time. Such goods are produced, transported and sold by companies in supply chains. Past supply crises all over the world have showcased numerous examples of spontaneous collaboration between public authorities and companies in supply chains. However, insights on formal collaboration which is agreed upon in the preparedness phase is rare in both practice and literature.

Therefore, this dissertation's first research objective is to identify under which circumstances companies are most willing to collaborate with public authorities. In this context, public authorities' and companies' characteristics, resources and roles in a collaboration are identified from literature research as well as real-life cases in Study A. Study B empirically determines companies' preferred preconditions for collaboration: Companies value the continuity of their business processes and expect to be compensated monetarily or by lifted restrictions. The second research objective is to develop collaborative supply chain concepts and evaluate them from public and private perspectives. Study C develops a collaboration concept in a real-time setting in which commercial trucks are jointly re-routed into crisis regions. In Study D, public authorities coordinate tactical use of commercial last-mile delivery vehicles for the home supply with food and drugs. In Study E, strategic collaboration in using dual-use warehouses is investigated with a focus on logistics networks. Study F determines the impact of demand shortfalls and payment term extensions on financial and physical flows in food supply chains. In Studies C-F, the main drivers for effectiveness and efficiency are investigated.

By examining collaboration between companies and public authorities in supply crises, this dissertation contributes to the research streams of supply chain risk management and so-called extreme supply chain management. The results provide public decision-makers with insights into companies' motivation to engage in public crisis management. The developed collaborative supply chain concepts serve public authorities as a basis for collaboration design and companies as starting points for integrating public-private collaboration into their endeavors to make supply chains more resilient.

Contents

Abbreviations

CCC	Cash conversion cycle
CSR	Corporate social responsibility
ESCM	Extreme supply chain management
FTL	Full truckload
HL	Humanitarian logistics
LTL	Less-than-truckload
MDSDVRP	Multi-Depot Split Delivery Vehicle Routing Problem
PPEC	Public-private emergency collaboration
RO	Research objective
RQ	Research question
SCRM	Supply chain risk management
UN	United Nations
UK	United Kingdom
US	United States
VRP	Vehicle Routing Problem

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Part I

Research framework, results and implications

1 Introduction

According to Article 25 of the *Universal Declaration of Human Rights* (1948), a living standard guaranteeing health and well-being should be a fundamental right for every person and cover the adequate access to food and medical services at any time. In line with this, governments in many countries are formally responsible for ensuring this access and oversee commercial supply chains which produce, transport and distribute food, drugs and medical equipment. At the end of these supply chains, people are able to buy essential goods in retail or drug stores or have them delivered to their home. If the availability or affordability of food or drugs is not given, their basic supply can be endangered. To varying extents, this was the consequence of some recent crises: During the COVID-19 pandemic, infected staff led to disruptions in food retail supply chains; due to the war in Ukraine and the blockade of grain exports, other countries lacked imports and faced higher costs in the food market (van Meijl et al., 2022); shifts in drug demand arising from the COVID-19 pandemic in combination with fragile pharmaceutical supply chains have lately been causing supply constraints in Europe (European Parliament, 2022; German Federal Ministry of Health, 2022). As a consequence of these impairments, empty shelves in food retail and drugstores as well as rising prices have brought the importance of supply chain continuity for everyday life into public focus in many countries (Sodhi et al., 2021; German Federal Ministry of Health, 2022).

Minor and partial disruptions in supply chains only cause minor fluctuations, supply constraints and unsatisfied customers. Companies usually deal with this type of disturbances through their supply chain risk management (SCRM). In case of major disruptions, public authorities usually have the responsibility to recover the population's basic supply with food and drugs (Y.-Y. Li et al., 2023; Ahlqvist et al., 2023), though do not and cannot possess enough resources to step in and replace an entire supply chain at any time. Consequently, public authorities intensify their relations with affected companies and aim to support commercial supply chains. Recent large-scale crises like the COVID-19 pandemic have therefore led to increased interest of public authorities in performance of commercial supply chains which produce, transport and sell essential goods (Y.-Y. Li et al., 2023; Xu et al., 2023; Müller et al., 2022; Jamal et al., 2022; Ahlqvist et al., 2023; Nikolopoulos et al., 2021; Scholten et al., 2020). This interest is likely to increase even further, since companies see disruptions as the major risk for supply chains in the next years (Capgemini Research Institute, 2023) and at the same time, the United Nations are predicting an all-time peak of humanitarian need globally in order to respond to supply crises (United Nations Office for the Coordination of Humanitarian Affairs, 2022).

Since both public authorities and companies are key actors for population's basic supply in crises, collaboration among them is crucial for effective crisis management (Y.-Y. Li et al., 2023; Akomea-Frimpong et al., 2023; Jamal et al., 2022; Besiou and Van Wassenhove, 2020; Quarshie and

Leuschner, 2020; Fontainha et al., 2017; Jahre et al., 2016; Koliba et al., 2011; Van Wassenhove, 2006). Correspondingly, spontaneous collaboration could recently be observed in many countries in setting up COVID-19 vaccine (DHL, 2020), face mask (Müller et al., 2022; Akomea-Frimpong et al., 2023), test kit (Jamal et al., 2022) and ventilator supply chains (Dube et al., 2022). However, when hastily intervening in supply chains, which is inevitable in sudden-onset crises (Van Wassenhove, 2006), public authorities need to acquire knowledge of supply chains and technologies from companies in short time to take effective crisis management measures. The downside of spontaneous collaboration is that it needs to be designed and set up during a crisis, which can cost valuable time for population supply. A short response time is also crucial from a commercial perspective in order to mitigate bullwhip effects in supply chains, which intensify with stronger demand or supply disruptions (Zighan, 2021).

If, on the other hand, public authorities and companies do not collaborate or collaborate poorly, resulting inefficiencies put the population's well-being at stake. In the US, for example, public authorities were criticized during the COVID-19 pandemic for not initiating a centralized reporting system for face masks, which tracks consumption, commercial inventory and production capacity in short time (Sodhi et al., 2021). Public authorities furthermore lacked transparency about the volume of pharmaceutical suppliers in China. This complicated the response to lockdowns in China which caused production stops at suppliers (Chopra et al., 2021). In Germany, public authorities stopped to regularly survey companies about their business activities with relevance for basic supply in 2014 and now lack crucial market information about companies' product portfolio, geographical coverage and size (Menski, 2016).

The latter example highlights the importance of public authorities and companies jointly preparing for crises before a crisis strikes (Jahre et al., 2016; Sheffi, 2001). This is underlined by the successful South Korean coronavirus testing infrastructure. In preparation for pandemics, public authorities designed legislation in a way that enables to quickly approve testing kits. As a result, public authorities collaborated with biotech companies in development and accreditation of test kits and thereby outperformed many other countries' testing infrastructure in speed and scale (Bloomberg, 2020). Another potential collaboration measure for public authorities in preparedness is to not only maintain inventory of essential goods themselves, but to also reserve production capabilities at companies already before a crisis happens (M. K. Li et al., 2022). In practice, this has been implemented by public authorities in Germany during the COVID-19 pandemic for drugs, face masks and medical equipment (tagesschau, 2020). In general, however, there would be very little collaboration in non-crisis times between public authorities and companies. Although Busch and Givens (2013) state that public-private collaboration would be an integral part of US public crisis management, insights from research are scarce.

In the case of Germany, public authorities can be given special legal power to confiscate company resources, though only during a formal supply crisis. Before that, however, collaboration concepts with companies are subject to negotiation. Thus, one possible explanation for the low application of public-private collaboration in supply chain-related crisis management is that public authorities face the challenge to understand and identify the incentives that convince companies to participate. Designing collaboration concepts from which both public authorities and companies with fundamentally different objectives, resources, experience and organizational culture benefit, is challenging and represents an obstacle to more extensive applications (Van Wassenhove, 2006; Maon et al., 2009). So far, literature does not provide sufficient insights into designing these collaborations (Quarshie and Leuschner, 2020; Busch and Givens, 2013).

Hence, the need for research on closer collaboration between companies and public authorities in supply chain-related crisis management is evident. In line with this, researchers formulate numerous explicit calls for investigating the role of public authorities (Ahlqvist et al., 2023; Quarshie and Leuschner, 2020) and companies (Besiou and Van Wassenhove, 2020; Fontainha et al., 2017) separately in supplying essential goods in crises, as well as collaboration between both actors (Quarshie and Leuschner, 2020; Busch and Givens, 2013; Maon et al., 2009).

In response to this research need, this dissertation further investigates the concept of public-private collaboration in supply chain-related crisis management. The focus lies on formal, jointly planned forms of collaboration including preparedness, as the opposite to spontaneous collaboration. The research objectives are to identify the preconditions of collaboration which are most favorable for companies and to propose effective supply chain concepts for public crisis management and evaluate them from both perspectives. On the commercial side, focal industries are those relevant for basic supply of the population with essential goods: food, healthcare and transportation (Holguín-Veras et al., 2022). The geographical focus is on Germany. This results from the author's involvement in the research project NOLAN[1], in the context of which this dissertation has been developed. In project workshops and numerous discussions with practitioners, the commercial perspective was especially enhanced by a large bottled-water producer, a logistics service provider and the supply chain consulting company *4flow*. The understanding of the public perspective was enriched by first-hand insights from public authorities responsible for emergency food supply and transportation infrastructure, namely the *Baden-Württemberg Ministry of Rural Areas and Consumer Protection*, the *Baden-Württemberg Ministry of Transport*, the *German Federal Agency of Civil Protection and Disaster Assistance* and the *German Federal Office for Agriculture and Food*.

In total, six studies with several implications were conducted in this dissertation. The identification of companies' preferred preconditions to collaborate can support public authorities to develop collaboration concepts which contain the right incentives. Beyond that, collaborative supply chain concepts were developed with practitioners from public authorities and companies, which can serve as starting points for practical implementation. Additionally, the concepts provide a more detailed understanding of how public authorities and companies need to prepare for these and which type of company data would have to be made transparent. In line with greater awareness of supply chain risk management among companies due to recent crises (Raman, 2021) and literature asking for more research on preparing supply chains for crises of high impact but low probability, so-called *extreme events* (Holguín-Veras et al., 2022; Sodhi and Tang, 2021), this dissertation also sheds light on how companies can collaborate with public authorities as part of their crisis management.

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The structure of this dissertation is as follows: Chapter 2 gives the theoretical background by characterizing public authorities' and companies' objectives and roles in a collaboration. In Chapter 3, two research objectives are developed from the identified research needs. The conducted studies are summarized in Chapter 4 with regards to the research objectives they contribute to. Implications for research and public and commercial decision-makers are presented in Chapter 5. Finally, Chapter 6 concludes with a summary, discusses limitations and paves the path for future research. The complete versions of all conducted studies can be found in Part II.

2 Theoretical background

2.1 Public and private roles and resources

2.1.1 Public authority perspective

While companies supply the population with essential goods in non-crisis times, public authorities are responsible to maintain supply in response to large-scale crises which jeopardize regular market supply to the detriment of the population. However, public authorities cannot at any time possess and maintain sufficient products and transportation capacities to supply the whole population with food and drugs. They always depend on commercial resources and thus, when a severe supply crisis happens, intensify links with companies in commercial supply chains (Besiou and Van Wassenhove, 2020; Jurica et al., 2019; Chopra et al., 2021; Quarshie and Leuschner, 2020; Wiens et al., 2018; Gabler et al., 2017; Prieto, 2006). Consequently, in crisis preparedness, public authorities influence supply chain design by shaping policies or providing subsidies. Furthermore, they prepare crisis response in coordination with the commercial sector by building and managing relationships and communication channels with companies (Xu et al., 2023; Chopra et al., 2021; Sodhi et al., 2021; Shaheen and Azadegan, 2020).

When a supply crisis strikes, public authorities first try to strengthen essential goods supply chains in order to mitigate a crisis' impact (Blackmon et al., 2021). This can happen through financial support, as observed during the COVID-19 pandemic when public authorities supported small- and medium-sized companies with loans that help to keep the workforce employed (Hofmann et al., 2023). Another commonly observed way to strengthen supply chains is to relax restrictions. In response to the COVID-19 pandemic, German public authorities for example loosened customs regulations and driving restrictions for trucks to maintain supply of essential goods for the population (German Federal Ministry for Digital and Transport, 2022; DHL, 2020). In preparation for a gas shortage, the German Federal Cartel Office also allowed sugar producers to collaborate with each other. Because their production is mainly powered by gas, the producers were given more operational flexibility by using competitors' machinery if a gas shortage occurred (Spiegel Online, 2022).

If such supportive measures are not sufficient or they do not apply because of a sudden crisis with a very short warning time, public authorities need to more actively coordinate population supply. For that, there are different opportunities for public authorities to involve commercial resources in public crisis management. In the case of Germany, for example, public authorities possess some backup resources like warehouses, emergency food stocks and trucks, though warehousing services are maintained by companies (German Federal Office for Agriculture and Food, 2023). Clearly, public authorities benefit from having such contracts with goods and service providers in place before a crisis happens, though insights from practice reveal a lack of application (DHL, 2020; Koliba et al., 2011). Such outsourcing of services is of mutual interest for public authorities and companies. However, public authorities might also confiscate goods or resources (Sodhi and Tang, 2021) by using the far-reaching legal power they can be given during a supply crisis.

In literature, Gabler et al. (2017) describe the ways public authorities can engage in essential goods supply chains in a crisis by ensuring communication, financial and transportation processes and by establishing points of distribution to the population. Quarshie and Leuschner (2020) define the roles for public authorities to engage in commercial supply chains as an organizer, supply network member or facilitator. An organizing public authority would regulate company activities or coordinate staff both before and during a crisis. In their role of the supply network member, which mainly applies to crisis response, public authorities can for example provide infrastructure to enable supply chain flows or connect buyers with suppliers. One example for that can be public authorities building up back-up production capacity in companies in the preparedness phase which is activated in crisis response to meet higher demand (M. K. Li et al., 2022). As a facilitator, public authorities collaborate with or train other actors in relief supply chains. This goes along with higher investments, as it requires for example industry and market knowledge to develop measures with companies (Quarshie and Leuschner, 2020). Regardless of the way of engagement in commercial supply chains, public authorities need to provide companies with clear guidelines for contribution of resources and responsibilities in order to make collaborative supply chain management succeed (Gabler et al., 2017; Busch and Givens, 2013).

At the same time, regardless the type of intervention in commercial supply chains, public authorities aim to ensure fairness and equity in the markets (Xu et al., 2023). When intervening in commercial supply chains, public authorities strive for their continuity and the avoidance of (further) market turbulence. The latter might impede effective collaboration with companies from a public authority perspective (Gabler et al., 2017). Additionally, public authorities must neither favor nor disadvantage specific companies through their intervention (Diehlmann, 2022). Especially the possibility to confiscate resources and the strive for fair market conditions make public authorities special stakeholders for companies' crisis management. Moreover, public authorities' crisis management is in general characterized by unique access to up-to-date information about further development of a crisis. Such information can be gathered from other public authorities, institutions with relevant know-how and other experts. Thereby, public authorities might also know early about potential crisis response measures taken by (other) public authorities (Holguín-Veras et al., 2012; Kovács and Tatham, 2010; Sheffi, 2001).

However, with regards to information about commercial supply chains, public authorities lack experience, detailed and up-to-date market knowledge and technological know-how about latest innovations in supply chain management (Wiens et al., 2018; Swanson and Smith, 2013; Koliba et al., 2011). This is amplified by the fact that public authorities set up supply chains themselves only rarely and for crises with specific characteristics. And if they do so, a lack of market pressure can impede efficient supply chain operations (Koliba et al., 2011). For these reasons, building up experience and market knowledge for different industries (e.g., food, pharmaceutical, face masks) in preparation for large-scale crises is complex and time-consuming for public authorities. In order to use such information for the effective involvement of commercial supply chains in crisis management, public authorities thus rely on companies (DHL, 2020; Holguín-Veras et al., 2012; Kovács and Tatham, 2010).

In conclusion, it is the public authorities' responsibility to maintain population supply, they possess a crisis information advantage and can and must decide how to best involve commercial supply chains in public crisis management. This indicates that public authorities are the ones who should first initiate collaborations with companies in crisis preparedness (Sardesai et al., 2023) and second control collaborative activities in crisis times. Since public authorities are given special legal power to enforce company involvement only during a formal crisis, they need to find the right incentives to involve companies already in the preparedness and escalation phase (Wankmüller and Reiner, 2020; Wiens et al., 2018; Tomasini and Van Wassenhove, 2009).

2.1.2 Company perspective

In case of a disruption of the supply chain, it is a company's objective to maintain its business processes. In order to keep the impact of a disruption as low as possible, companies design flexible supply chain processes and have backup capacities like buffer inventory or additional transport capacities in place. In other terms, companies aim for robust supply chains (Mackay et al., 2020). If a company's robustness measures from the preparedness phase cannot sufficiently maintain operations and delivery reliability is compromised, which in turn leads to sales losses, a company aims to return to normal operations as soon as possible (Gabler et al., 2017; Izumi and Shaw, 2015). Both robustness and recovery speed determine a supply chain's resilience (Vega et al., 2023; Wieland and Durach, 2021; Zobel, 2011).

To achieve supply chain resilience, companies conduct supply chain risk management (SCRM), which in chronological order consists of risk identification and assessment, selection and implementation of SCRM strategies and the mitigation of risks (Manuj and Mentzer, 2008). Typical SCRM strategies are increasing buffer inventory, developing emergency plans, improving supply chain transparency, reducing dependency on suppliers and strengthening supplier relationships (Sheffi, 2001).

Most commonly, companies prepare for internal disruptions, which they can control, and for frequent disruptions with low impact on business operations. For disruptions of low probability and with high impact, they would rather lack preparedness (Izumi and Shaw, 2015; Scala and Lindsay, 2021). However, in line with recent large-scale crises like the COVID-19 pandemic, the war in Ukraine and disruptions in global sea freight caused by the blockade of the Suez canal and ports in many countries (Hou et al., 2022; Gast et al., 2021), many authors therefore propose more elaborate preparation for large-scale disruptions which go beyond typical supply chain risk management (Holguín-Veras et al., 2022; Sodhi and Tang, 2021; Sodhi et al., 2021; Flynn et al., 2021; Ran et al., 2021). For example, Sodhi and Tang (2021) introduce the term *extreme supply chain management* (ESCM), which is characterized by sharp disruptions of supply or demand.

Holguín-Veras et al. (2022) propose researching new supply chain concepts for severe crises. With large parts of the society including supply chain partners and infrastructure being affected in such crises, public authorities play a more important role in supply chain management due to their potential influences on commercial supply chains described above (Sodhi and Tang, 2021; Sodhi et al., 2021; Scala and Lindsay, 2021; Wiens et al., 2018).

For an effective response to any type of crisis, collaboration with partners like other companies, public authorities and NGOs can improve a company's SCRM (Scholten and Schilder, 2015; Christopher and Peck, 2004; Sheffi, 2001; Urciuoli and Hintsa, 2018). For example, data-sharing with customers or suppliers helps to detect disturbances and take alternative measures earlier. Sharing risk management practices with customers, suppliers and competitors increases overall supply chain resilience (Sheffi, 2001; Christopher and Peck, 2004; Klöckner et al., 2023). Moreover, collaboration with other companies in for example resource-sharing, communication and joint knowledge creation can increase supply chain resilience (Scholten and Schilder, 2015). However, it is neither clear in literature how exactly collaboration measures influence resilience (Hosseini et al., 2019; Scholten and Schilder, 2015), nor what exactly would characterize collaboration with public authorities (Busch and Givens, 2013). Nevertheless, Tukamuhabwa et al. (2017) consider collaboration with public authorities as a measure to increase supply chain resilience as well as Urciuoli and Hintsa (2018) surveyed Finnish companies regarding their SCRM and found that information-sharing with public authorities in supplier accreditation would be seen by companies as a field to improve supply chain risk management. However, the authors do not specify this idea any further.

With a less immediate link to resilience, companies also offer donations to other stakeholders as part of their crisis management. This can include monetary and physical donation or support for and partnerships with non-governmental organizations and public authorities. Such partnerships could be observed in the cases of the logistics companies TNT and DHL, who share their logistics expertise and offer training to their partners (Vega and Roussat, 2015; Maon et al., 2009). Whether or not companies make such donations can depend on the corporate performance at that time and can thus stand in conflict with companies' business models. In dynamic business environments, this can limit the preparedness for and commitment to donations at any time (Koliba et al., 2011).

For that reason, it can also be assumed that companies' preferred timing of engagement in public crisis management is in the response phase (Quarshie and Leuschner, 2020; Koliba et al., 2011). At this time, the fact that support and effort are better measurable and the additional advantage that it can be used for publicity are incentives to engage (Bealt et al., 2016; Van Wassenhove, 2006). Notably, Bealt et al. (2016) found that logistics service providers consider the preparedness phase slightly more appropriate for collaboration with humanitarian organizations (like Red Cross or UNICEF) than the response phase.

2.2 Reasons for public authorities and companies to collaborate

2.2.1 Advantages and risks for public authorities

Greater efficiency in costs (i.e., achieving the same supply chain performance at lower costs) in relief supply can be reached by collaboration with companies in logistics preparedness. According to the United Nations, "every dollar invested in emergency preparedness (...) can save $7 in the disaster aftermath" (Jahre et al., 2016). Logistics preparedness can include establishing relationships or communication channels already in non-crisis times (Jahre et al., 2016; Sheffi, 2001). Examples for this are databases about regional availability of physical transportation resources like trucks and warehouse space and equipment (Sheffi, 2001). If public authorities can plan with and rely on company contributions in crisis response, they face less planning and purchasing decisions during the crisis and can focus on other planning tasks (Busch and Givens, 2013; DHL, 2020).

In addition, greater operational efficiency (i.e., achieving better supply chain performance at the same costs) can be achieved. The use of existing commercial supply chain resources and communication channels can be assumed to be more operationally efficient than setting up entirely new public supply chains. Moreover, companies' would bring in experience in understanding and predicting customer demand for products and services. This can support more efficiently matching demand and supply in crisis response. In an often uncertain aftermath of a crisis, this is especially challenging (Swanson and Smith, 2013).

Besides the access to commercial physical resources, information and expertise, public authorities might also accelerate the release and distribution of financial and physical resources from a collaboration with companies. Due to more bureaucratic processes in public institutions, public authorities might have a more difficult access than companies do. Also, in general, less bureaucracy in corporate decision-making can further contribute to the efficiency of overall crisis management (Busch and Givens, 2013; Swanson and Smith, 2013; Maon et al., 2009).

When collaborating with companies, public authorities make themselves in parts dependent on companies' contributions. From this, two major risks arise for public authorities. First, companies act in a more dynamic way than public authorities and change strategies about product types or geographic spread rather frequently. In line with this, their most opportunistic crisis management strategies vary and hence, public authorities fear that they cannot fully rely on company support in crises (Van Wassenhove, 2006). Second, if companies engage in public crisis management but there is no transparent bid process, they might rise prices. The consequences could be high costs for tax payers (Busch and Givens, 2013).

2.2.2 Advantages and risks for companies

An obvious advantage for companies is that they can find short- and long-term economic benefit in identifying new business opportunities by selling products and services to public authorities. This can be a promising field for companies, as public authorities can be reliable and financially strong customers in crises (Vega and Roussat, 2015; Busch and Givens, 2013). However, according to Swanson and Smith (2013) and Sheffi (2001), companies should and would also collaborate with public authorities at the dispense of short-term profit if the assistance of public authorities would pay back as long-term economic benefit.

It can further be assumed that companies operate more efficiently as the result of a collaboration with public authorities by better protecting "their assets, customers, suppliers, or other interests" (Swanson and Smith, 2013) in the crisis area (Busch and Givens, 2013; Kayyem and Chang, 2002). For example, with more insights into companies' business processes, public authorities can also more effectively adjust legal requirements temporarily to strengthen commercial supply chains.

In addition, companies can get information from public authorities about crisis development or potential measures taken by them to protect their operations (Kayyem and Chang, 2002). By reducing uncertainty about the extent or duration of a crisis and public authorities' potential countermeasures, companies can assess a crisis situation faster and make better and quicker decisions (Pal and Altay, 2022; Mehrotra and Schmidt, 2021; Wiens et al., 2018; Busch and Givens, 2013). Responding quickly to demand or supply disruptions is especially important for companies in order to mitigate bullwhip effects which in turn cause inefficiencies in upstream and downstream supply chains (Zighan, 2021; Mehrotra and Schmidt, 2021; Audy et al., 2012). Beyond that, undersupply of food and drugs can cause panic and even riots among the population. Thus, quickly recovering supply can help to protect business processes and staff (Kayyem and Chang, 2002). All this could motivate companies to proactively share information about their vulnerabilities with public authorities in crisis preparedness (Sardesai et al., 2023; Sheffi, 2001).

On the other hand, in terms of information-sharing, companies might fear that confidentiality of their information is not guaranteed and that they suffer from competitive disadvantages as a consequence (Prieto, 2006; Kayyem and Chang, 2002). Additionally, public authorities' far-reaching power can be seen as a risk in information-sharing by companies. During the COVID-19 pandemic, companies in the United States feared that public authorities could take companies' inventory of face masks and shift it to other states for a more equal distribution among the population. Therefore, honest and open sharing of inventory-data with public authorities might have actually negatively impacted or even disrupted business operations (Sodhi et al., 2021). However, this risk does not arise from the collaboration only, though public authorities' right to confiscate goods and to intervene in commercial supply chains poses a permanent threat to supply chain operations in crises. An example for the latter could be observed after Hurricane Maria in Puerto Rico, where companies suffered from public authorities controlling ports and imposing a water rationing plan. Due to these public authorities' interventions, companies' representatives reported that their business processes were disrupted even more. Companies consequently had to adapt and offer substitute products to meet customer demand (Serra and Sanchez-Jauregui, 2021). Therefore, companies might also view collaboration with public authorities as a protective measure, through which they can try to influence public crisis management towards measures with a less damaging or even beneficial impact on companies' supply chain operations.

Similarly, companies can benefit from a collaboration with public authorities in the long run in public policy development for crisis management (Kayyem and Chang, 2002). If companies actively engage and are transparent about what they can or cannot contribute during a crisis, public policies can include this in more effective policy-making from both public and commercial perspectives (Busch and Givens, 2013). Especially the current times with more large-scale crises require public authorities to formulate SCRM-related policies. For example, public authorities making domestic sourcing more favorable or imposing traceability along supply chains provide opportunities for companies to shape these (Grover and Dresner, 2022).

Furthermore, collaboration with public authorities can contribute to companies' corporate social responsibility (CSR) strategy or enable positive publicity (Lüttenberg et al., 2022; Bealt et al., 2016; Swanson and Smith, 2013), like in the cases of the logistics companies TNT and DHL (Maon et al., 2009). For TNT, advantages from the collaboration were additionally improved customer loyalty, employee morale and motivation and skills to make supply chains more resilient (Van Wassenhove, 2006). Communication of crisis management skills can also strengthen customer loyalty (Kayyem and Chang, 2002).

However, according to a survey among logistics service providers about collaboration with humanitarian organizations by Bealt et al. (2016), the companies' motivation to do good and altruistically help people in need seems to be relatively little motivation. Rather, strategic decisions, CSR and publicity were perceived as main drivers to collaborate with humanitarian organizations. Thus, one might conclude that companies need to see sufficient benefits for them and internal rules to collaborate with other parties in crisis management.

3 Research needs and objectives

3.1 Research needs on public-private collaboration in supply chain-related crisis management

With several advantages for both parties and areas of collaboration being known, one would expect to read about successful implementations of public-private collaboration in supply chain-related crisis management. Even though Sheffi (2001), Maon et al. (2009), Busch and Givens (2012) and Busch and Givens (2013) predicted increasing numbers of application and Maon et al. (2009) asked for research on how such collaborations can best work, literature examining these from a commercial supply chain perspective remains scarce. The need for public-private collaboration has been brought up several times though after some large-scale crises in the past, for example in the last decade's German national security research program (Hamann and Strittmatter, 2014; German Federal Ministry of Education and Research, 2018) and in the political discourse in the US (US Government Printing Office, 2007).

After 9/11, Sheffi (2001) discussed the need for and areas of public-private collaborations in supply chains in order to improve defense against terrorism. Among others, it is suggested that companies should share information about their vulnerabilities with public authorities and use public authorities' experience in crisis management (see also Prieto (2006)).

In 2005, in response to Hurricane Katrina in the US, Walmart efficiently managed to ship goods into the crisis region and thereby outperformed public authorities' relief supply chains. Afterwards, when Walmart was asked to become public authorities' permanent supplier of essential goods, the retailer rejected the offer since it would, among others, not fit into its business model. These developments have received much attention in literature and have since then been picked up in several discussions about public-private collaboration in supply chain-related crisis management (Sobel and Leeson, 2006; Cigler, 2006; Prieto, 2006; Rosegrant and Leonard, 2007; Horwitz, 2009; US Chamber of Commerce Foundation, 2012; Chen et al., 2013; Busch and Givens, 2012, 2013). Despite the attention the case of Walmart has received, the questions under which circumstances companies would collaborate and how this collaboration can be effectively operationalized in supply chains remained unanswered in literature.

With the COVID-19 pandemic, many links between public authorities' crisis management and commercial supply chain management could be observed. For example, pharmaceutical supply chains for COVID-19 vaccines created new business opportunities for companies (DHL, 2020). Such partnerships would have been effective in the US and Farhadi and Galloway (2022) further conclude that applying public-private partnerships in other sectors would increase resilience of society, also from a defense perspective. In the US, public authorities initiated new supply chains through a food box program and connected commercial suppliers and distributors like food banks, shelters or soup kitchens to supply the population in need, with food (Blackmon et al., 2021). Hence, public authorities' role in this case corresponds with that as the supply network member (Quarshie and Leuschner, 2020). As a consequence, companies could sustain their operations, though the authors do not further discuss benefits for companies.

In line with this, several researchers proposed new research topics in the field of public-private collaboration in supply chain-related crisis management. For example, de Moura et al. (2020) propose research on the type of resources shared in public-private collaborations and how know-how from both parties could best be used. In addition, suggestions for joint control of supply chains were made: Scala and Lindsay (2021) state that healthcare supply chains should be considered as critical infrastructure and be managed jointly by public and private actors in crises. Sodhi et al. (2021) suggest public authorities to run stress tests to make supply of essential goods more resilient (see also Sheffi (2001)).

Further, more policy-oriented research proposals were made. Joint policy development can improve supply chain resilience and thus offer public authorities levers to incentivize collaboration of companies (Ahlqvist et al., 2023). Sodhi and Tang (2021) suggest research on subsidy schemes and joint re-shoring programs and Chopra et al. (2021) propose investigation of government-sponsored commons. The authors define commons as "a set of pooled resources for the flow of information, product, or funds" which can be used across companies or industries and thereby increase companies' efficiency and resilience. Since they are expensive to set up for private actors, it should be researched how government-sponsored commons can mitigate extreme disruptions of supply chains.

In conclusion, the need for a deeper understanding of public-private collaboration in supply chain-related crisis management is evident – from both researchers' and practitioners' perspectives. Recent literature indicates that the COVID-19 pandemic has revealed some shortcomings in this field. However, current research lacks a comprehensive overview about roles, advantages and risks from a company perspective. Beyond that, little is known about the circumstances under which companies would be most willing to collaborate with public authorities in supply chain-related crisis management (see also Prieto (2006)).

It is also not clear in literature what effective and efficient collaborative supply chain concepts can look like (Kayyem and Chang, 2002). Although Busch and Givens (2013) suggest that collaboration contracts should be designed in the preparedness phase with clear deliverables and even be made available to the public, no example of planned collaboration could be found. It is known that Walmart rejected to become contractual supplier for public authorities and to thus maintain stock for public authorities and to supply when needed (Chen et al., 2013). As the US faces crises rather regularly, the incentive for retailers in countries with fewer crises to maintain stock for public authorities might be even lower. Hence, another design for reliable supply from companies in disaster relief operations will be needed.

Closest to that is the study of Swanson and Smith (2013) which investigates the applicability of four commercial supply chain concepts in relief supply chains. 52 logistics professionals rated the concept *push/pull* (first *pushing* roughly estimated supply volumes until more accurate demand forecast can be made for *pull*) highest, followed by inventory allocation under limited supply, order fulfillment at retail stores and transportation. The authors, however, only take a public authorities' perspective when assessing the concepts' effectiveness. In addition to that, Sodhi et al. (2021) and Hecht et al. (2019) propose that public authorities and companies should apply known supply chain concepts like redundancy and multi-sourcing or flexibility to strengthen essential goods supply.

Moreover, a few supply chain concepts for spontaneous collaboration during the COVID-19 pandemic exist, like the above-mentioned food box program (Blackmon et al., 2021), COVID-19 vaccine supply chains (DHL, 2020) or a last-mile delivery concept to supply vulnerable people in the UK (Department for Environment, Food and Rural Affairs, 2020). The Chinese retailer JD.com and the government of Hubei province collaborated and used a platform to track production, inventory and distribution of emergency supplies, which improved the matching of demand and supply (Shen and Sun, 2021). However, insights into companies' perspective on efficiency of supply chain concepts or main drivers to participate in which supply chain concepts are barely known.

To sum up, current research does not provide decision-makers in companies and public authorities with sufficient operational insights into public-private collaboration in crisis management nor with what business cases could look like that incentivize companies.

In the following, the term public-private emergency collaboration (PPEC, Wiens et al. (2018)) will be used for public-private collaboration in supply chain-related crisis management for the provision of essential goods like food or drugs. According to Wiens et al. (2018), PPEC combines regular commercial supply chains with relief supply chains. It is further agreed upon in the preparedness phase and thereby distinguishes from spontaneous collaboration.

3.2 Research objectives

The identified research needs are (1) the preferred circumstances under which companies would collaborate with public authorities in supply chain-related crisis management and (2) supply chain concepts for collaboration. From both needs, one respective research objective was derived.

Research objective 1: Preconditions for company engagement in public supply chain-related crisis management

The first research objective (RO 1) was investigated using two studies. Study A identifies both actors' characteristics, resources and roles in a collaboration. For that, existing literature, real-life cases as well as discussions with public authorities and companies in essential goods supply chains were reviewed. This resulted in a framework which summarizes the main characteristics of public-private collaboration and provides guidelines for future research which models collaboration concepts. With regards to RO 1, preconditions for company engagement in PPEC are listed.

Study B empirically investigates how companies weigh these potential preconditions in order to give a view of companies preferred design of a PPEC. With that, the study fits into research needs stated by Gabler et al. (2017) who explicitly suggest to investigate public-private relations through surveys. Consequently, in Study B, a survey among German companies from essential good supply chains was conducted to identify the circumstances under which companies would prefer to collaborate. Thereby, the study directly contributes to the answer of RO1 and goes beyond Study A by weighting preconditions for company engagement.

Both studies were motivated by discussions with and insights from public and private practitioners in workshops during the NOLAN project. Especially in Study B, survey design, pre-test and validation of results are backed up by practitioners.

Research objective 2: Development and evaluation of concepts of supply chain-related crisis management from public and private perspectives

The second research objective (RO 2) was investigated using four studies that examine supply chain concepts in detail for crisis management which include public and private perspectives. Thereby, RO 2 addressed the need for new supply chain concepts which should be investigated to respond to an increased frequency of severe crises according to Holguín-Veras et al. (2022) and Sodhi and Tang (2021). In line with calls from researchers for more real-life features in crisis management (Besiou and Van Wassenhove, 2020; Baharmand et al., 2022), the studies were moreover developed with public and private practitioners.

Study C develops and evaluates a collaborative supply chain concept for the immediate response to a tap water failure and resulting high demand for bottled water in retail stores. The underlying idea is to use commercial trucks, which are on the road at the time of the crisis, for faster immediate relief supplies than (public or private) trucks which would have to be provided and loaded first. Public authorities can lift competition restrictions to enable more efficient relief supply. The concept is evaluated regarding service level and transport distances.

Motivated by real-life challenges during the COVID-19 pandemic, Study D develops a supply chain concept for home delivery during pandemics. The objective is to plan efficient supply of essential goods for vulnerable people while last-mile delivery vehicles are modeled as scarce resources. Hence, the concept's main indicator of efficiency is the number of vehicles used.

Study E investigates the concept of public-private dual-use warehouses for emergency food stock. Since companies and public authorities have different preferences regarding their warehouses' locations, the modeled warehouse networks are evaluated regarding costs and response time and a developed attractiveness score.

Study F is inspired by the lack of research on the interplay between physical and financial flows in supply chains. This is especially true for crisis situations, which is why the research topic is a stylized gastronomy supply chain during the COVID-19 pandemic. The study analyzes the impact of extended payment terms during demand shortfalls in restaurants.

In all studies, different settings (e.g., demand, collaboration and operational characteristics) are modeled in order to better understand the dynamics of the supply chain concept. This is crucial in uncertain crisis situations. In addition, most of the studies associated with RO 2 aim to contain actionable research to result in ideas of supply chain concepts which can be (at least partly) implemented by practitioners. This would be especially helpful for practitioners in SCRM for severe disruptions according to Ketchen and Craighead (2020). Moreover, different disaster types (e.g., sudden-onset tap water failure and comparably slow-onset COVID-19 pandemic) and different areas of supply chain management (operational re-routing of trucks, strategic warehouse location planning, tactical last-mile distribution planning) are covered. Both are formulated as research needs in PPEC by Gabler et al. (2017).

All conducted studies are shown in Figure 3.1 and will be summarized in Chapter 4 with a focus on the ROs they address. The complete studies can be found in Part II.

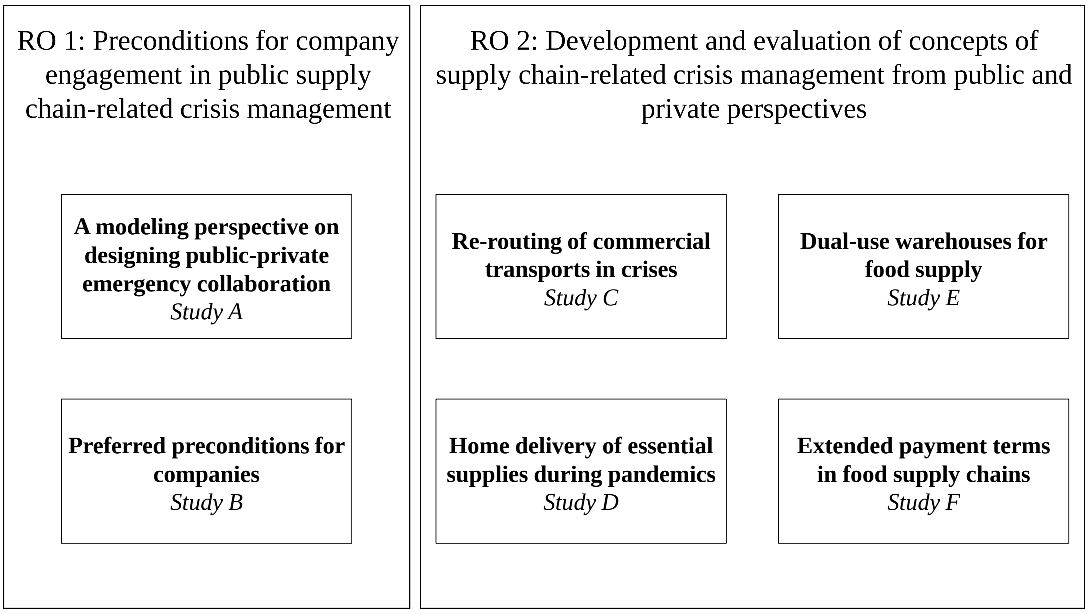

Figure 3.1: Research objectives and the corresponding studies (studies are presented with short titles)

4 Study results

4.1 Study A: A modeling perspective on designing public-private emergency collaboration

4.1.1 Background and motivation

Next to the lack of research on PPEC (see Chapter 2), studies of real-world cases in relief supply rarely take a public authorities' perspective. One explanation for the absence of extensive research can be the fact that critical data at public authorities is more rarely shared with researchers than data from companies and humanitarian organizations (Goolsby, 2005). With regards to RO 1, the first objective of this study was, therefore, to sharpen the definition of the PPEC concept through examining the roles of both companies and public authorities. In addition, an overview of potential preconditions for company engagement in PPEC should be identified and provided.

4.1.2 Method and results

Study A aims first to examine the scope and potential of PPEC. Literature, documented real-world cases and discussions with practitioners are examined for this purpose. As a result, the contributed resources and roles taken by both actors are defined. Thereby, this study develops a modeling framework covering logistical differences in PPEC.

Scope and potential of PPEC are further enriched by its understanding of the background of the different phases of escalation in a crisis (see Figure 4.1). Typically, in case of a disruption, companies try to protect their processes as long as they can or resume processes as soon as possible (Palin, 2017). If the crisis affects many companies, critical infrastructure or the population in general, public authorities should become more active to maintain supply of the population with essential goods (I). If companies and public authorities cannot maintain basic supply to the population, NGOs provide further support by supplying goods (II). Similarly, the de-escalation of a crisis would work with NGOs first withdrawing (III) and, after that, public authorities (IV) until companies alone take over supply of the population again. In case of a sudden-onset crisis, however, NGOs can engage right away (V) or, in case of severe crises, stay engaged until companies take over again (VI).

Following this, a PPEC can prevent a crisis from further escalation and reduce the necessity of public authorities and NGOs setting up temporary supply chains. Moreover, it can be concluded

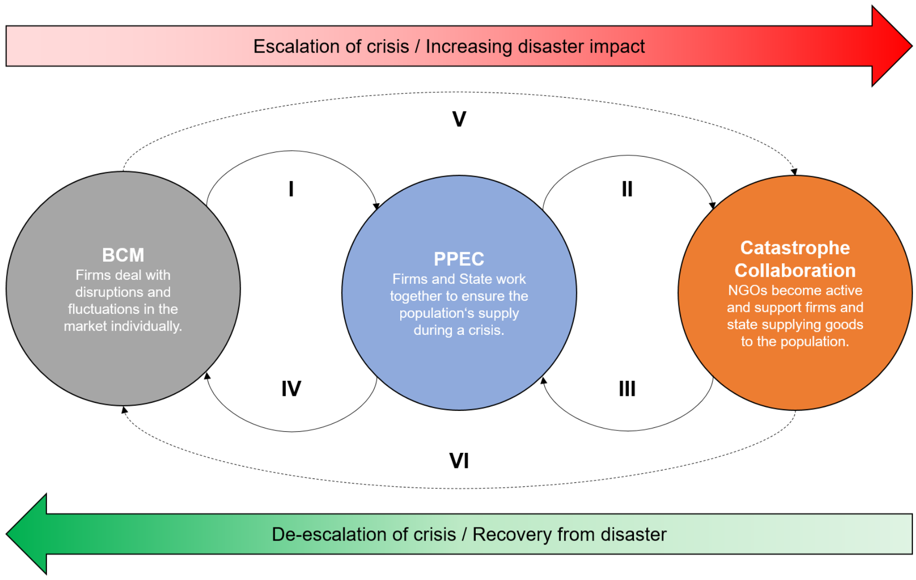

Figure 4.1: Phases of crisis management and PPEC (see also Figure A.1)

that companies can provide a strong contribution to crisis management at an early stage of escalation and to a fast deescalation at any time.

Furthermore, in a logistical modeling framework, some preconditions of PPEC are examined. The modeling framework covers *Strategy and motivation*, *Interaction between public authorities and companies* and *Capabilities and resources* and is summarized in the following.

4.1.2.1 Strategy and motivation

First, there are fundamental differences in both actors' strategies. Companies are mainly profit-oriented and on the other hand, public authorities' goal is the well-being of the population. This can be modeled through equity, fairness and deprivation aspects. The company perspective could be modeled by for example a profit maximization or cost minimization. However, this can be complex if disruptions with cascading effects are hard to quantify.

Moreover, the planning horizon in supply chain management differs between both actors. Companies develop strategies, set up supply chains and invest resources to be profitable in the long-term (mostly in non-crisis times) and adapt to the specific circumstances of a crisis if necessary. Contrary to that, public authorities' strategy can include setting up supply chains only temporarily for a crisis if necessary which makes them more flexible in decisions about locations or products.

4.1.2.2 Interaction between public authorities and companies

Public authorities can be given far-reaching rights to confiscate goods, though they can also take measures to support companies' operations. During the COVID-19 pandemic, public authorities gave companies greater flexibility by allowing trucks with essential supplies to drive on Sundays which is not allowed in Germany in non-crisis times (German Federal Ministry of Transport and

Digital Infrastructure, 2020). Another example is the extension of shop hours for grocery stores to reduce contacts among shoppers (Rundschau, 2020). Better understanding the impact on business activities and exploring other effects of public authorities' restrictions could be considered in modeling PPEC. Besides that, trust and partner selection are worth modeling, as public authorities might question the reliability of company support and companies might perceive public authorities as bureaucratic and thus slow-moving.

In addition, mechanisms for the division of costs of products, logistics and coordination are an important criteria for companies to engage in a PPEC.

4.1.2.3 Capabilities and resources

Assuming that companies' capabilities and resources are still available despite the crisis, companies can contribute with established routines, communication networks and market knowledge. However, they might face severe uncertainties about crisis dynamics (e.g., supply, capacity, lead time) and the appropriate response measures which should be considered in modeling decision support.

In terms of uncertainty, literature research revealed a time gap in crisis response: The case of tap water failure in Heidelberg showed that retailers were immediately affected by a sudden demand peak and thus aimed to replenish retail stores as soon as possible. Retailers had to bridge some hours until public authorities would have agreed on and developed a supporting water supply chain.

Additionally, regarding resources, the challenge for public authorities to control company resources under uncertainty and the difference in staff availability is highlighted. While companies hire staff for non-crisis times, public authorities depend on volunteers. Hence, the ability to plan with staff and flexibility in temporarily deploying more staff are considerable differences between public authorities and companies.

4.1.3 Implications

The main theoretical implication lies in the developed modeling framework which provides a basis for future research on PPEC by providing key differences with relevance for studies in the research field of operations management. Additionally, a basic game-theoretic model completes the modeling framework considering motivation and incentives of public authorities and companies. Thereby, it supports public decision-makers in the incentive-based design of PPEC. Finally, the study supports the implementation of PPEC in practice by informing decision-makers from both parties about key characteristics of the other party.

4.2 Study B: Preferred preconditions for companies in public-private emergency collaboration

4.2.1 Background and motivation

On the basis of the aforementioned logistical characteristics of PPEC and the identified opportunities and advantages for companies to engage in PPEC (Chapter 2 and Study A), Study B investigates how PPECs need to be designed to make them favorable for companies. The objective of Study B is to weigh the preconditions of PPEC from a company perspective. Thus, Study B directly contributes to RO 1.

In workshops with public authorities on state and federal level during the NOLAN project, they revealed that they would lack knowledge of how to incentivize companies so that these engage in a PPEC in the most reliable way. Therefore, the public authorities explicitly formulated the need to learn more about companies' preferred design of a PPEC.

Moreover, public authorities highlighted that they were contacted by several companies who asked whether they would be recognized as critical infrastructure during the COVID-19 pandemic. With this, the companies would have hoped for public crisis management providing more effective regulations in support of their supply chains. On the other hand, company representatives mentioned that data privacy concerns would keep them from actively initiating a collaboration with public authorities. From these practical insights, some first empirical indications for barriers and incentives can be derived, but a more sound empirical basis is needed for a more reliable picture of companies' preferred PPEC design.

4.2.2 Method and results

4.2.2.1 Data collection

To investigate companies' preferred PPEC design, three research questions (RQ) and two hypotheses for each research question are formulated (see Figure 4.2). RQ 1 addresses the main incentives and barriers for companies to collaborate, RQ 2 deals with the opportunity to promote PPEC through publicity and the timing of company involvement and RQ 3 asks for identification of companies' preferred contributions.

A quantitative survey is developed to answer the research questions. The survey consists of 13 questions and tracks 12 characteristics of the respondents and their companies. The respondents were from companies in production, retailing, wholesaling and logistics in the food and healthcare industries. The survey was conducted in summer 2021 and about 9,000 German companies were contacted. From that, 398 responses were received which means a low but common response rate for large-scale surveys among managers from food and retail companies (Ellis et al., 2010; Dora et al., 2014).

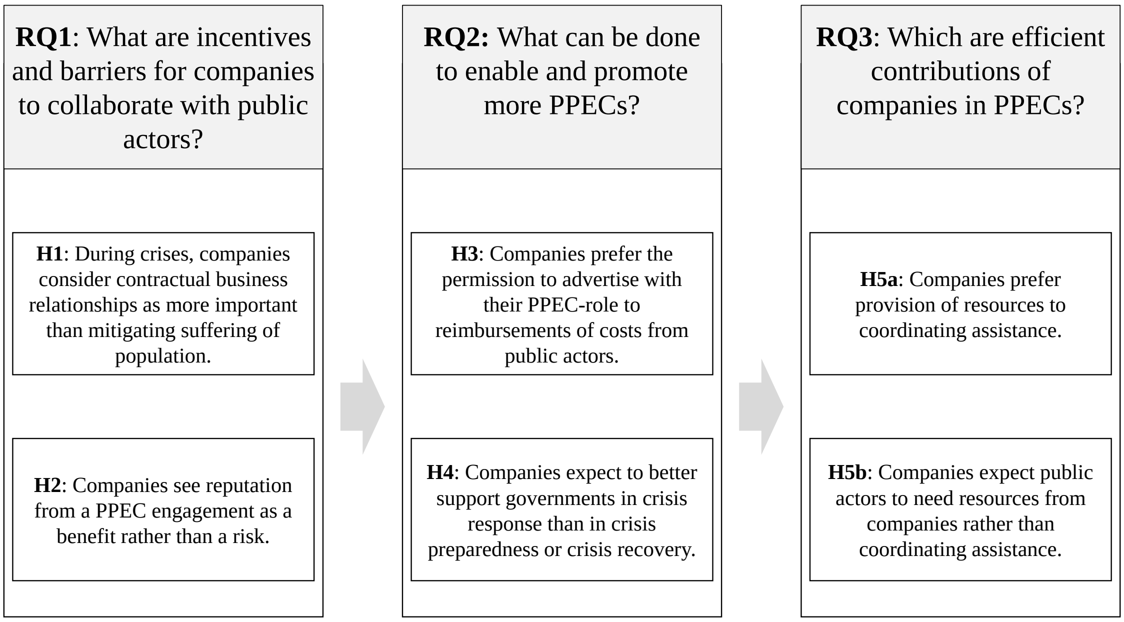

Figure 4.2: Research questions and corresponding hypotheses (see also Figure B.1)

The characteristics of the respondents and their companies are listed in Table 4.1. About 75% of the respondents were from (top-) management which is why a strong approximation of corporate decisions can be assumed from the replies. Remarkably, the share of replies from persons with responsibility in business continuity management seems rather high.

4.2.2.2 Companies' preferred preconditions

In the following, two hypotheses are presented. The hypothesis *Companies prefer the permission to promote with their PPEC-role to reimbursements of costs from public actors* (H3) is tested through the question in Table 4.2. On a Likert scale from one (*very important*) to five (*not important*), the respondents rated *Incurred costs need to be reimbursed* higher than the *Permission to promote* ($Means$ 1.95 vs. 2.97). A one-sided t-test indicates a statistically significant difference ($p = 0.000$, confidence interval $\alpha = 95\%$). Therefore, H3 is rejected. H3 could also be rejected separately across respondents from every industry, supply chain stage and company revenue category.

In addition, a weak positive correlation is measured between the responses to both questions ($r = 0.172, p = 0.001$). Thus, the more important the reimbursement of costs is to the respondent, the more important is the permission to promote and vice-versa. So, there is a subgroup which is characterized by a general demand of compensation of some kind. This includes both the cost perspective and a CSR perspective with positive publicity. We also find that small companies rated *Cost reimbursement* higher than large companies and assume that this is due to higher liquidity among large companies. Moreover, respondents rate *Operational processes* highest within this question, followed by *No internal information to competitors* and *Public actors grant special rights*.

Variable	Sample companies	
	Number	Percentage (%)
Industry		
Grocery	146	36,7
thereof: Production	*91*	*22,9*
thereof: Retail	*55*	*13,8*
Healthcare	125	31,4
thereof: Production	*46*	*11,6*
thereof: Retail	*79*	*19,8*
Logistics	97	24,4
thereof: Grocery	*9*	*2,3*
thereof: Healthcare	*7*	*1,8*
thereof: Others	*80*	*20,1*
No answer	30	7,5
Employees		
$1 - 10$	41	10,3
$11 - 20$	183	46,0
$21 - 100$	136	34,2
> 100	37	9,4
No answer	1	0,3
Annual revenue		
$<$10 Mio €	256	64,3
10 Mio - 50 Mio €	90	22,7
$>$50 Mio €	36	9,0
No answer	16	4,0
Family business		
Yes	334	83,9
No	55	13,8
No answer	9	2,3
Area of responsibility of respondent (multiple answers possible)		
(Top-)Management	301	75,6
Business Continuity Management	140	35,4
Logistics or SCM	131	32,9
Corporate Social Responsibility	94	23,6
Other	34	8,5
No answer	16	4,0

$n = 398$

Table 4.1: Companies' characteristics (see also Table B.1)

We conclude that public authorities should incentivize companies with preconditions that contain compensation regulations, ensure confidentiality towards competitors and maintain business operations. Notably, to be granted special rights in a crisis is preferred to cost reimbursement. Enabling publicity is of rather low importance to companies.

How important would the following conditions be in a collaboration with public actors?	Mean	SD
Operational processes must not be endangered	1.42	0.71
Competitors must not have access to internal corporate information	1.46	0.79
Incurred costs need to be reimbursed	1.95	0.83
Permission to promote with the relief	2.97	1.05
Public actors need to take over some of the risks associated with the company's investments in crisis management	2.02	0.92
Willingness of public actors to grant special rights (e.g., opening or driving times)	1.51	0.71

$n = 375$, $1 =$*very important*, $5 =$*not important*

Table 4.2: Preconditions for collaboration with public actors (H3) (see also Table B.3)

4.2.2.3 Companies' preferred contributions

The hypothesis *Companies prefer the provision of resources to coordinating assistance* (H5a) is tested with the questions in Table 4.3. For each type of contribution, respondents were asked to indicate how willing they would be to provide it. For that, we used a Likert scale consisting of $1 =$*free of charge*, $2 =$*against reimbursement* and $3 =$*no willingness at all*.

Type	For each type of assistance mentioned, please indicate the conditions under which you would be willing to provide it.	Mean	SD
Resources	Providing goods	1.75	0.512
Resources	Providing transportation capacity	1.70	0.594
Resources	Providing storage	1.62	0.696
Coordination	Tactical planning	1.93	0.883
Coordination	Strategic planning	1.59	0.608

$n = 381$, $1 =$*free of charge*, $2 =$*against reimbursement*, $3 =$*no willingness at all*

Table 4.3: Preferred contributions in a PPEC (H5a) (see also Table B.6)

The willingness to provide *Resources* is rated significantly higher than to taking part in *Coordination* activities ($Mean = 1.69$, $SD = 0.43$ compared to $Mean = 1.76$, $SD = 0.63$; one-sided t-test with $p = 0.016$). As a result, H5a is not rejected.

Moreover, *Providing storage* is rated highest among the respondents. For this question, no significant differences across industries could be observed. This is noteworthy because one could also expect logistics service providers to be most willing to share, as they have large storage capacities. On the other hand, this is maybe just because it is logistics service providers' core business to sell their storage capacities. Contributing them in a PPEC would therefore directly impact their business operations.

Into a similar direction points that companies prefer *Strategic planning* to *Tactical planning*. With *Tactical planning* we refer to planning production or transports for the next weeks or months. Hence, this is closer to business operations than *Strategic planning* and therefore in line with answers to the question of H3 (Table 4.2). Remarkably, this preference of *Strategic planning* is quite strong, as the relatively wide range between *Strategic planning* and *Tactical planning* indicates.

4.2.3 Implications

Beyond testing H5, the corresponding question revealed that companies across industries, supply chain stages and company sizes are very open to share data with public authorities. 91% of the respondents replied that they would share information with public authorities *free of charge* or *against reimbursement of costs*. This means that they would rather share information with public authorities than with competitors (77%) and that they would be as willing to share information with public authorities as with companies from their own supply chain (91%). Thus, public authorities should use this potential and provide companies with opportunities for safe data transfer. Since companies aim to avoid long-term involvement in PPEC, such data transfer would require a digital solution with low effort on the company-side.

Moreover, the more benefits respondents see in a PPEC, the less monetary compensation they expect for their contribution. Thus, public authorities should promote the benefits of a PPEC to the public. On this basis, public authorities might try to first improve the non-financial conditions for only some companies and afterwards communicate their contribution more extensively. At the same time, quick compensation processes need to be developed.

Furthermore, Study B revealed that companies highly value the continuity of their business processes and compensation of their contribution. In compensation, there were also some industry-specific differences: Logistics companies prefer the relaxation of regulations and healthcare companies value potential reputation gains higher than others.

These insights can be used to design and operationalize PPECs in the best way with respect to the companies' incentives. In the near future, a greater focus among companies on SCRM may lead to more robust supply chains than nowadays. Companies with more robust supply chains might be more willing to contribute, as they have lower opportunity costs because of their robust and agile operations. In addition, these companies are likely to have higher competence in crisis management than other companies.

4.3 Study C: Public-private collaborative re-routing of commercial transports in crisis situations

4.3.1 Background and motivation

In case of sudden-onset crises with an immediate high demand for essential goods, it is crucial to activate relief logistics within a short time. However, discussions with German public authorities from the *German Federal Agency of Civil Protection and Disaster Assistance*, the *German Federal Office for Agriculture and Food* and the *Baden-Württemberg Ministry of Rural Areas and Consumer*

Protection revealed that for the immediate response to a large-scale tap water failure, the detailed procedures are largely undefined. After taking over responsibility and gathering physical resources, valuable time might have passed. In this setting, people would most likely turn to retail stores to satisfy their increased demand with bottled water (Heidelberg24, 2019; Menski, 2016; LZ.de, 2016). The most commonly observed response of retailers is to send trucks from warehouses loaded with safety stock to affected stores (Heidelberg24, 2019; LZ.de, 2016; Horwitz, 2009). However, providing and loading these trucks as well as the driving time to the affected stores takes time. Due to leaner supply chains and decreasing stocks, large amounts of bottled water are usually in transport on the road. In discussions, a large bottled water producer therefore brought up the idea to re-route trucks based on real-time data into crisis areas.

In line with public authorities claiming to involve companies more in emergency food supply, Study C therefore investigates public-private collaborative re-routing in the immediate response to a crisis. When involving retailers' resources in public crisis management on such short notice, time dynamics such as store opening times, customers' expected purchasing behavior, inventory management and replenishment processes need to be considered. By addressing the resulting intra-day fluctuations in demand as well as vehicle availability and the impact on beneficiaries, this is, to the best of my knowledge, one of the first studies to evaluate relief logistics concepts regarding the time when a crisis strikes.

4.3.2 Method and results

4.3.2.1 Re-routing approach

We propose a supply chain concept for the re-routing of commercial transports into a crisis region (see Figure 4.3). The approach re-routes vehicles within a defined range around the crisis region and plans new tours to satisfy demand there. These vehicles can be fully or partially loaded depending on their tour progress. If the vehicles' load is not sufficient to meet demand, safety stock from the nearest warehouse(s) is also sent to affected stores with additional trucks. The mathematical formulation of the corresponding Multi-Depot Split Delivery Vehicle Routing Problem (MDSDVRP) is presented in Chapter C.3 and is based on Ramos et al. (2020), Ray et al. (2014) and Cordeau et al. (1997). The MDSDVRP has three special characteristics. Stores can be supplied by more than one vehicle (i.e., split delivery), because store demand is likely to exceed vehicle load. Supply can (slightly) exceed demand, since vehicles are only fully re-routed and return empty to their original warehouse for operational efficiency. Fairness among stores is created by ensuring that as many stores as possible are the first stop on any vehicle's re-routed tour.

4.3.2.2 Case study

We apply our approach to a developed case study. This consists of a large-scale tap water failure in the German city of Stuttgart and considers state authorities which lift competition law as well as three retailers operating in the corresponding state of Baden-Württemberg. Real locations of

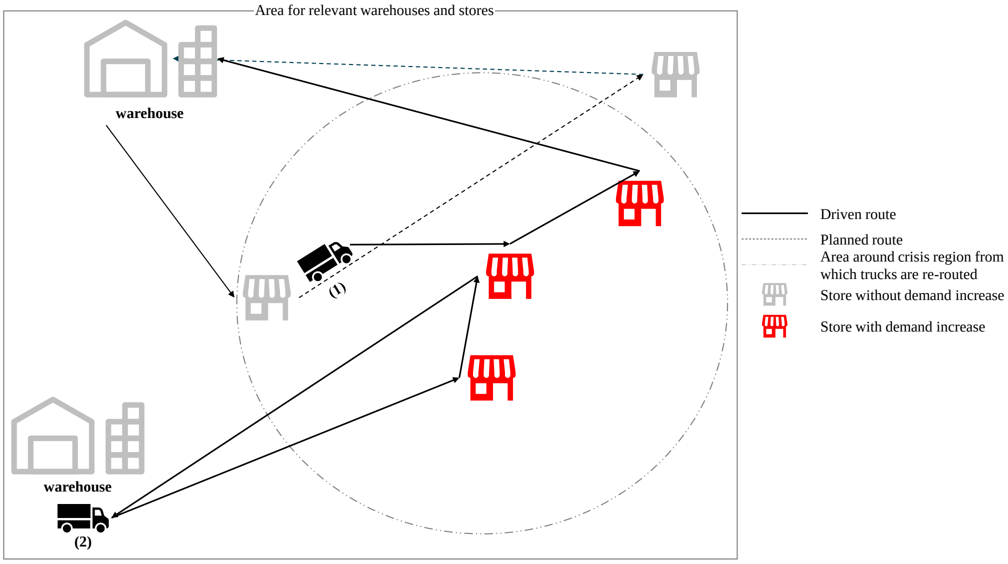

Figure 4.3: Trucks on the road (1) and additional trucks with warehouse safety stocks (2) are routed to affected stores. A store can be supplied by more than one vehicle (see also Figure C.1).

retailers' warehouses and stores are used to model their distribution networks at minimum distance applying a Multi-Depot Capacitated Vehicle Routing Problem. Stores' daily demand is assumed to be three pallets.

Store opening hours are assumed to be from 8:00 to 20:00. Tours are randomly assigned to potential departure times in the morning (8:00, 8:30, 9:00) and in the afternoon (13:00, 13:30, 14:00). With the HERE API, every truck's position at the time of the crisis is approximated. As a result, Figure 4.4 illustrates the number of trucks passing by the crisis area throughout a day.

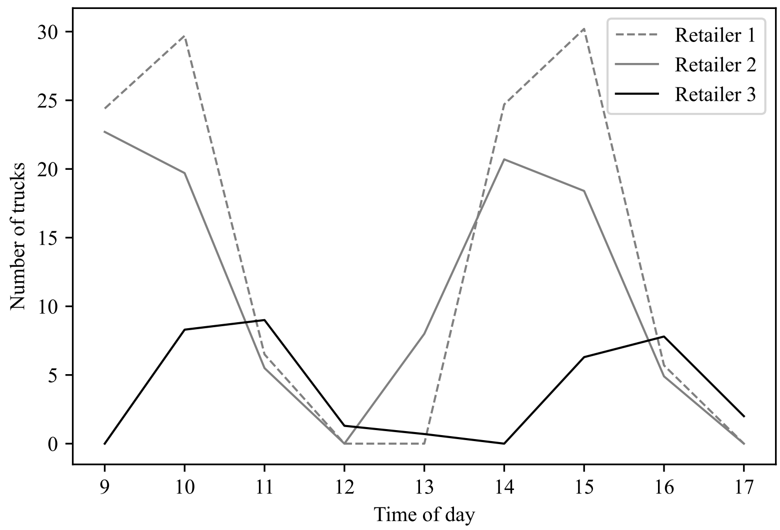

Figure 4.4: Partially or fully loaded trucks within range of 40 km around the crisis area (average values over ten departure time distributions, see also Figure C.3)

In order to showcase the effects of collaborative re-routing (scenario C), it is compared to retailers sending additional trucks from warehouses (scenario A) as well as retailers re-routing individually (scenario B). Furthermore, different settings regarding crisis timing (10:00, 12:00, 14:00), crisis extent and radius from which trucks are re-routed (see Table 4.4) are modeled. Ten simulation runs are performed to account for the random generation of tours' departure times.

		Radius					
		20		30		40	
	Nr trucks in range	30.2		44		58.1	
Demand	Scenario	**B**	**C**	**B**	**C**	**B**	**C**
300	Service level [%]	96.85	97.86	97.62	97.93	97.71	97.93
	Nr. additional trucks	4.5	1.5	3.5	0	1	0
	Nr. re-routed tours	25.1	29.6	27.6	32.6	33.4	32.6
	Total supply [pallets]	200.5	197.2	200.9	200.1	202.5	200.1
	Distance [km]	2,358.39	2,512.83	2,493.87	2,692.71	2,871.61	2,692.71
600	Service level [%]	89.41	94.52	91.74	94.88	93.91	94.93
	Nr. additional trucks	11.2	11.8	8.8	6.1	6.9	1.4
	Nr. re-routed tours	28.2	30.2	37.2	44	45.5	57.1
	Total supply [pallets]	310.4	350.9	324.5	350.9	350.2	351.7
	Distance [km]	3,619.86	3,869.03	4,303.8	4,617.22	4,928.46	5,569.6
900	Service level [%]	73.9	91.69	76.76	93.07	84.17	93.31
	Nr. additional trucks	15.4	24.4	12.5	17.3	10.3	12.2
	Nr. re-routed tours	29.2	30.2	39.3	44	53.4	58.1
	Total supply [pallets]	380.5	511.5	394	511.5	432.1	511.5
	Distance [km]	4,286.11	6,610.07	4,940.27	6,455.89	6,283.22	7,073.67

Table 4.4: Results for crisis time 10:00 from ten simulation runs (see also Table C.4)

Across all crisis timings, collaborative re-routing achieves a greater service level than individual re-routing. If a retailer cannot fully meet the greatly increased demand by itself, the joint use of other retailers' resources intensifies the benefit of collaboration.

In all settings, at 10:00, re-routing individually achieves a better service level than scenario A. At 12:00, with few trucks on the road, both scenario B and scenario C achieve a lower service level than the reference scenario (A: 87.92%, B: 86.01% and C: 87.83%). However, scenario A requires significantly more additional trucks for this (A: 21, B: 10, C: 9).

Furthermore, retailers' benefits and contributions vary with different settings. Retailer 1 has the most stores and thus more trucks on the road than other retailers. Compared to Retailer 2, Retailer 1 also operates less stores in the crisis region. Consequently, when re-routing collaboratively, Retailer 1 often faces a lower service level compared to re-routing individually. Contrary to that, Retailer 2 barely faces a worse service level from collaboration. Retailer 3 operates only one remote warehouse, which means longer tours. Hence, Retailer 3 has more trucks than other retailers around the crisis area at 12:00 and thus performs relatively well in re-routing individually and faces a lower service level in collaborative re-routing. Furthermore, Retailer 2 operates the nearest warehouse to the crisis region and consequently, if required, this warehouse's safety stocks and trucks are used first in the collaborative re-routing.

4.3.3 Implications

The proposed re-routing approach and results from the case study support decision-makers from public authorities and companies in assessing most suitable preconditions and operational strategies for collaborative re-routing. Furthermore, the results raise the awareness for crisis timing and retailers' distribution network structure.

Given these dynamics, public authorities need to develop flexible compensation mechanisms before crises in order to provide companies with incentives to collaborate under different crisis timings and extents. For an immediate crisis response, public authorities should provide the digital infrastructure for companies to share the required data. Therefore, public authorities might want to involve large companies, since their data-sharing infrastructure is expected to be more sophisticated. Moreover, such retailers operate many stores and move large amounts of goods.

From a company perspective, public-private collaborative re-routing in crises can mean new business opportunities if companies agree with public authorities in non-crisis times to sell their re-routing services in times of crisis. Furthermore, re-routing can be seen as a way to increase flexibility in a logistics network – both in crisis times and in case of smaller demand disruptions, as stated by food supply chain professionals. For crisis contexts, the COVID-19 pandemic has shown several examples of production conversion (Müller et al., 2022). The proposed collaborative re-routing approach can accordingly be considered as a way for the food retail sector to gain agility across companies.

4.4 Study D: Home delivery of essential goods during pandemics

4.4.1 Background and motivation

The COVID-19 pandemic required a reduction of social contacts, influencing the way of grocery shopping. Many close contacts happen in retail stores which is why the frequency of visits should be reduced during pandemics according to public regulations (Ekici et al., 2013; Haug et al., 2007). Especially for vulnerable people, other concepts for their supply with essential goods had to be established during the COVID-19 pandemic (see Section D.1.2 for examples). The set of criteria to assess a person's vulnerability can vary and these vulnerability criteria need to be specified for the unique characteristics of a pandemic (Vaughan and Tinker, 2009). In this study, a person's age is used as an indicator for vulnerability to pandemics, inspired by characteristics of the COVID-19 pandemic (Jordan et al., 2020; Yang et al., 2020).

As pandemics are of rather long-term nature, supply chain concepts for home delivery of essential goods require a tactical planning horizon of weeks or months. By that, pandemics differ from sudden-onset crises of short duration such as earthquakes. In practice, during the COVID-19 pandemic, only small-scale concepts for delivery of fresh and dry goods could be observed for certain districts and with single logistics service providers. This brings up the question of requirements of a large-scale home delivery concept. Therefore, the objective of Study D is to identify resource and operational requirements for large-scale home delivery concepts in an urban area which includes collaboration across logistics service providers.

4.4.2 Method and results

4.4.2.1 Solution approach

A case study is developed for a district of Berlin in which transportation resources for home delivery are planned on a tactical level. The tactical transportation planning is modeled with a solution approach that uses a variant of the Capacitated Vehicle Routing Problem (CVRP) (see Table 4.5). The developed CVRP minimizes the total delivery time in the objective function. Thus, the number of necessary vehicles, i.e., the fleet size for average daily demand is calculated. The designed CVRP considers loading time at a depot, travel time and service time at a household. Maximum tour duration (the sum of loading time, travel time of a tour and service time at every stop) and vehicle capacity are restricted. Due to a fixed loading time at the beginning of every route, the CVRP builds as few routes as possible (see Chapter D.3.2 for the complete mathematical formulation). This is enhanced by a high demand point density and short travel times in an urban setting.

Categories of a CVRP	Characteristics of the designed CVRP
Capacities	Vehicle capacities
Fleet size	Multiple vehicles
Fleet composition	Homogeneous
Route origin	Single depot
Demand type	Known deterministic demand
Demand location	In each destination node
Network type	Non-oriented or oriented
Maximum time per route	Yes
Multiple routes per vehicle	Yes
Implementation of FTL	Yes
Product type	Multiple
Time categories	Loading time, travel time, service time
Cost calculation	None
Objective	Minimize delivery time

Table 4.5: Characteristics of the developed CVRP (inspired by Faulin et al. (2011), see also Table D.1)

Around the CVRP, some pre-processing steps are part of the solution approach. Before applying the CVRP, first, full truckloads are planned if a demand point's demand exceeds vehicle capacity. Additionally, if the problem size is too large to solve the CVRP in reasonable time, a k-means clustering algorithm is applied to split the problem into manageable sub-problems. Due to its application in tactical planning, the focus is to achieve good results from the CVRP rather than reducing the computation time.

4.4.2.2 Case study: home delivery for vulnerable groups in Berlin

The case study is developed for the district Berlin-Lichtenberg due to its proximity to the average population per district and vulnerable population density of Berlin. The city administration of Berlin divides Berlin into 447 areas and provides data about the population's age and population density. Each of these areas represents one demand point in the case study which covers multiple households and vulnerable persons. Based on that, the number of people over 64 and over 69 determine the quantity of food to be supplied per demand point in the respective age scenarios. The demand per person is calculated from the average consumption of food and beverages in Germany and is assumed to be 1.71 kg of dry goods and 0.65 kg of fresh goods per person per day. Applying the k-means algorithm results in eight clusters with 103 demand points in average which is a problem size typically solvable optimally in reasonable time (Toth and Vigo, 2014).

Further, the real location of a last-mile food delivery depot is used, vehicle capacity is restricted with 1,200 kg and loading time is 15 min per trip. Travel time is based on shortest road distances and an assumed driving speed of 24 km/h.

In different scenarios, the number of weekly deliveries per household (once or twice), the service time per household (1.5 min or 3 min), the daily delivery service working hours (8 h or 10 h) and the minimum age of inhabitants to deliver (64 years or 69 years) are varied. Moreover, delivery with two different types of vans is investigated: (1) delivery with actively cooled vans only and (2) delivery of fresh food with cooled vans and dry food with parcel delivery vans. The second concept uses fewer cooled vans, as these are more expensive than normal vans and could be a limiting factor in practice.

4.4.2.3 Results

The results show significant differences in the number of required vehicles between the operational measures (Figure 4.5). Reducing the delivery frequency can result in vehicle savings of 44%. Combining one of the three measures (A1-A3) with another one (A5 to A7) further reduces the number of vehicles required. Combining all three would reduce the fleet size by 72% compared to the baseline assumptions.

Collaborative delivery with food delivery services for fresh food and parcel services for dry food is modeled in scenarios B1 (one delivery per week, three minutes service time and eight working hours) and B2 (one delivery per week, 1.5 min service time and ten working hours). B1 needs less

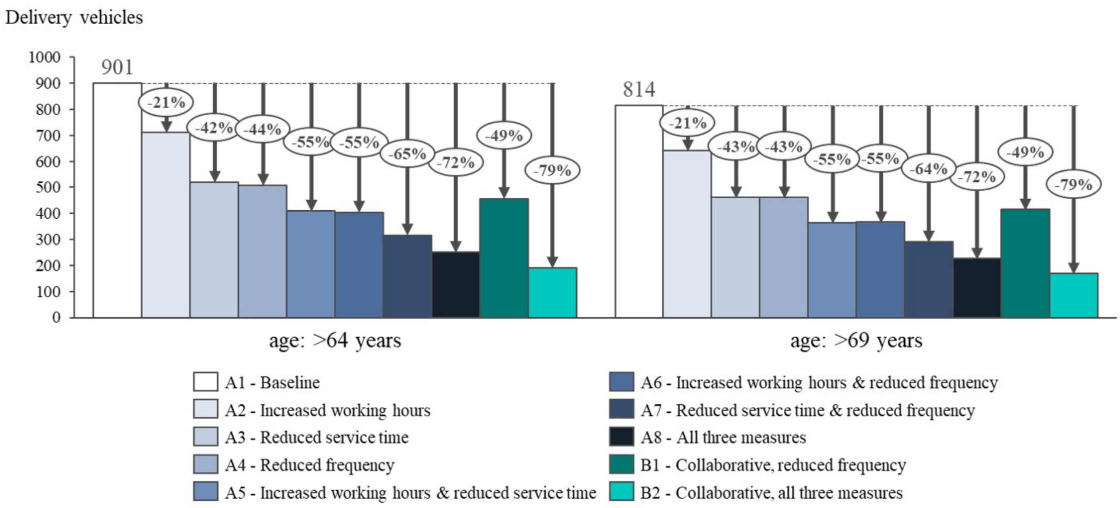

Figure 4.5: Required delivery vehicles for all scenarios in delivery mode A and B (see also Figure D.3)

cooling vehicles than A4 which indicates that the breakdown in two product categories pays off under reduced frequency. Especially if cooling vans are a limited resource, the lowest number of cooling vans can be achieved when delivering fresh and dry food separately and taking the three other measures to reduce the number of vehicles (B2).

In every scenario, the service time is the predominant time category. Figure 4.6 illustrates how reduced service time per stop and reduced delivery frequency can significantly decrease total service time and total operating time of the vehicles. Age groups do not influence time distribution to a meaningful extent.

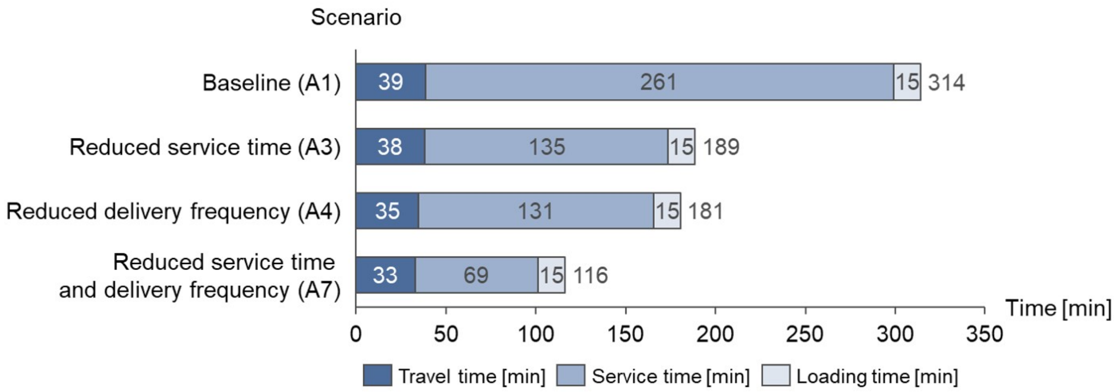

Figure 4.6: Average time distribution per trip (see also Figure D.4)

4.4.3 Implications

Study D addresses RO 2 by providing and evaluating operational measures for a large-scale home delivery concept during pandemics. To implement such a concept, transparency about vehicle availability and their characteristics, demand and supply is needed in the first place. However, it could not be realized by companies alone due to a high coordination effort with the vulnerable groups and across companies, yet unclear economic incentives and collaboration restrictions in competition law. In non-crisis times, public authorities could therefore collect data from companies about the amount of food supply and the available capacities of vehicles. Before implementing the concept, the vulnerable population should first be incentivized to use and accept home deliveries in a way that creates stable demand and thus simplifies transportation planning. In order to gather the required transportation capacities in times of crisis, public authorities should intensify and control a collaboration with several logistics service providers and food suppliers. This could also include the tactical transportation planning. By establishing such a concept in the preparedness phase already, predefined responsibilities and available supply, demand and vehicle data would reduce the response time.

From a theoretical perspective, Study D contributes to existing research by applying a CVRP with variable fleet size for home delivery with food during pandemics. These areas of research have not yet been combined.

Future research could look into drivers as the limiting resource in home delivery, as shortage of drivers is a pressing issue regardless the pandemic context. Moreover, research could take into account multiple hub locations and heterogeneous fleets with larger trucks for direct deliveries or supporting vehicles from fire brigades, army or NGOs. Finally, differently defined vulnerable groups could be researched if data is available.

4.5 Study E: Public-private dual-use warehouses for food supply

4.5.1 Background and motivation

In preparation for food supply crises, public authorities in the US or Germany maintain stocks of food supply in public warehouses (Table E.1). Maintaining such an emergency food stock, however, is costly for public authorities and in countries like Germany, often unused or at least underutilized. In contrast, companies in retail supply chains move large volumes of food every day. Having two parallel food supply infrastructures in place brings up the question for the logistical effectiveness and efficiency of combining these infrastructures for commercial and emergency purposes.

Therefore, Study E investigates the supply chain concept for PPEC with dual-use warehouses for emergency food supply which means to use commercial warehouses for supplying both retail stores for commercial purposes and public points of distribution for emergency purposes. In non-crisis times, warehouses would be used for commercial supply only and would keep stock of public emergency food supplies. Public authorities would monitor the stock at any time. In addition, standard warehouse and supply processes would be established for emergency supply. The latter would then be coordinated by public authorities.

From this strategic PPEC concept, companies would gain new business and receive compensation from public authorities for warehousing processes. They could additionally benefit from up-to-date demand and supply information in a crisis, from subsidies for positioning new warehouses, staff training and positive advertising.

The PPEC concept was suggested to public authorities which considered it a very promising option that would go well in line with their strategic objective to stronger involve companies in emergency food supply. Company representatives confirmed the technical feasibility. Currently, the concept is being investigated with public authorities in a separate research project called ALANO (Karlsruhe Institute of Technology, 2023).

The PPEC concept of dual-use warehouses would also mean an innovative approach compared to known concepts in US, UK and Switzerland (Table 4.6). Walmart's engagement in the US is voluntary without formal agreements, the FCELG in the UK is also informal. Closest to the proposed PPEC is the concept in Switzerland, where publicly controlled stocks by retailers are compulsory. However, this concept also uses a parallel infrastructure and is thus different from the PPEC concept in this study.

In Germany, public authorities run less warehouses than all German retailers together. The retailer LIDL alone, with a market share below 20%, has around 40 warehouses in Germany for the supply of 3,200 stores. In comparison, public authorities in Germany run 150 warehouses for a smaller product portfolio to supply the whole population in case of an emergency. Hence, public authorities follow a more centralized logistics network structure.

The network structure determines to a large extent retailers' efficiency and speed in supplying retail stores as well as, from a public authority perspective, how quickly the affected population can be supplied in case of a crisis. This indicates both actors' different objectives in dual-use warehouse network design: In non-crisis times, companies aim for cost-efficient supply of retail stores, short storage times and high inventory turnover. Contrary to that, public authorities would, in non-crisis times, monitor stock and establish communication channels. When a crisis strikes, companies aim to maintain or quickly re-start their business operations. Public authorities are responsible for population supply and might thus set up points of distribution which they aim to supply as quickly as possible. Hence, due to different location requirements, public authorities and companies should jointly decide about dual-use warehouse locations.

Constructing all warehouses is, however, expensive and not practically feasible, so the use of existing retail warehouses is the starting point in this study. With that, companies bring in their resources and services into a PPEC and compensating them is very likely to mean a significant reduction of operating costs for public food inventory. In addition, public authorities could divide their inventory across more warehouses and such a more decentralized network facilitate shorter transport distances and response times. Consequently, a warehouse network needs to be identified which is suitable for commercial and public use. Therefore, this study's objective is to analyze the PPEC concept of dual-use warehouses from a logistics network perspective by taking into account both actors' specific location criteria as well as costs and distribution speed.

	Walmart, United States	**Food Chain Emergency Liaison Group (FCELG), United Kingdom**	**Compulsory stocks, Switzerland**
Private actor(s)	Walmart Inc.	Companies in food industry, retail associations	Sellers of compulsory stocked items, stockholding organizations
Public actor(s)	State and local authorities (e.g., Florida)	Department of Environment, Food and Rural Affairs, lower-level authorities	Federal Office for National Economic Supply
Agreement	None	Informal	Contracts
Details	Emergency Operation Center for monitoring and coordination in crises, six disaster distribution centers; regular donations; increased engagement since Hurricane Katrina (2005)	Focus on business continuity management; regular meetings for information exchange; regular donations	Organized through stockholding organizations for each product group, sellers hold compulsory stocks of pre-defined goods (e.g., cereals, rice, sugar); compensation through surcharge for consumers
Authorities' role	Sharing disaster information (at most)	Facilitator; sharing public planning and research insights in normal times; sharing disaster information during crises	Contract partner; monitoring stocks and adjusting requirements; may release reserves in crises
References	German Federal Office for Civil Protection and Disaster Assistance (2019a); Walmart (2021); NBC Universal (2006)	German Federal Office for Civil Protection and Disaster Assistance (2019a)	réservesuisse (2021); German Federal Office for Civil Protection and Disaster Assistance (2019a, 2019b)

Table 4.6: Examples of private sector involvement in emergency food supply and preparedness from the US, UK, and Switzerland (see also Table E.3)

4.5.2 Method and results

4.5.2.1 Attractiveness of regions

First, in order to detail and transfer both actors' objectives into warehouse location decisions, their respective preferences are empirically investigated. For that, relevant criteria were determined from literature research. Next, these criteria are weighted in surveys among public and private practitioners. It turned out that companies, among others, value labor costs high, while reliable transport infrastructure and equipment are decisive for public authorities. Combining these weights with a region's performance in all criteria leads to a summarizing score about the attractiveness of a region from commercial and public perspectives. Thereby, using the attractiveness of a region for a warehouse location determines whether the region is suitable for public use, private use or both (Figure 4.7).

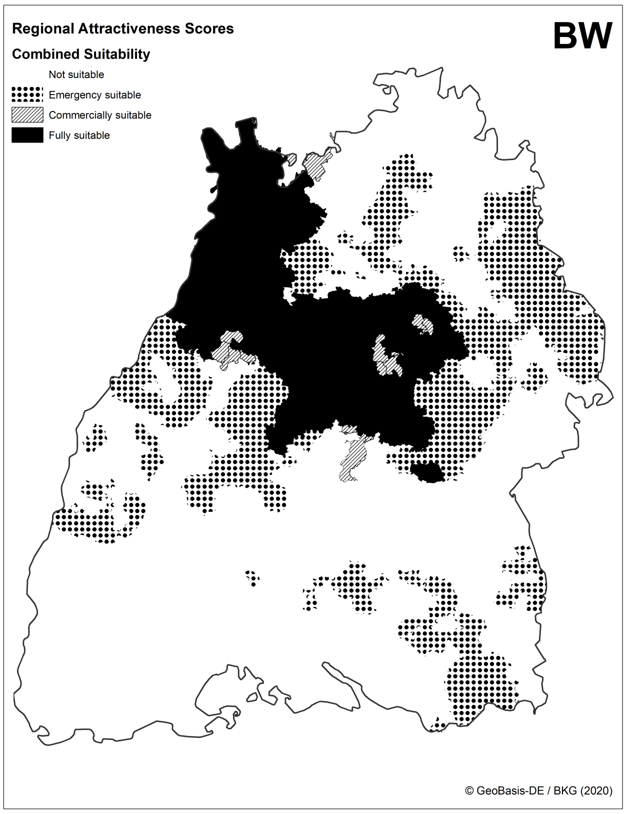

Figure 4.7: Attractiveness scores for Baden-Württemberg per LAU2 unit - suitability for both actors (see also Figure E.1)

4.5.2.2 Warehouse location planning

Next, a location-allocation model is used to determine the number and location of warehouses and allocation of demand points. In the commercial scenario, logistics costs consisting of warehouse set up costs and transportation costs, are minimized. In the public scenario, the social costs consisting of logistics costs and deprivation costs are minimized.

To take into account the attractiveness of every region, a multi-objective optimization model additionally includes the attractiveness score in the location decisions. This is necessary because attractiveness and logistics costs can be competing objectives.

The model is applied on a developed case study for the German federal state of Baden-Württemberg (BW) with approximately 1,100 municipalities and 11 million residents. From a commercial perspective, demand locations are municipalities on LAU2 level with at least 5,000 inhabitants (502 of 1,102 municipalities). Retailers' market share is considered. Demand is assumed to be 3.64 kg per person in the commercial scenario and 3.20 kg in an emergency. Transport costs are € 0.0583 per ton and km and the average truck speed is 45 km/h.

At each location, the model can decide about one out of two warehouse types: The smaller one has a capacity to supply 300,000 people with food and comes with implementation costs of 50 million €. The larger warehouse can supply 1,800,000 people and costs 100 million €. For warehouse capacity and utilization, it is considered that food is about 76% of a food retailers assortment (EHI Retail Institute, 2017).

The existing warehouses in Baden-Württemberg of the six largest retailers are used as the basis for planning additional warehouses (Figure 4.8). As a reference, warehouses are also planned for both actors in a greenfield planning scenario.

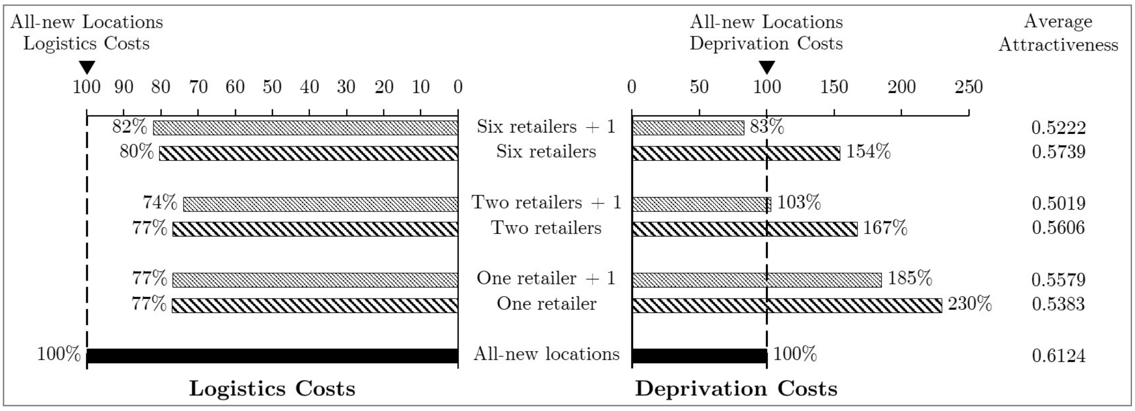

Figure 4.8: Logistics costs, deprivation costs, and average attractiveness for different numbers of retailers and locations being included in public (emergency) brownfield planning, relative to all-new locations (bottom, greenfield) (see also Figure E.4)

In different scenarios, the number of retailers involved in the PPEC are varied. For every retailer, the effect of jointly opening an additional warehouse is investigated.

The results show that with more retailers and warehouses, the network becomes more decentralized and improves the outcome in deprivations costs. Jointly adding an additional warehouse to the network significantly lowers deprivation costs. However, in terms of logistics cost, the warehouse network of lowest costs involves two retailers jointly opening an additional warehouse. In the case of involving six retailers, higher warehousing costs rise logistics costs.

4.5.3 Implications

Through the attractiveness score, Study E provides practitioners with empirical insights into different warehouse network strategies. Moreover, the modeling results can support decision-makers regarding the trade-off between costs, deprivation, attractiveness and number of retailers involved. In a PPEC, public authorities could use the results from the evaluation of attractiveness to provide retailers with subsidies for opening warehouses in areas critical for emergency supply. Another possibility is to, for example, increase such a region's attractiveness through investments in infrastructure.

Moreover, it should be highlighted for practitioners that representatives from both public authorities and companies in food supply chains acknowledged the potential of a PPEC in dual-use warehousing to increase effectiveness and efficiency of the emergency food supply.

Lastly, for a successful implementation, public authorities highlighted in discussions the need to be able to monitor stock at any time as well as the importance of controlling market power of few large retailers in Germany. Company representatives stressed the importance of compensation and that warehouse processes would have to fit into their every-day business.

4.6 Study F: Impact analysis of extended payment terms in food supply chains during a demand shortfall

4.6.1 Background and motivation

Disruptions of financial flows in supply chains can affect physical flows and vice-versa. If a company delays a payment, the monetary funds at hand as well as liquidity increase short-term. At the same time, for the upstream company, the later incoming payment decreases liquidity. Reduced liquidity in turn can compromise the ability to purchase raw material or to produce goods for the downstream company. This is especially critical if the upstream company does not have large financial reserves. However, also small companies with smaller financial power can be crucial for supplying the population with essential goods. From a public authority perspective, it is therefore necessary that such companies have enough liquidity to maintain their business processes in times of crisis.

When discussing with practitioners (before the COVID-19 pandemic) the potentials to improve the efficiency of public authorities' financial support for essential goods supply chains in crises, a noteworthy controversy was observed: Taking a rather optimistic view, managers stated that trust between companies might cause that delayed payments could be accepted and be made later in the crisis recovery phase. Another practitioner stressed that if payments are delayed, one party would always take over the financial risk and that consequently extended payment terms would most likely not be a long-lasting situation in supply chains.

During the COVID-19 pandemic, companies for example received less supplies or demand decreases reduced the sales volume (Barman et al., 2021). Due to this pressure, many companies no longer managed to pay their liabilities and thus extended their payment terms (Di Marcantonio et al., 2022). A precondition for extending payment terms is, however, sufficient market power to forward the financial risk to the upstream company. If the upstream company cannot take over the risk, the company extending the payment terms can suffer from supply risks (Esenduran et al., 2022).

Despite this direct link between payment term extension and supply risk, the consequences of extended payment terms are so far scarcely researched. Esenduran et al. (2022) investigate the impact of extended payment terms together with SCRM measures like quick response and backup suppliers and are able to show how extended payment terms impair operations at the company delaying its payments. Another study related to this study is Tsai (2008) who models financial risks in supply chains and shows how a decreasing cash conversion cycle (CCC) increases cash flow risks.

Therefore, the objective of Study F is to provide a better understanding of the impact of extended payment terms in crises. As a result, insights for decision-makers from both companies and public authorities for collaborative crisis management can be derived.

4.6.2 Method and results

4.6.2.1 Model development

Inspired by restaurant closures during the COVID-19 pandemic, extended payment terms are modeled for a stylized multi-echelon food supply chain consisting of gastronomy, wholesaler, producer and supplier (Figure 4.9).

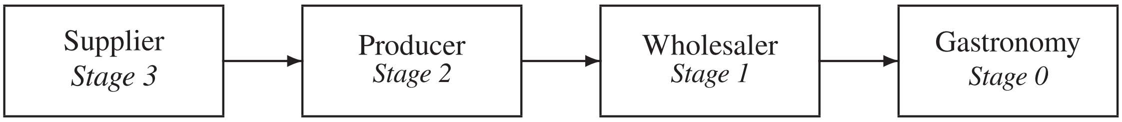

Figure 4.9: Serial system (see also Figure F.1)

On a daily basis, the gastronomy stage places aggregated demand from the gastronomy sector at the wholesaler. The physical flows at stages *1* and *2* are designed accordingly to meet the downstream service level applying a (s,S) order policy. For stages *1* to *3*, the service level evaluates the performance of physical flows. The financial flow for stages *1* to *3* emerges from the physical flow and payment terms of 30 days. The financial performance is evaluated through the CCC. The CCC indicates how many days it takes to convert expenses into income from customers by taking into account *Days Inventory Held*, *Days Sales Outstanding* and *Days Payables Outstanding*. Companies aim for a low CCC, since the faster the conversion of expenses into revenue, the better the financial performance of a company. Even a negative CCC is possible for mostly large companies with very high bargaining power. Such companies manage to receive monetary funds from their customers before they pay their suppliers (Stewart, 1995).

The demand received by the wholesaler is assumed to be uniformly distributed according to $D_{1,t} \sim \mathcal{U}(900, 1100)$. Following a lockdown in Germany with a demand shortfall in the gastronomy, demand drops by 60% for 60 days (Destatis, 2022) as shown in Figure 4.10. As a response to the crisis, the stages adjust their production capacities, reorder points and target inventory levels accordingly to the new demand situation.

The supply chain model takes crisis response measures into account by linking physical and financial flows in a way that restricts operations if the available liquidity is not sufficient. In addition to

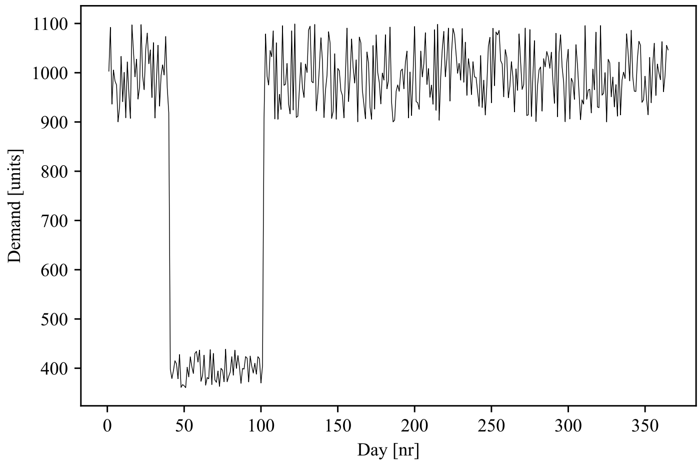

Figure 4.10: Demand received by wholesaler

payments to the respective upstream company, all stages (*1* to *3*) pay fixed costs, wholesaler and producer pay inventory holding costs and producer and supplier pay production unit costs. The available liquidity then determines the amount of finished goods the producer and supplier can produce. The production quantity at the supplier can affect the inventory of raw material at the producer which in turn affects production quantity at the producer. If one stage cannot make a payment, it is postponed to a day when sufficient funds are available, but an interest rate applies for late payments.

In addition, delivery lead time of producer and supplier is assumed to be five days. Order quantities are determined by the (s,S)-order policy. Target service levels are 90% and backlogs are possible at wholesaler up to a maximum accepted backlog. For the detailed mathematical formulation, see Section F.2.

In non-crisis times, physical and financial flows are designed in a way that supplier and producer achieve a profit margin of 10%, and the wholesaler a profit margin of 6%. Profit margins in wholesale are typically lower than these in food processing and in general, profit margins in the competitive food industry are rather low.

For the simulation of the demand shortfall, the supplier is given capital to cover one month of fixed costs. Given the higher market power of producer and wholesaler, they are given initial capital to cover fixed costs of four months.

4.6.2.2 Results

In different modeling scenarios, the stage extending payment terms is varied (wholesaler, producer or wholesaler and producer) as well as the number of days Δr the payment terms are extended (15 or 30 days) (see Table F.1). An extension by 30 days is chosen as upper limit, since according to Directive 2019/633/EU, the legally allowed maximum payment delay in food supply chains is 60 days.

The *Service level* at the wholesaler is measured in % and serves as an indicator for the supply chain's physical performance. A *Disruption* at the supplier stage is measured as the number of days the supplier has insufficient monetary funds to produce at all. Accordingly, each day the producer does not have any raw material, production is disrupted at stage *2*. Any day the wholesaler has to turn down demand from the gastronomy because it exceeds the maximum backlog level is also evaluated as a disruption. The column *Breakdown* indicates whether a supply chain member went bankrupt and at which day of the simulation this occurred. Note that up to a certain point, payments can be postponed, but the *Breakdown* means an irreversible inability to pay. All results in Table 4.7 are the average results over 10 simulation runs.

		Disruption				CCC		
Scenario	Service level	Sup	Prod	Wh	Breakdown	Sup	Prod	Wh
Normal	90.61	0.00	0.10	0.00	no	31.99	6.87	6.55
Crisis	84.70	0.00	0.60	1.70	no	32.20	7.88	7.46
$\Delta r_1 = 15$	85.01	0.00	0.30	1.80	no	32.20	22.78	-3.44
$\Delta r_1 = 30$	85.04	0.00	0.60	1.30	no	32.23	40.48	-13.57
$\Delta r_2 = 15$	42.01	180.60	121.90	113.80	311.90	41.85	-10.41	1.75
$\Delta r_2 = 30$	34.75	233.30	207.30	199.90	200.40	49.82	-19.46	3.75
$\Delta r_1 \& \Delta r_2 = 15$	42.95	177.40	117.90	118.20	321.10	42.12	3.08	-11.58
$\Delta r_1 \& \Delta r_2 = 30$	34.22	233.10	207.90	201.30	200.20	49.69	0.58	-22.67

Table 4.7: Scenarios and results (see also Table F.1)

The comparison of the scenarios *Normal* and *Crisis* shows that the crisis causes minor disruptions upstream, a lower service level and greater CCC at all stages. This decrease in financial performance could motivate companies with high market power to extend payment terms with their upstream partners. If the wholesaler does so ($\Delta r_1 = 15$, $\Delta r_1 = 30$), this decreases the wholesaler's CCC. However, this comes at high cost for the producer's financial performance and the wholesaler's service level does not improve significantly. If only the producer extends payment terms, the producer can also lower the CCC. However, this causes a drop in service level, more disruptions at all stages and even a breakdown of the supply chain. If at the same time both wholesaler and producer extend their payment terms, this has similar effect as if only the producer extends payment terms.

4.6.3 Implications

Extending payment terms can be attractive in the short-run, though the wholesaler and producer suffered from supply disruptions themselves if extending payment terms too long. Still, practice showed that this was often the case during the COVID-19 pandemic (Di Marcantonio et al., 2022).

In practice, moreover, companies are usually not linked to only one upstream and downstream partner. Therefore, a company's liquidity risk that results from the downstream partner's payment term extension increases with a greater sales share with the downstream partner.

The results demonstrate the need of coordinated action and that unilaterally enforced self-protection measures in a crisis can seriously backfire and even lead to a breakdown of the whole supply chain. Moreover, the results show that it is best if no company in the supply chain extends payment terms. The best performance across the supply chain would be achieved if the whole supply chain bears the consequences of the demand shortfall in a coordinated manner. This would also be in public authorities' interest which is why they might need to find incentives to avoid extensions beyond the restriction to 60 days in the food industry. It should therefore be investigated whether public authorities can support supply chains more efficiently through regulations or financial support. Offering targeted financial support like (free) loans based on supply chain stage and time might be a path for future research. However, this would require companies disclosing relevant information to public authorities. In addition, it could be investigated how targeted support would affect different supply chain actors and how fairness among supply chain actors from a legal perspective can be ensured.

5 Implications

5.1 Managerial implications

5.1.1 Implications for companies

It lies in the nature of PPEC that no trivial business case calculation can accurately portray the complexity of a collaboration with manageable implementation effort but high uncertainty about time, frequency and extent of collaborative operations. As Studies C and D showed, effectiveness and efficiency of a concept can vary a lot due to the demand increase (i.e., extent of the crisis) or operational decisions (e.g., time of the crisis supply or route planning parameters). Under extreme conditions, planning of effective and efficient supply chain concepts is even more complicated, since many external and internal factors that influence supply chain planning change radically at the same time (e.g., demand and/ or supply disruptions, staff absence, failure of communication technology, available vehicles or fuel). All this makes the operational effectiveness and efficiency of a PPEC concept hard to assess before a crisis and difficult to generalize.

This is, however, true for companies' supply chain preparedness for large-scale disruptions in general. Companies understandably struggle to assess the resilience of long global supply chains against numerous potential disruption scenarios and thereby also to estimate in advance how exactly innovative concepts improve resilience[1]. Therefore, the developed concepts, to begin with, inform about potential collaboration concepts for selected types of crises. Joint concepts for home delivery, re-routing of commercial trucks into crisis regions and dual-use warehouses indicate how collaborative approaches can be designed in an innovative, feasible and effective way and which roles authorities and companies can take herein. It is worth to highlight that especially the supply chain concepts from Studies C (re-routing of commercial transports) and E (public-private warehouses for emergency food stock) were of interest to public and private practitioners in discussions: In both concepts, potentials to improve crisis management's effectiveness were seen and the concepts were widely regarded as technically feasible and manageable.

Despite the uniqueness of extreme events and the challenge to generalize supply chain concepts, the potential benefits are manifold for companies of collaborating with public authorities. To name a few, insights into public crisis management and loosened regulations can support continuity of

[1] This information stems from interviews within an empirical study about data-sharing and data transparency as part of supply chain risk management in automotive supply chains. The author of this dissertation conducted the study together with authors from Bundesvereinigung Logistik e.V., 4flow SE and Technical University of Munich. Interviews were conducted with Europe-based supply chain managers from automotive manufacturers and suppliers.

companies' business processes. Companies can moreover receive monetary compensation and even open up new business segments (Study E). If they share data with public authorities, they can use synergies in data collection and preparation for improving their own supply chain transparency (Study C, Study D, Study F). Additionally, positive reputation towards staff and customers can be long-term advantages. The detailed developed concepts support decision-makers to negotiate collaboration conditions with public authorities, including the amount of resources, compensations and required preparedness effort. Hence, on a general level, companies can find interesting insights for the following fields of collaboration:

- operational flexibility to respond to crises immediately (Study C),
- contribution of transportation resources short-term (Study D) and
- strategic warehousing services (Study E).

To further reduce uncertainty about effectiveness and planning complexity, companies could start first with either a PPEC concept in which they contribute a limited amount of (planning or physical) resources only or with spontaneous collaboration. Both approaches would provide companies with wider operational freedom than planned as well as binding collaboration. At the same time, they could build up relationships with public authorities and learn about their case-specific assessment of effectiveness and efficiency. PPEC is an innovative field for public authorities, too, so both parties would learn from a step-by-step intensification of PPEC. This might also give companies a first-mover advantage due to opportunities to shape the design of supply chain concepts, including compensation schemes.

Companies want and need to develop compensation claims towards public authorities in the process of assessing a PPEC concept's effectiveness and efficiency. As a basis, the positive or negative impact on business operations is quantified in Studies C-F by service level, transportation costs, impact on the (daily) logistics operations, liquidity and warehouse costs. This dissertation is limited to the supply chain perspective, but more comprehensive cost-benefit analyses or strategic reasons can outweigh supply chain (in-)efficiencies. From a strategic perspective, the conducted studies should also be seen as starting points for companies aiming to conduct proactive SCRM and influence public policy-making. For example, companies' geographical footprint can be of public authorities' interest for dual-use warehouses (Study E), for quick access to transportation resources (Study D) and for re-routing trucks into crisis regions (Study C). Hence, companies which consider PPEC as part of their strategy might communicate this with public authorities and receive subsidies in return.

Another link between PPEC and long-term policy provide the fields of digitization and data-sharing in commercial supply chains. Data-sharing and standard exchange platforms are a trend public authorities are aiming to strengthen in the near future (German Federal Government, 2021; Hallak and Tacsir, 2022). By actively engaging, companies can shape such policies towards a favorable environment in which better transparency about their supply chain improves SCRM. Since, as Study B shows, a large share of companies is open to data-sharing with public authorities and other companies, companies could also partner within their supply chains to develop PPEC concepts based on shared data. Jointly shaping digitization policies with public authorities can thereby increase resilience along essential goods supply chains (in other terms, develop *industry commons* as suggested by Chopra et al. (2021)).

To conclude, companies should develop PPEC contracts together with public authorities which allow for a relatively straightforward cost-profit calculation on an operational level. Additionally, companies should see PPEC engagement from a strategic perspective as a potential to increase the probability of more successful SCRM and ESCM.

5.1.2 Implications for public authorities

The suggested collaborative supply chain concepts (Studies C - F) all have in common that public authorities should be the ones to propose, initiate and coordinate the collaboration. In doing so, Study B revealed that public authorities need to first convince companies with collaboration design that maintains business processes and ensures confidentiality. Public authorities then should communicate benefits from loosened regulations, monetary compensation or positive publicity. Depending on the type of company, public authorities should emphasize different benefits, according to the findings from Study B. With regards to compensation, public authorities face the challenge to find just the right amount of financial compensation: If public authorities offer too little, companies are not convinced to voluntarily engage, and if they offer too much, they put fairness among market participants' at risk and use tax payers' money inefficiently.

Furthermore, the calls for public authorities to collect and analyze data about commercial supply chains as part of supply chain preparedness in crisis management have been made for a long time (DHL, 2020; Prieto, 2006; Kayyem and Chang, 2002; Sheffi, 2001). However, the preconditions for that might never have been as favorable as they are today, with growing amounts of data being gathered digitally in companies, stronger awareness for supply chain risk management and a great willingness of companies towards data-sharing with public authorities (see Study B).

Despite this high degree of openness, companies prefer to engage in crisis preparedness with public authorities with low continuous effort. Therefore, public authorities need to find ways to collect data through digital interfaces with low effort on the company-side. In addition to that, data must be kept confidential and could therefore already be requested in a way which contains less sensitive company information but which is sufficient for public authorities to analyze and interpret the data.

On the other hand, Studies C and D show the benefits of using very specific supply chain data: a certain product (bottled water), a certain geographical scope (a district of Berlin) and a certain type of transport vehicles (last-mile delivery vans). However, collecting, analyzing and interpreting data of such granularity across a country or state and all essential goods at any time requires large computation effort and would be difficult to manage in practice. In addition, companies would most likely prefer to share just as much data as needed by public authorities.

Therefore, it can be suggested to collect only company master data in non-crisis times and to extend information-sharing in times of crises and for the specifics of the crisis at hand. While population supply of basic food like grain might be worth monitoring at anytime, face masks are only critical in specific crises like pandemics. Information-sharing should correspondingly be crisis-, time- and product[2]-dependent. Such a *zooming* into supply chains' critical areas could for example be observed in automotive supply chains during the last years' major disruptions, as discussions with supply chain professionals from the industry revealed: During the semi-conductor crisis, car producers reached beyond their first-tier supplier in their information-sharing endeavors and asked second-tier suppliers for increased transparency about supply reliability[3]. In addition, during numerous congestions at border crossing points caused by the COVID-19 pandemic, car producers and their suppliers temporarily increased data transparency about products in transport – data they did not share in non-crisis times.

It is therefore worth considering whether this behavior can be transferred into digital information-sharing between companies and public authorities in essential goods supply chains. In non-crisis times, public authorities could collect master data from companies. This could for example contain the essential product groups with aggregated volume indicators like market shares, locations of main production sites and warehouses, and the most critical first-tier suppliers. At the same time, a digital infrastructure would have to be established which quickly allows to share and interpret more detailed data if needed to respond to a specific crisis event. The fact that the European Union enforced and coordinates traceability systems in global agri-food supply chains further suggests the technical and organizational feasibility of such a concept (Hallak and Tacsir, 2022).

In order to keep amount and complexity of data collection low from a public authority perspective, they should only collect information from companies in essential good supply chains which are most critical for population supply. Note that the company size might be an appropriate selection criterion for among others food retailers, as usually few large retailers cover a large market share. Since more than 70% of the companies in the food industry are small- or medium-sized, the criticality of upstream companies for population supply should be determined by its connections in supply networks, i.e., by identifying nexus suppliers (Ali et al., 2021; Hobbs, 2020; Yan et al., 2015). Achieving transparency about companies' criticality for essential goods supply and letting especially small upstream companies know about their importance for basic supply might also foster the companies' accountability.

5.2 Theoretical implications

The results of this dissertation contribute to the field of ESCM. Recent years and the latest research highlighted the need for research about better preparation for large-scale crises with low probability of occurrence (Holguín-Veras et al., 2022; Sodhi and Tang, 2021). For that, so far the terms *extreme*

[2] See also Swiss Federal Office for National Economic Supply (2021) for product-dependent agreements with companies to hold stocks for emergency supply.

[3] This information stems from interviews within an empirical study about data-sharing and data transparency as part of supply chain risk management in automotive supply chains. The author of this dissertation conducted the study together with authors from Bundesvereinigung Logistik e.V., 4flow SE and Technical University of Munich. Interviews were conducted with Europe-based supply chain managers from automotive manufacturers and suppliers.

events (Holguín-Veras et al., 2022), *extreme conditions* (Sodhi and Tang, 2021) and *abnormal times* (Ahlqvist et al., 2023) exist in literature, all indicating structural changes in supply chains caused by radical changes of multiple influence factors like demand, supply or staff availability. The present results bring concrete supply chain concepts into the scientific discussion and give insights into how companies can develop relationships with public authorities as part of companies' SCRM and ESCM. Especially studies assigned to RO 2 provide insights into supply chain concepts for ESCM and how companies can partner with public authorities. However, it lies in the nature of large-scale crises that many parts of society are affected at the same time and multiple influence factors on supply chains undergo a dynamic change. Therefore, as the conducted studies and recent real-life crises show, crisis dynamics and resulting dynamics in public countermeasures can impede or strengthen the success of collaborative countermeasures in practice.

Moreover, this dissertation contributes to existing research about companies collaborating with external parties as part of their SCRM. Typically, if companies collaborate with other companies, they share similar characteristics like planning horizons and similar objectives like increasing supply reliability, profit maximization or cost reduction (Scholten and Schilder, 2015). This makes the provision of incentives and division of benefits relatively easy to compare and divide. However, collaboration with public authorities is special in several ways. The main objective of public authorities in emergency food supply is to maintain basic supply for the population, and the secondary objective is to do so at low cost. To achieve this, they have the legal power to lift restrictions for strengthening supply chains and to confiscate commercial resources. Additionally, a PPEC means implementation effort for both parties, though might afterwards be rather passive until a crisis happens (Wiens et al., 2018). Similarly, while some public authority and company implementation effort would happen in the PPEC set-up phase, public authorities wait for their main return from the PPEC until crisis response. If there is no crisis for a long time, companies' shorter planning horizons (Swanson and Smith, 2013) still require a positive cost-benefit perspective.

All these aspects make it difficult to quantify the benefit of a PPEC for both parties in advance. Therefore, this dissertation further explores the role of public authorities and their impact on commercial supply chain management. Especially Studies C and D show how companies can coordinate commercial resources in times of crises and Study C shows how competences and measures of public authorities can strengthen commercial supply chains.

Across the conducted studies, this dissertation additionally enhances the concept of companies sharing data with public authorities in crisis preparedness. In principle, a great openness among companies towards data-sharing with public authorities was discovered in Study B. Next, while the need for data-sharing has been formulated by several authors in the past (DHL, 2020; Prieto, 2006; Kayyem and Chang, 2002; Sheffi, 2001), the conducted studies in this dissertation specify the type of data needed for different PPEC concepts. Study C uses warehouse and store locations as well as their inventory levels, in combination with operational real-time data truck load and position to re-route trucks. Study D uses the number and type of delivery vehicles as well as population data for home delivery. The concept of dual-use warehouses (Study E) is, during operations, based on warehouse locations and inventory levels. Study F uses transparency about companies' liquidity, payment behavior and physical flow. All these data types, in combination with the corresponding PPEC concept, serve as suggestions for the type of data companies could share with public authorities in crisis management.

6 Conclusions

6.1 Summary

Both companies and public authorities play crucial roles in supplying the population with essential goods. In case of a supply crisis, public authorities become responsible for this task. Consequently, they intervene in and proactively support commercial supply chains, which produce, transport and sell large amounts of essential goods every day. The COVID-19 pandemic showed some examples of spontaneous engagement, such as extended shopping hours in retail stores or temporarily allowing trucks to drive on Sundays in Germany. Expecting potentials for improving public crisis management from collaboration with companies, public authorities stressed their strategic goal to involve companies more formally in public crisis management including preparedness efforts, in discussions during the research project NOLAN.

In literature, one would expect to learn from these recent spontaneous collaborations about potentials from a company perspective and how to best design collaboration from a public authority perspective. However, the field of public-private collaboration in supply chain-related crisis management is scarcely researched so far. This dissertation therefore developed two research objectives to investigate the design of PPEC and supply chain concepts:

Research objective 1: Preconditions for company engagement in public supply chain-related crisis management

Research objective 2: Development and evaluation of concepts of supply chain-related crisis management from public and private perspectives

RO 1 was addressed with Studies A and B. Study A reviewed literature, real-life cases and included insights from public and private practitioners. Since collaboration with public authorities is different from collaboration with other companies, Study A first sharpened the definition of PPEC and gave an overview of potential preconditions. This included both actors' strategies, interaction between both parties as well as their capabilities and resources. In Study B, empirical research was carried out to weigh the identified preconditions. A survey among Germany-based companies in production, transportation and retail in the food and healthcare industries was conducted. The results revealed a high openness among companies to share data with public authorities, but also that companies preferred preconditions include the continuity of their business processes, confidentiality towards competitors and being granted special rights by public authorities. Moreover, companies preferably contribute to a PPEC with resources rather than coordination support. Notably, companies are also highly willing to contribute to strategic planning of public crisis management free of charge. To conclude, these are the main preconditions public authorities could create in a PPEC to motivate companies to engage.

RO 2 was addressed with Studies C-F covering a variety of supply chain areas including planning on operational, tactical and strategic level (Table 6.1).

Study	Supply chain scope	Planning horizon
Study C	Re-routing of commercial transports into crisis regions	operational
Study D	Home delivery concept for vulnerable people	tactical
Study E	Dual-use warehouses for emergency food supply	strategic
Study F	Financial perspective on supply chains during demand shortfalls	tactical

Table 6.1: Conducted studies with regards to RO 2

Re-routing of commercial transports into a crisis region (Study C) was evaluated with the service level in the crisis region, number of trucks used and distance traveled. The results show that the involved retailers' network design and time of re-routing shape effectiveness and efficiency of the collaborative supply chain concept. In Study D, the home delivery concept's efficiency is evaluated by the vehicles required. Efficiency is mainly driven by reduced delivery frequency, followed by reduced service time at demand points and increased working hours. Combining these further reduces the number of vehicles required. The dual-use warehouse concept studied in Study E is assessed by logistics cost and deprivation costs. Increasing the number of retailers involved as well as their warehouses and jointly planning additional warehouse locations gradually improves emergency response. In Study F, the impact of extended payment terms in food supply chains is investigated. Note that Study F did not yet develop an explicit collaborative supply chain concept, though it provides public decision-makers with a better understanding of the consequences of lockdowns and restricting payment term extension. For that, besides measuring service levels, financial performance of three supply chain stages is evaluated with the CCC.

Thereby, Studies C-F (1) make suggestions to public authorities and companies in essential goods supply chains on how collaboration can be meaningful, (2) show relevant influence factors for every supply chain concept to keep in mind when assessing effectiveness and efficiency and (3), when possible, set these influence factors into relation with each other to gain an understanding of the dynamics behind the concepts. Taking these dynamics into account is crucial for both public authorities and companies to cope with numerous uncertainties in the context of a crisis.

This also reflects the main implications for corporate decision-makers, complemented by the challenge to reliably assess costs and benefits of a PPEC beforehand. If many influence factors change unpredictably and radically in the course of a large-scale crisis, so do effectiveness and efficiency of collaborative supply chain concepts with public authorities. Therefore, companies should evaluate any PPEC concept from a strategic perspective as well as opportunities to co-design public policy-making and to increase the chance for a favorable political environment. For public authorities, the results from RO 1 and RO 2 emphasize the importance of preparedness. Public authorities should find ways to collect commercial supply chain data with little effort on the company-side and prepare supply chain concepts in the preparedness phase.

Theoretical implications lie in contributing to the research stream of ESCM through insights about collaboration designs between companies and public authorities as well as collaborative supply chain concepts. This dissertation contributes to the topic of collaboration in supply chain management by identifying collaboration characteristics between companies and public authorities, which brings some unique characteristics compared to company-to-company collaboration.

6.2 Limitations

The findings of this dissertation have to be seen in light of some limitations: Legislation as well as public authorities and their responsibilities differ between countries. Therefore, especially the empirical results of Study B and of interactions with practitioners about how German companies assess collaboration with German public authorities might not be easily transferable to settings in other countries. The same accounts for legislative powers to lift restrictions (Study C).

It was also difficult to obtain, due to confidentiality reasons, more detailed practical information about supply chain planning as well as operations of companies and public authorities. This would have been especially useful against the background of different time aspects of PPEC. While public authorities aim to improve crisis response, a significant share of both actors' effort would be in the preparedness phase, e.g., in setting up data-sharing infrastructure to enable transparency of last-mile delivery vehicles (Study D) and real-time re-routing of trucks (Study C). In industry settings, the implementation of logistics outsourcing can involve a significant share of total costs. Hence, in case of setting up a collaboration and if no or few crises occur and companies do not receive compensation, this means a high share of implementation costs in their PPEC-related investment. Hence, the question remains how compensation schemes can reimburse implementation efforts if some benefits for companies, for example insights into public crisis management and publicity, do not apply. Such an operational cost-benefit perspective going beyond logistics costs could not be investigated due to a lack of access to reliable real-world data.

6.3 Future research

Future research on PPEC could benefit from a better understanding of the company perspective on spontaneous collaboration in recent crises. In-depth case study research could retrospectively identify the main advantages for companies, details about logistics operations and lessons learned from both parties. Thus, the company perspective on formal collaboration could be further enriched.

Next, researchers should investigate supply chain data-sharing mechanisms between food and healthcare companies and public authorities. Recently, the German Federal Ministry of Health imposed data transfer of healthcare companies as a countermeasure to drug shortage. As a result, public authorities expect more supply chain transparency and shorter response times to supply shortages (German Federal Ministry of Health, 2022). For example, details about data type are not known to the public, so the question remains which data type, granularity and frequency from which supply chain stage would be just enough but meaningful for public authorities' crisis management. In this regard, data transparency might also help public authorities to support specific parts of commercial supply chains, such as critical suppliers, infrastructure or geographical outliers. This could happen temporarily through provision of staff, trucks, warehouses or products and could address current trends like shortage of truck drivers. Moreover, the question which companies public authorities should partner with deserves more attention. Every additional collaboration partner increases coordination complexity and ties up resources. This brings up the question how the concept of nexus suppliers can be applied in the context of PPEC as well as food and healthcare supply chains. For this purpose, a legal investigation might be necessary: If public authorities pick selected companies for collaboration and these companies benefit, they still need to consider fairness among all market participants.

Finally, the concept of PPEC should be investigated against the background of global food and healthcare supply chains. Regarding food supply, only twelve countries worldwide produce more food than their population consumes and therefore nearly every country in the world depends on food import (Smyth et al., 2021). Recent disruptions of grain export from Ukraine and their impact on several countries' food supply illustrated the dependencies among countries. In case of the healthcare industry, recent supply shortages of drugs in Germany as well as large trade volumes between Asia and Europe motivate further research (German Federal Ministry of Health, 2022; Senn-Kalb et al., 2022). From a public authority perspective, on the one hand, interaction with and provision of incentives for suppliers in foreign countries might be even more challenging. On the other hand, as part of public crisis management, public authorities have an interest in strengthening local companies and protecting their competitiveness against foreign trade policies (Fan et al., 2022; Farhadi and Galloway, 2022). Hence, companies which are critical for essential goods supply and which have suppliers abroad or capital invested in other countries deserve policymakers' attention in the first place. Therefore, future research might investigate how public authorities can leverage synergies between relations in trade policies and PPEC.

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Part II

Conducted studies

Overview of studies

Study A

Diehlmann, F., Lüttenberg, M., Verdonck, L., Wiens, M., Zienau, A., Schultmann, F. (2021). Public-private collaborations in emergency logistics: A framework based on logistical and game-theoretical concepts. *Safety science*, *141*, 105301. doi: 10.1016/j.ssci.2021.105301.

Study B

Lüttenberg*, M., Zienau*, A., Hansen, O., Wiens, M., Diehlmann, F., Schultmann, F. (2023). How to enhance company engagement in public-private emergency collaborations in the supply of essential goods. *Submitted to a scientific journal*.

Study C

Zienau, A., Hansen, O., Wiens, M., Verdonck, L., Diehlmann, F., Schultmann, F. (2023). Public-private collaborative re-routing of commercial transports in crisis situations. *Submitted to a scientific journal*.

Study D

Breitbarth, E., Groβ, W., Zienau, A. (2021). Protecting vulnerable people during pandemics through home delivery of essential supplies: A distribution logistics model. *Journal of Humanitarian Logistics and Supply Chain Management*, *11*(2), 227–247. doi: 10.1108/JHLSCM-07-2020-0062.

Study E

Löffel, M., Diehlmann, F., Zienau, A., Lüttenberg, M., Wiens, M., Wagner, S., Schultmann, F. (2023). Improving emergency preparedness through public-private collaboration - dual-use warehouses for food supply. *Submitted to a scientific journal*.

Study F

Zienau, A., Alazzeh, M., Hansen, O., Imdahl, C., Wiens, M., Schultmann, F. (2023). Impact analysis of extended payment terms in food supply chains during a demand shortfall. In O. Grothe, S. Nickel, S. Rebennack, O. Stein (Eds.), *Operations Research Proceedings 2022: Selected Papers of the Annual International Conference of the German Operations Research Society (GOR), Karlsruhe, Germany, September 6-9, 2022 (in press)*. Springer Nature.

* These authors contributed equally to the study.

A Public-private collaborations in emergency logistics: A framework based on logistical and game-theoretical concepts

Abstract

Collaboration in emergency logistics can be beneficial for governmental actors when supply chains need to be set up immediately. In comparison to research on humanitarian-business partnerships, the body of literature on so-called Public-Private Emergency Collaborations (PPEC) remains scarce. Private companies are only rarely considered within research on emergency collaborations, although they serve as an important chain in the efficient supply of goods given their resources and existing communication networks. Based on this research gap, we contribute to the research field by quantitatively evaluating public-private collaboration in emergency logistics. A framework for public-private emergency collaborations is developed based on logistical and game-theoretical concepts. In addition, we characterize both public and private actors' possible roles in emergency logistics based on literature research and real cases. Furthermore, we provide a structured overview on existing PPECs and the challenges they are confronted with. The game-theoretic PPEC model created in this paper provides more detailed information into the motivation and incentives of the partners involved in emergency collaborations. Inspired by game-theoretic accounts of conventional public-private partnerships, this model sheds light on the partners' participation constraints (which define the scope of collaboration), the effects on the outcome if the partners' contributions are strategic substitutes, and on reputational effects. Finally, we illustrate how a mechanism design approach can be used by the state to transform the firm's incentives into lower levels of undersupply or deprivation.

This chapter includes the article:
Diehlmann, F., Lüttenberg, M., Verdonck, L., Wiens, M., Zienau, A., Schultmann, F. (2021). Public-private collaborations in emergency logistics: A framework based on logistical and game-theoretical concepts. *Safety Science*, *141*, 105301. doi: 10.1016/j.ssci.2021.105301

A.1 Introduction and motivation

In 2018, earthquakes and tsunamis resulted in the loss of 10,733 lives, while extreme weather led to 61.7 million people affected by natural hazards (UNISDR, 2019). According to Worldbank (2019), global losses caused by natural hazards have quadrupled from $50 billion a year in the 1980s to $200 billion in the last decade. Moreover, population growth and increased urbanization lead to rising disaster impacts (Worldbank, 2019).

Van Wassenhove (2006) highlights that around 80% of all relief efforts after disasters are related to logistics. Consequently, all involved actors need to establish well defined relief logistics procedures to protect the affected population. While emergency management focuses on the management of all actions directly after the impact of a disaster (see for instance Tatham and Spens (2011)), the term "emergency logistics" can be defined as "a process of planning, managing and controlling the efficient flows of relief, information, and services from the points of origin to the points of destination to meet the urgent needs of the affected people under emergency conditions" (Sheu, 2007).

Within the limits of the concrete disaster scenario, private companies can still dispose over most of their capabilities to respond to the disaster, while public supply chain structures are severely interrupted during catastrophes (Holguín-Veras et al., 2012). In this context, the complementary risk competences of cooperating public and private partners as well as the collaboration opportunities in terms of joint planning, joint knowledge management and joint use of resources, can help to prevent the shift from a critical or disastrous situation to a catastrophic disaster, resulting in a reduction of the burden on the population and companies (Wiens et al., 2018).

The focus of this paper is to describe and model the scope and potential of emergency collaboration between private firms on the one hand and the government on the other, hence a Public-Private Emergency Collaboration (PPEC). Although researchers agree that multiple actors play an important role in relief logistics (Balcik et al., 2010; Kapucu et al., 2010; Kovács and Spens, 2007), real world cases that develop quantitative disaster relief models for civil protection agencies and other governmental authorities are rarely considered in the literature. One reason for this phenomenon could be that - compared to governmental agencies - humanitarian organizations are more willing to provide researchers with data that they are allowed to publish (and/or funding) in exchange for scientific knowledge and experience (Arnette and Zobel, 2019; Duran et al., 2011; Gatignon et al., 2010; Pedraza-Martinez and Van Wassenhove, 2013; Saputra et al., 2015; van der Laan et al., 2016). In contrast, data received in cooperation with public authorities and governments often contains critical knowledge that researchers might not be allowed to share publicly (Goolsby, 2005). However, an exclusive research focus on non-profit humanitarian organizations in the quantitative relief management context might lead to a trend to analyze ways to fight the symptoms instead of tackling the roots of the problem. It can be argued that the role of non-profit humanitarian organizations in humanitarian logistics primarily exists due to a lack of resilience in the market or in the public disaster management system.

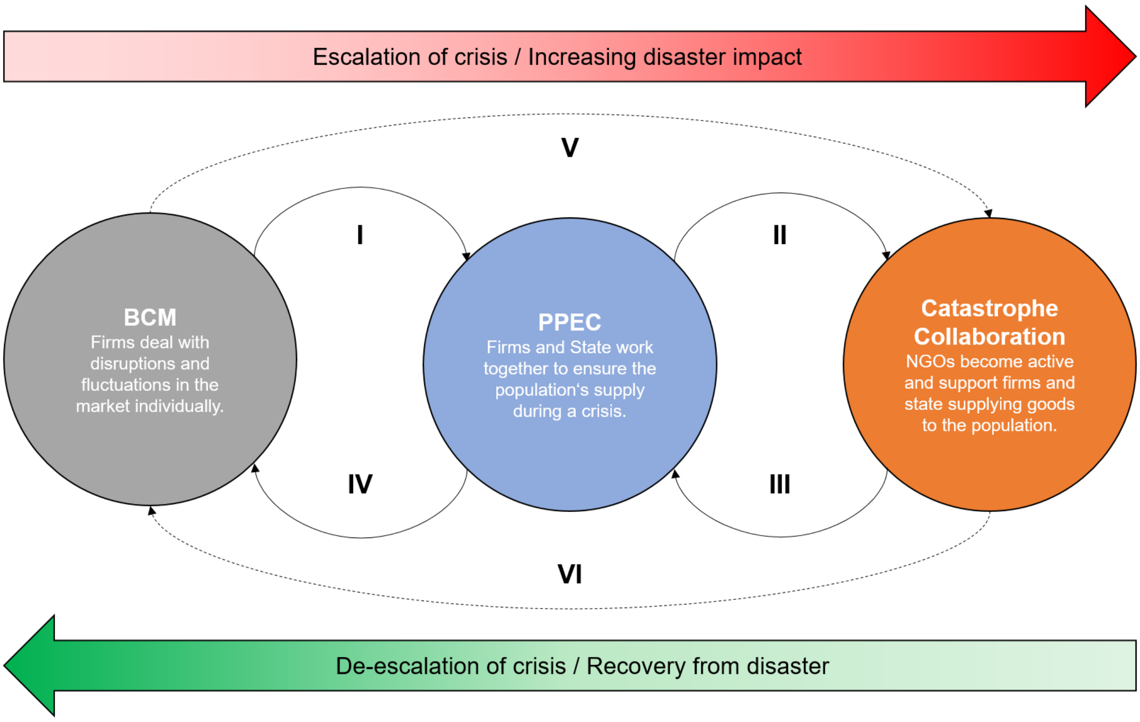

Figure A.1: Classification of phases or activities for different types of actors during a crisis.

From a conceptional point of view, activities of actors after a disaster can be classified as in Figure A.1 (note that real cases may vary from this - for instance due to very strong and active NGOs or comparably ineffective public or private actors). Firms deal with fluctuations in demand or supply as well as with disruptions in their supply chain in the context of their Business Continuity Management (BCM) on a regular basis (see for instance Schätter et al. (2019)). Their reactions focus on getting back to "business as usual" as soon as possible (Palin, 2017; Macdonald and Corsi, 2013). Once a disruption in supply impacts the population or critical infrastructures significantly, the state needs to become active to ensure the population's well being (Wiens et al. (2018), "I" in Figure A.1). These operations can be significantly improved by a collaboration with private firms (PPEC). The importance of the private sector is underlined by Izumi and Shaw (2015), who point out that 70-85% of investments in emergency logistics are expected to come from the private sector.

While humanitarian organizations (HOs) can operate humanitarian supply chains without the occurrence of a disaster, they sometimes play an important role in emergency logistics as well. Their activity usually starts once the impact of the disaster reaches another critical threshold - for instance, because they get significantly more donations if the crisis receives more attention by the media due to increased severity, or due to the time it takes to collect donations (II). In this phase, all actors fight the situation at the same time and need to directly or indirectly work together to ensure efficient relief management (Catastrophe Collaboration). Once the disaster becomes less severe or the HOs run out of funding, HOs leave the area again (III). Finally, the private sector takes over and processes normalize again once the state stops its intervention (IV). Moreover, it has to be noted that in extremely severe situations, NGOs might become active right away (V) or stay active until the market takes over again (VI).

Accounting for these phases, improved emergency management procedures within the private and the public sector can reduce the burden on the population significantly (Papadopoulos et al., 2017). Therefore, it prevents the worsening of the situation and that the disaster turns into a catastrophe. One way to achieve improvement is to establish sustainable collaboration mechanisms, since collaboration significantly improves efficiency and effectiveness of emergency response activities (Balcik et al., 2010; Kapucu et al., 2010). However, in spite of the prominent opinion stressing the importance of multiple actors in crisis management, most of the studies in the field of humanitarian supply chain management focus on a single actor (Behl and Dutta, 2018). In our view, sustainable and – from a welfare perspective – efficient crisis management research primarily requires in-depth research on the way private firms and public organizations deal with emergencies together. While collaboration increases the efficiency of the logistical operations, incentives and a surplus for all involved partners are critical as well. Consequently, a comprehensive account on collaboration in emergency logistics operations requires a profound understanding of both, the operational logistics perspective on the one hand and the incentive-oriented game-theoretic perspective on the other.

However, in comparison to research on humanitarian-business partnerships (Fikar et al., 2016; Nurmala et al., 2018; Tomasini and Van Wassenhove, 2009), the body of literature on PPECs remains scarce (Chen et al., 2013; Gabler et al., 2017; Stewart et al., 2009; Swanson and Smith, 2013; Wang et al., 2016; Wiens et al., 2018). Moreover, to the best of our knowledge, only two publications exist that explicitly consider logistical and game-theoretical approaches in the disaster context simultaneously (Nagurney et al., 2016, 2019). Even though the authors analyzed competition and collaboration of humanitarian organizations, they did not regard the collaboration of public and private actors in disaster management. This paper aims to fill this research gap.

The main contribution of this paper can be summarized as follows. A framework for public-private emergency collaborations is developed based on logistical and game-theoretical concepts. On the one hand, the operations research perspective on PPECs is highlighted by describing the requirements, characteristics, and challenges for logistical PPEC-models. On the other hand, game-theoretical questions are considered regarding contract design and the requirements for collaboration that are mandatory to ensure stable and efficient relationships. In this way, we contribute to the research field by quantitatively modeling public-private collaboration in emergency logistics while considering the problem-specific challenge of the parties' different objectives.

The remainder of this paper is organized as follows. Section 2 discusses the concept of PPECs. Following, we analyze the role of public and private actors involved in emergency logistics and address relevant characteristics of a PPEC from both perspectives. An overview on logistical challenges that need to be regarded in PPEC models follows in Section 4. We complete the modeling framework by considering game-theoretical aspects of a PPEC and providing an illustrative game-theoretical example in Section 5. Section 6 draws conclusions from our findings.

A.2 Public-private emergency collaborations

The concept of a PPEC is closely related to the well established concept of a Public-Private Partnership (PPP). Therefore, we first provide an overview on PPPs in general and build the bridge to PPECs in crisis management, which are confronted with specific challenges but also entail high potential for improvement of crisis operations. We discuss the potentials and limits of a PPEC from a wider economic perspective and focus on the incentives of the collaborating partners. Following, we present different forms of already established PPECs. In line with the definitions provided by Wankmüller and Reiner (2020), the term "collaboration" is preferred in the PPEC context as a collaboration aims to establish a close, intense and long-term relationship between organizations to solve problems jointly. On the contrary, "cooperation" is a short-term phenomenon, which primarily relates to partnerships established in the preparedness and immediate response phases to disasters (Schulz and Blecken, 2010).

A.2.1 Public-private partnerships in general

There is no official definition of public-private partnerships (PPPs) available in literature (Worldbank, 2018). However, PPPs follow the general principle that the collaboration of the public sector with the private sector leads to (1) efficiency gains and (2) an optimal distribution of the risk (Iossa and Martimort, 2015). PPPs ensure the involvement of private partners with both the expertise and the financial resources that may not be readily available in the public sector (Swanson and Smith, 2013). The concept of PPPs was first established in the infrastructure sector (Delmon, 2011) and the transportation sector (Grimsey and Lewis, 2004). Nowadays, they are also applied to social projects (Fandel et al., 2012), in the healthcare sector, for schooling projects, or in waste management (Spoann et al., 2019). Saussier and de Brux (2018) provide an overview on the current status of PPPs in theory and practice.

Several characteristics described in the literature are typical for PPP projects. First, PPP projects are aimed to last for a long-term period (Iossa and Saussier, 2018), typically at least for 20 years. Second, PPP projects may be divided into different organizational parts - the building part, the operating part and the financing part (Morasch and Toth, 2008). Morasch and Toth (2008) argue that the building part is usually executed by private firms, while the financing part belongs to the power of the public sector. The operating part may vary in responsibility. Furthermore, the authors emphasize that in comparison with conventional procurement, where the public sector invites tenders for orders and the whole project is divided into several minor parts that are conducted from different firms, in PPP projects, tasks are bundled and under the responsibility of a single firm. As such, the degree of bundling is higher in PPP projects. Third, in comparison with a conventional project, the cost of a PPP project can exceed or undercut (Iossa and Martimort, 2015). Iossa and Martimort (2015) further elaborate that an important cost-driver of PPPs are transaction costs which are almost uncorrelated with the total PPP volume. High transaction costs arise due to complexity of projects and contractual relationships (Carbonara et al., 2016). Therefore, Iossa and Martimort (2015) suggest that only high volume projects are relevant for consideration of a possible PPP contract. Fourth, Iossa and Martimort (2015) provide an overview on quality factors which need to be considered in PPP projects. They emphasize that every evaluation needs to be performed on a case by case basis, that the quality of the products and services that are part of the PPP contract needs to be analyzed, and that the quality is adequately specified.

To summarize this section, major factors under consideration for the evaluation of a PPP are (1) the period of time the project is forecasted to last, (2) what parts of the projects are privatized and which remain under the control of the public counterpart, (3) the complexity of the contractual design together with the resulting transaction costs (Osei-Kyei and Chan, 2015) and, (4) the quality factors of the project itself.

A.2.2 PPEC barriers, requirements and potential benefits

In general, PPECs should be consistent with the ten "Guiding Principles for Public-Private Collaboration for Humanitarian Action" acknowledged by the World Economic Forum and UN-OCHA (World Economic Forum and UN-OCHA, 2008). The idea is that partnerships with firms facilitate the transfer of knowledge and skills on collaborative logistics and supply chain management, leading to efficiency gains in humanitarian logistics (Nurmala et al., 2017). Moreover, PPECs may help to create more resilient infrastructure systems, thereby helping to improve the situation of the population (Boyer, 2019).

However, several real-life examples highlight that the public sector struggles to collaborate with the private sector efficiently. One case is Hurricane Katrina, in which the successful emergency response of retailers, including Walmart, diametrically opposed the insufficient performance of government agencies (Horwitz, 2009; Sobel and Leeson, 2006). Exemplary was the private sector's fast delivery of necessary goods like food and clothes to the places where they were needed, while the trucks under control of the governmental organization FEMA experienced a lot of difficulties organizing and distributing essential supplies (Horwitz, 2009). Another well-discussed case is the earthquake and tsunami hitting Japan in 2011, where the government excluded private companies from the impact zone and attempted to create entirely new supply networks. As a result, millions of people with a real need for food could not reach commercial organizations, while those outside the disaster area started hoarding (Palin, 2017). This raises the question why such collaborations between public and private actors did not succeed in the way they were supposed to. We argue that there is a significant potential for collaboration but that this potential is more difficult to identify and "extract" compared to other forms of collaboration.

The motivation for both partners to participate in disaster management differs (Gabler et al., 2017), and so do the required incentives. In the following paragraphs, we will briefly outline the basic economic prerequisites for collaboration, especially from an incentive (or game-theoretic) perspective. In Section 4, we will discuss the options for collaboration in the field of logistics and emergency logistics in more detail.

In economics, the agency theory (Milgrom and Roberts, 1992; Townsend, 1982), contract theory (Salanié, 1997) and the theory of relational contracts (Gintis, 2000; Macaulay, 1963; Macleod,

2006) form the methodological framework for the analysis of collaboration between actors with, at least partially, conflicting objectives. In addition to the theoretical foundation, behavioral experimental economics contributed enormously to this field of research over the last decades. Collaborative agreements can significantly reduce transaction cost but have to cope with agency-specific risks based on asymmetries of power and information, such as exploitation, hold-up problems, or moral hazard (Fudenberg and Tirole, 1991). Key factors for a stable and efficient collaboration are (among many others) open (Jüttner, 2005) and credible communication (Farrel and Rabin, 1996) about the partners' objectives and intentions (Falk and Fischbacher, 2006), transparent and fair allocation of risks and benefits (Fehr and Gächter, 2000) as well as the future perspective of an enduring relationship (Fudenberg and Maskin, 1986). The possibility of a longer-term relationship allows the partners to stabilize their relationship on the basis of reciprocity and parallel expectations. From a game-theoretical point of view, relational contracts are self-enforcing contracts, since no external body (such as a court) is required to enforce the contractual interests, but the contract is fulfilled by mutual agreement and in the best self-interest. The range of application of these established concepts is broad and includes labor markets, project management, R&D collaboration and also public-private partnerships (Bing et al., 2005; Desrieux et al., 2013).

In principle, most of these mechanisms can also be transferred to collaboration in crisis management (Solheim-Kile et al., 2019). However, there are a number of special features that should be emphasized because they could make (at least in part) collaboration more difficult if they are not adequately taken into account. First, in a PPEC the interests of the partners could be even more divergent than in classical infrastructure PPPs because the state's priority is on civil protection and on the provision of services of general interest. For companies, excessive investment in disaster prevention can result in competitive disadvantages. Second, this type of collaboration serves to prepare for a future event (disaster) that is only expected to occur with a relatively low probability. Large investments for this purpose must not only be economically justified, but also legally permissible.

However, there are private companies that directly participate in or support humanitarian operations with varying intensity and frequency (see section A.2.3 for a brief account on already established PPECs). Wiens et al. (2018) summarized the four major benefits of a PPEC as follows: (1) Set up an early warning system based on real-time data, (2) allow information sharing between the partners and joint planning of evacuations, (3) avoid undesirable crowding out effects and (4) make use of the infrastructure, expertise and (technological) knowledge of the private sector. In addition to these collaborative benefits, a PPEC can help to avoid costs and provide the requirements for a more efficient crisis management and an appropriate prioritization of tasks (Pettit et al., 2010).

Additional advantages can result from an optimized division of tasks and improved coordination of logistics operations (see also Section A.4). As such, it can be concluded that a number of starting points for a public-private partnership in crisis management exist and that each of these aspects justifies an in-depth model-based analysis.

A.2.3 Already established PPECs

Even though the number of real-life cases is small, there are already a few existing examples of partnerships and networks which are structured as a public-private collaboration for crisis management. Spontaneous and less structured examples were rapidly established during the COVID-19 pandemic. For example, the German government instructed internationally operating companies to procure urgently needed equipment after public authorities struggled to purchase enough goods (Tagesschau.de, 2020). Another example can be found in Sweden, where PPPs are implemented into the Swedish emergency preparedness management (Kaneberg, 2018). Additionally, the US National Business Emergency Operations Center works as "FEMA's virtual clearing house for two-way information sharing between public and private sector stakeholders in preparing for, responding to, or recovering from disasters" (FEMA, 2019). Participation works on a voluntary basis and is free of cost. Moreover, the German UP KRITIS - a public-private partnership focusing on critical infrastructures out of nine different sectors (e.g. water, nutrition, or energy) - has the goal to increase the resilience of these infrastructures and to facilitate the exchange about current topics (UPKRITIS, 2019).

These examples highlight the high potential of PPECs to increase efficiency in emergency response. Furthermore, they show that the adequate management of involved actors is challenging and requires thorough preparation. While this list is by far not complete, it indicates the status of partnerships that have already been established and points to the difficulties of taking into account the roles, interests and capabilities of the partners.

To conclude, Section A.2 clearly demonstrates the opportunities and impediments associated with PPECs both from an academic and practical perspective. Following, we present the distinct roles public and private partners should take on in emergency logistics.

A.3 On the role of public and private actors in emergency management

Kovács and Spens (2007) identify six types of actors in supply networks for humanitarian aid – donors, aid agencies, NGOs, governments, military, and logistics providers. Since these groups of actors pursue different (sub-)objectives and act under different conditions, uncoordinated intervention in a crisis can quickly lead to an aggravation of the situation rather than to an improvement. Therefore, Balcik et al. (2010) highlight the need to collaborate and discuss challenges in the coordination, which are highly discussed in academic literature and which are the focus of Section A.4.

Although collaboration can happen on a voluntary, altruistic basis, the moral responsibility of private actors should not be neglected. For instance, Hesselman and Lane (2017) investigate roles and responsibilities of non-state actors during disaster relief from an international human rights perspective (inter alia, Article 25, which addresses food and shelter (United Nations, 1948), connects PPECs with human rights issues). They conclude that non-public actors in disasters are indirectly obligated to become active, even though it might be difficult to hold them directly accountable. Therefore, Hesselman and Lane (2017) suggest that it could be one of the state's core task to include non-public actors into the disaster management processes using regulations. Within this context, it is necessary to understand the roles and tasks of the respective partners.

A.3.1 The role of public actors in emergency logistics

In this paper, we define "public actors" as all types of institutions and organizations under the control of public authorities on a federal and/or provincial level. This includes – inter alia – public disaster management institutions (for instance the US FEMA or the German THW), the military, police forces and firefighters (as long as they are not privatized), and all types of ministries directly or indirectly involved in the relief process (legal, environmental, financial etc.).

In general, the function of public actors in the domain of civil protection is to "provide security against unexpected threats that individual citizens cannot meet alone" (Comfort, 2002). During emergency relief, they need to establish a safe environment for beneficiaries and relief organizations. Moreover, public actors have critical resources at their disposal (Kovács and Spens, 2007), which they use to support relief action physically (e.g. THW trucks) or financially (e.g. through the FEMA Disaster Relief Fund). Furthermore, governments can ask foreign governments or HOs for support.

At the same time, "no international action can take place if the local government does not request it" (Day et al., 2012). In some cases, governments accept foreign humanitarian work without supporting it actively (Akhtar et al., 2012) or even put up barriers to impede a HO's intervention (Kunz and Reiner, 2016). Moreover, in very drastic cases, public actors can – if the legal context of the crisis area accounts for it – enforce the right to take possession over critical goods or resources (EIAS, 2016). This can catch private actors by surprise and interfere with their planned processes significantly. Due to legislative and moral responsibilities, public actors first and foremost need to support the population during an emergency. This includes, for instance, to fight the reason of the crisis, to maintain public security, or to ensure that the population has access to essential goods.

The delivery of goods for a large amount of people requires a variety of resources (e.g. trucks, people). However, purchasing and maintaining resources is extremely costly – especially if the resources are only needed in extraordinary times. Consequently, public actors only have a comparably low number of resources at their direct disposal. Without a PPEC, public actors therefore need to hire logistics companies (for instance in the US via the Disaster Response Registry (U.S. Small Business Administration, n.d.)) or buy goods directly from private companies during a crisis. In developing countries, where the private sector is not as well equipped as in developed countries, the lack of resources therefore leads to, among others, the very prominent role of NGOs in crisis management.

Regarding logistical challenges of a crisis, public actors can benefit from a PPEC due to an increase in logistics capacities (Nurmala et al., 2018; Wang et al., 2016) or access to logistical competences (Qiao et al., 2010; Tomasini and Van Wassenhove, 2009). During the COVID-19 outbreak, the

German state clearly acknowledged the important role of private supply in crisis response by supporting firms as much as possible. For example, authorities loosened restrictions on truck driving hours and trucks with essential supplies were allowed to drive on Sundays (German Federal Ministry of Transport and Digital Infrastructure, 2020), shop hours for grocery stores were extended to Sundays (RL, 2020), and even an exemption from the strict COVID-rules on immigration was made for harvest workers from Eastern Europe (German Federal Government, 2020).

At the same time, public actors provide special capabilities for a PPEC (see for instance Kovács and Tatham (2009)). First, public actors have specialized equipment and competences at their disposal. For instance, the German THW owns multiple mobile water purification plants (THW, n.d.). Military forces can provide necessary resources, communication devices, means of transport, medical services, water supply, and strong logistical and organizational structures (Carter, 1992). Second, the government is legally empowered to enforce safety. They can do this with the help of police and/or military (Byrne, 2013), or - in the case of a very strong escalation of a crisis – by adapting the laws (see for instance Halchin (2019)).

Furthermore, the involvement of private actors in the crisis management process can speed up the recovery process and help to let the market take over again faster (Palin, 2017; Wiens et al., 2018). Strengthening these processes will help to increase the resilience of communities and supply chains (Chen et al., 2013; Mendoza et al., 2018; Pettit et al., 2010).

A.3.2 The role of private actors in emergency logistics

Emergency logistics becomes necessary if commercial supply chains are not capable to supply the population with sufficient essential goods. This could be the case due to supply chain disruptions or a sudden increase in demand. When talking about private actors in the context of emergency logistics, we refer to those firms involved in the supply of essentials like food or medicine (e.g. producers, retailers, or logistics service providers).

These companies can contribute to emergency logistics with monetary donations, products, and services which can be provided in a commercial and non-commercial way (Hesselman and Lane, 2017; Nurmala et al., 2018). This could be observed during the COVID-19 pandemic, when some companies reacted proactively with immediate shifts in production to highly-demanded products, such as disinfectant (e.g. Jägermeister) or face masks (e.g. Trigema, Focus (2020)).

From a firm perspective, involvement in emergency logistics is an issue in BCM and CSR. BCM includes companies' planning and preparation of response and recovery to disruptions of business processes (D. Elliott et al., 2010). Even in times of crises, companies' actions are predominantly motivated by long-term profit, which is why they put the strongest emphasis on the protection of their assets and fast recovery of their business processes. In doing so, some factors are directly controllable by the company while others are not (Macdonald and Corsi, 2013; Horwitz, 2009; Li and Hong, 2019; Palin, 2017; Rifai, 2018).

CSR is a company's involvement in social topics under the expectation that social improvement will lead to long-term profit (Horwitz, 2009; Van Wassenhove, 2006). CSR efforts of private firms are proven means to improve corporate reputation (Donia et al., 2017). Reputation implies both the prominence of a company – the label as *being known for something* - and the image in the sense of holding a *generalized favorability* towards other companies (Lange et al., 2011). Through CSR related actions like food donations, firm reputation might increase in or after crisis situations (Cozzolino, 2012; Dani and Deep, 2010; Tomasini and Van Wassenhove, 2009). Next to positive reputation, Binder and Witte (2007) name improvement of government relations, staff motivation and the "desire to do good" as motivation for the private sector to engage. However, Izumi and Shaw (2015) emphasize that companies would also indirectly protect themselves by being involved in crisis response and thereby mitigating crisis effects that would affect the economy, like loss of life or economic downturn. It shows that emergency logistics is included in both, BCM and CSR. The specific concept of reputation is discussed later in the game-theory part in Section A.5.1.3.

In the following, we present real-life examples of the private sector facing a crisis. One example is the contamination of tap water in the city of Heidelberg, Germany, on February 7th, 2019 (Heidelberg24, 2019). The duration of the event was uncertain in the beginning. Hence, people started to hoard bottled water and buy large amounts from retail stores, which in turn had to be refilled as soon as possible (Heidelberg24, 2019). A sudden increase of demand affects different stages in the supply chain, which can cascade along the supply chain (Kildow, 2011; Snyder et al., 2016). In Figure A.2, we visualized a commercial bottled water supply chain facing a tap water failure. In personal discussions with companies from food supply chains, we found that in case of sudden demand peaks, rush orders are one measure to quickly refill warehouses and retail stores. However, rush orders would involve higher costs. Another measure would be to skip handling steps in the transport chain in order to offer larger amounts faster to customers. Here, additional coordination efforts would again cause higher costs. The case of Heidelberg shows how commercial retail supply chains can be affected by crisis situations without being directly hit. Moreover, companies' stock values might decline when announcing supply chain disruptions (Dani and Deep, 2010).

A second intensively discussed example of private sector donations during a crisis is Walmart's response to Hurricane Katrina in 2005. The retailer donated food, drinks and other goods fast and efficiently in the affected area (Horwitz, 2009). Not only in this case, supply speed compared to governmental response is seen as a core strength of private actors in crisis response (Nurmala et al., 2018). This goes along with findings from Dani and Deep (2010), who found that supply chain collaboration can help move goods faster and more efficiently during crisis.

The above examples highlight the important role of private companies during crises. However, after Hurricane Katrina, Walmart rejected the government's offer to become an "emergency merchandise supplier" (Chen et al., 2013). Among others, the huge capacities in such a business and large inventories for disaster preparedness did not fit with Walmart's corporate strategy. The authors suggest that Walmart's decline was further due to risks perceived with a contractual agreement with a strong partner, which could impede its operational freedom (Chen et al., 2013). This further hints at the importance to take the risks and incentives of the PPEC-partners into account.

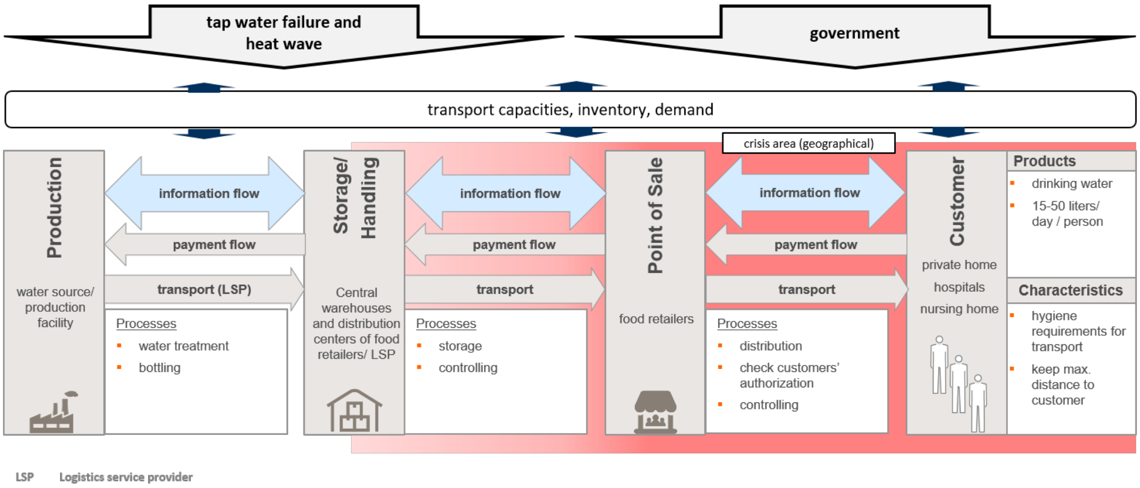

Figure A.2: Exemplary visualization of commercial water supply chains in case of tap water failure (based on Dani and Deep (2010)).

The examples show that improvisation and speed are crucial for companies' efficient crisis management. The necessity to immediately react and adapt to new circumstances by possibly re-engineering supply chain processes indicates the flexibility of the corresponding processes. Thus, the more flexible a company's processes, the more resilient it is towards disruptions (Scholten et al., 2014; Snyder et al., 2016; Tomasini and Van Wassenhove, 2009; Tukamuhabwa et al., 2015). Usually, companies would lack preparation for disruptions of low probability and high consequences (Pettit et al., 2010; Izumi and Shaw, 2015; Van Wassenhove, 2006) and focus on rather internal disruptions they can control (Kildow, 2011). Consequently, companies might acquire knowledge during a crisis from which they can benefit afterwards. Furthermore, collaboration with public actors can provide access to up-to-date information during a crisis with numerous uncertainties (Wiens et al., 2018). Not only access to information, but also the involvement in governmental resource control can be beneficial.

Summarizing Section A.3, the combination of public and private partners' strengths and capabilities provides a significant opportunity for change in emergency management.

A.4 Modeling PPECs: logistical challenges

While supply chain collaboration aims to decrease uncertainty and increase efficiency, it is also confronted with multiple challenges hampering the achievement of these goals. In the next two sections, challenges associated with modeling and coordinating collaborations, in a commercial and an emergency context respectively, are reviewed and discussed.

A.4.1 Collaboration in logistics

The main goal of all commercial partnerships is to jointly generate value in the exchange relationship that cannot be generated when the firms operate in isolation. However, numerous surveys report that 50 to 70 percent of all these collaborations fail for one reason or another (Schmoltzi and Wallenburg, 2011). Because every partner remains independent, the risk of opportunism remains real.

According to Verdonck (2017), challenges related to sustainable partnerships can be divided into six groups - partner selection and reliability, identification and division of joint benefits, balance of negotiation power, information and communication technology (ICT), determination of operational scope and competition legislation.

A first challenge in the establishment of a sustainable horizontal collaboration refers to the selection of suitable partners. The analysis of the strategic and organizational capabilities of a potential partner requires knowledge about its physical and intangible assets, its competencies and skills and its main weaknesses. This type of information is often held private in the respective organization. Moreover, the amount of attainable collaborative savings is influenced by the degree of fit between the collaboration participants. When partners have been selected and the partnership has been established, uncertainty about partner reliability and their commitment to promises also contribute significantly to the complexity of the collaboration (Verdonck, 2017).

Next, it appears that partnering companies find it difficult to determine and divide the benefits of collaborating. It is essential, however, to ensure a fair allocation mechanism in which the contributions of each partner are quantified and accounted for, since this should induce partners to behave according to the collaborative goal and may improve collaboration stability (Wang and Kopfer, 2011). Besides selecting a mechanism to share collaborative benefits and costs, deciding on the operational and practical organisation of a collaboration might turn out to be a challenging task (Verstrepen et al., 2009). Partnering companies need to agree on the collaboration strategy, the allocation of resources and the applicable key performance indicators (KPIs), among others (Martin et al., 2018).

Another threat to the sustainability of a collaboration is the evolution of the relative bargaining power of the participating companies over the lifetime of the collaboration (Cruijssen et al., 2007).

A fifth challenge in the establishment of sustainable collaborations deals with the implementation of the necessary supporting ICT, which could hamper those forms of collaboration that require intensive data exchange (Cruijssen et al., 2007).

Finally, companies engaging in a collaboration project need to consider the applicable legislation on market competition. Legally binding rules prevent companies from working too closely together as this may restrict competition on the market at hand. European competition rules not only prohibit explicit collaborations, such as price-setting agreements, production limits or entry barriers, but also forbid any multi-company arrangements that have similar effects (Verdonck, 2017).

A.4.2 Collaboration in emergency logistics

We developed a framework that originates from several (review) papers, which set up frameworks for humanitarian logistics or commercial supply chains facing risks or disruptions. The first (Kochan and Nowicki, 2018; Scholten et al., 2014; Snyder et al., 2016; Swanson and Smith, 2013; Tukamuhabwa et al., 2015) and second category (Scholten et al., 2014; Snyder et al., 2016; Tukamuhabwa et al., 2015) are often discussed topics in literature. These two categories are expanded with the consideration of different characteristics of public and private actors in the context of emergency logistics. Assuming PPECs are coordinated and managed indirectly through the use of game-theoretical methods like (relational) contract design (see Section A.5), they are confronted with the following challenges: differences in strategies and motivations, complex and uncertain interactions between actors, and different characteristics of the actors' resources and capabilities (see also Figure A.3).

We will address all these aspects in the following subsections, while a detailed game-theoretical discussion of PPECs follows in Section A.5.

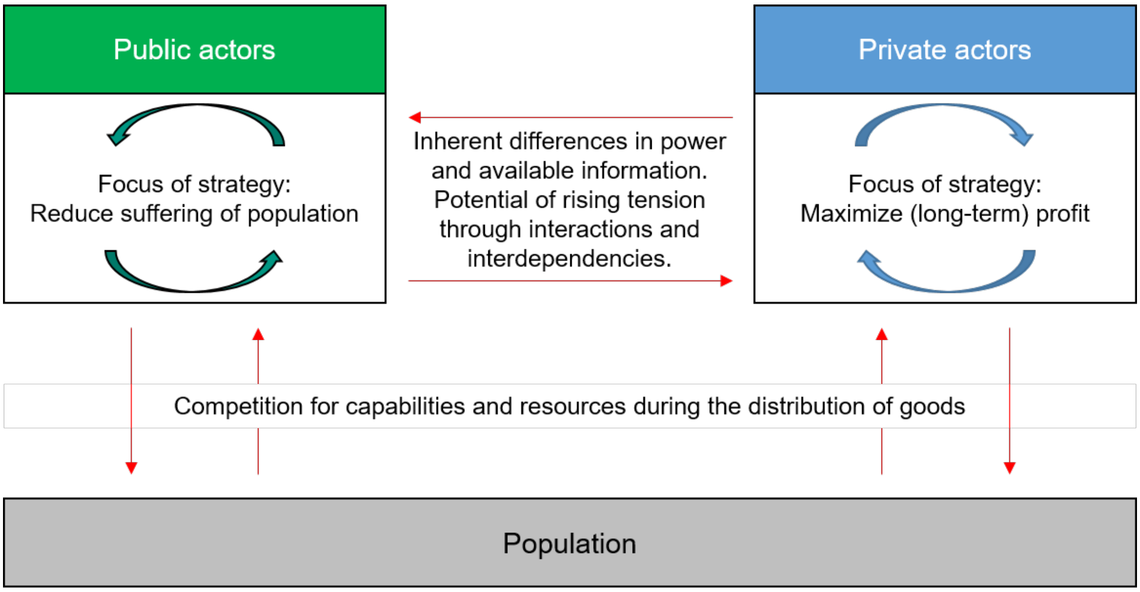

Figure A.3: Interdependencies in public-private emergency logistics.

A.4.2.1 Strategy and motivation

Public and private actors engaged in an emergency collaboration are driven by different strategies and motivations. These aspects are reflected by their different general objectives and opposing time horizons of decision making.

Multi-objective nature of logistic models

The long-term profit and efficiency orientation of the private sector is mainly modelled through a cost focus (Holguín-Veras et al., 2012). This is also the case when modeling supply chain disruptions, although this implies the challenge of quantifying the consequences (Ivanov et al., 2017; Ribeiro and Barbosa-Povoa, 2018). Usually, supply chain disruptions are analyzed by opposing models of the normal supply chain and the disrupted supply chain (Ivanov et al., 2017). In their review on disruption recovery in supply chains, Ivanov et al. (2017) classify the modeling of supply chain performance during crises into different types of costs: fixed, variable, disruption, and recovery costs.

Regarding public actors, as mentioned in Section A.3.1, the primary concern is the well-being of the population. This is closely related to the objectives of HOs, where optimization models in the literature focus on fulfilling the needs of the beneficiaries and the reduction of the misery of the population (Holguín-Veras et al., 2012). However, HOs always work on some sort of a limited budget or – dependent on their organizational structure – need to be profitable in some ways. One of the most prominent approaches regarding this setup is the social cost approach by Holguín-Veras et al. (2013). In this approach, the authors include logistics costs and combine them with deprivation costs to define "social costs". In this context, deprivation costs account for the damages that happen after being undersupplied for a long time (Holguín-Veras et al., 2013). Consequently, the minimization of social costs allows HOs to focus on both financial and non-financial aspects. Various studies include approaches that minimize some form of social or deprivation cost (Cotes and Cantillo, 2019; Khayal et al., 2015; Loree and Aros-Vera, 2018; Moreno et al., 2018; Pradhananga et al., 2016).

Furthermore, Gutjahr and Fischer (2018) were able to show that the minimization of deprivation costs leads to unfair solutions in case of budget limitations. They therefore developed an approach that includes measures similar to the Gini-coefficient to increase the fairness of the resulting allocations. Consequently, public actor's high degree of financial flexibility indicates that the focus on social cost minimization seems to be appropriate for them, while HOs optimizing on a limited budget are recommended to use the approach of Gutjahr and Fischer (2018) as a guideline.

Time horizon of decision making

A fundamental difference between the public and private perspective is the general supply chain layout and the time horizon of the actors. Private actors design their network to be profitable in normal times. However, during a crisis, they need to adapt to the specifics of the crisis quickly (Macdonald and Corsi, 2013). On the other hand, public actors do - except from long term storage facilities - not possess established supply chain structures in normal times. Therefore, they need to set up completely new supply structures under high time pressure and at high costs (Holguín-Veras et al., 2012). Consequently, there is a high degree of flexibility in regards to location, transportation, and product portfolio selection when setting up public emergency supply chains. Moreover, mixed forms are possible, in which, for instance, public actors use the private actors' established structures to distribute goods.

A.4.2.2 Interaction between actors

Another important aspect to consider is the interactions between actors. As a substantial amount of actors is involved in emergency collaborations, the efficient coordination of their interactions is often very challenging (Balcik et al., 2010; Kabra et al., 2015). These challenges can include the fundamental power difference, aspects of trust and partner selection, the information that the actors share, or the identification and division of costs.

Power differences
Both public and private actors' involvement is determined by the power they possess in times of disaster. The public sector is only entitled to intervene if the situation provides the legal prerequisites for an intervention. If this is the case, public authorities can have far-reaching rights which give them access to several resources (e.g. goods, transport capacities, production facilities) (Daniels and Trebilcock, 2006; Wood, 2008). Private sector involvement in emergency logistics is voluntary if not being forced through governmental seizure. However, motivated to implement CSR and BCM strategies, companies still possess their operational freedom in decision-making. Hence, they can determine their level of involvement in emergency logistics (Johnson and Abe, 2015). Moreover, power differences within commercial supply chains are crucial. For example, firms can have strong negotiation positions with their suppliers (Spence and Bourlakis, 2009), which can also affect the abilities to respond quickly in crises.
Information sharing
Research has shown that a lack of information sharing among commercial supply chain members results in increased inventory costs, longer lead times and decreased customer service (Simatupang and Sridharan, 2002). Since logistics is responsible for 80% of relief operations (Van Wassenhove, 2006), coordination of information flows has a critical influence on relief chain performance (Balcik et al., 2010). As opposed to a commercial supply chain environment, however, the sources of information can be limited or even unidentifiable in the aftermath of an emergency (Sheu, 2007) and the information themselves incomplete (Yagci Sokat et al., 2018). For this reason, the UN Joint Logistics Center has been formally established in 2002 with the aim of collecting and disseminating critical information and setting up information-sharing tools (Kaatrud et al., 2003).

Trust and partner selection
Collaborative relationships could also suffer from a lack of trust between public and private partners. Governmental organizations might doubt the good intentions of private companies, while the latter often perceive public partners as bureaucratic (Christopher and Tatham, 2011). Moreover, in comparison to commercial environments, the development of trust is impeded by the ad-hoc nature of the hastily formed networks (Tatham and Kovács, 2010). In line with the partner selection challenge addressed in Section A.4.1, differences in geographical, cultural and organizational policies may create additional coordination barriers (Van Wassenhove, 2006). Moreover, Kabra et al. (2015) discuss management, technology and people characteristics which may hamper efficient

emergency collaborations.

Identification and division of costs
Xu and Beamon (2006) identify three cost categories associated with coordination of supply chain collaborations: coordination cost, opportunistic risk cost, and operational risk cost. Coordination costs are directly related to physical flow and coordination management. Opportunistic risk costs are associated with a lack of bargaining power, while operational risk costs result from unsatisfactory partner performance (Balcik et al., 2010). A survey of Bealt et al. (2016) revealed that the cost of logistics services is considered the most important barrier in the formation of collaborative relationships between private companies and humanitarian organizations. Given the uncertain environment emergency collaborations operate in and the lack of clear visibility of required operations and resources, the magnitude of these cost levels is hard to identify. In addition, effective collaboration requires mechanisms to allocate the associated costs to each partner. Due to the non-financial aspects of emergency logistics, mechanisms developed for commercial applications, such as penalty fees, cannot be directly implemented to PPECs (Dolinskaya et al., 2011).

A.4.2.3 Capabilities and Resources

Public and private actors dispose over various capabilities and resources. In the case of severe disasters, these capabilities and resources can be limited heavily. Therefore, the specific circumstances of the crises need to be taken into consideration during the development of a logistical model. In the context of the following subsection, we assume that both public and private actors' capabilities and resources after the disaster are still available.

Capabilities
Under this assumption, commercial supply chains can still make use of their established routines, their communication network, and their knowledge of market and demand during crises (Holguín-Veras et al., 2012). Retail supply chains can quickly adapt to changes and uncertainties. Hence, they are designed to act in an environment where flexibility and speed are crucial (Bourlakis and Weightman, 2004). These capabilities are also crucial for private supply chains in their response to disasters (Kochan and Nowicki, 2018; Ribeiro and Barbosa-Povoa, 2018). Following Kochan and Nowicki (2018), such capabilities can be classified into readiness, responsiveness and recovery.

Contrary to commercial supply chains, knowledge in public supply chains can be categorized as general disaster knowledge rather than detailed market knowledge. This is highlighted by Kovács and Tatham (2010), who compared skills required for commercial logistics positions to requirements for humanitarian logisticians. They concluded that – in spite of some similarities – significant differences exist. For example, humanitarians consider problem-solving skills more important than their commercial counterparts do (Kovács and Tatham, 2010).

Furthermore, public actors need to cope with numerous uncertainties that are typical for disaster situations (Olaogbebikan and Oloruntoba, 2017). To model these uncertainties related to supply chain disruptions, Snyder et al. (2016) suggest supply, capacity, and lead time uncertainty. However, it needs to be considered that uncertainties during and after a disaster significantly exceed the fluctuations companies are normally prepared for (Holguín-Veras et al., 2012). Moreover, sudden demand peaks (Snyder et al., 2016) as well as the above-mentioned lack of preparedness for low-probability and high-consequence events can be considered in modeling PPECs.

In addition, private actors are hit by the disaster right away. In case of a shortage, retail stores try to satisfy the high demand immediately (see also Holguín-Veras et al. (2012)). In the case of the suspected contamination of the tap water in Heidelberg, this led to a time gap: until public actors set up an emergency water supply chain, commercial supply chains were the only distributor of water. However, they struggled to cope with such unexpected extraordinary demand peaks (Heidelberg24, 2019). Therefore, support from public actors would have been necessary if the crisis lasted longer.

It can be concluded that modeling commercial logistics capabilities should focus on the optimization of steady flows, while public supply chains are designed to immediately cope with large transport volumes (Holguín-Veras et al., 2012; Olaogbebikan and Oloruntoba, 2017).

Resources

Public actors have the opportunity to choose locations for warehouses and distribution points out of a large number of buildings (e.g. schools, sports arenas) and – due to the legislative option to take possession of resources and goods – indirectly over a huge variety of additional resources. However, the high flexibility goes hand-in-hand with a high degree of uncertainty. For instance, public actors could try to take possession of the goods in a warehouse without knowing about quantities and the exact product specifications beforehand. On the other hand, private actors physically possess resources and have knowledge and control over their location, while they have to work under the permanent threat of seizure.

Furthermore, there is a large difference regarding the up-scaling of available staff at different sites. Except for temporary employees, the size of the workforce of private organizations is rather fixed. Moreover, the process to hire additional employees is time consuming and challenging. Therefore, private organizations need to navigate through heavy supply chain disturbances with the staff they have at their disposal in normal times. On the other hand, public relief organizations staff consists of volunteers at a high degree. This is closely related to the risk of taking possession of physical resources since the volunteers, which are activated by public actors, cannot keep working in their usual job during the crisis and therefore the staff at companies is even further reduced.

Section A.4 demonstrates that, while collaboration in logistics always coincides with various challenges, the complexity of humanitarian operations creates additional impediments making it impossible for public partners to simply adopt best practices from the commercial sector. Collaboration between humanitarian actors thus needs to be intensified for crisis management to become more efficient and effective (Besiou and Van Wassenhove, 2020).

A.5 A basic game-theoretic PPEC-approach

In this section, we approach PPECs from a game-theoretical perspective to carve out its potential and limits with a focus on the actors' incentives. Game-theory formally describes the effects and interdependencies of strategic decision makers (Myerson, 1991; Rasmusen, 2007). Similar to Seaberg et al. (2017), we argue that in the context of disaster management partners act strategically as long as their goals are not completely congruent. Although the number of articles in the area of disaster management is limited, there are some first contributions that analyze the strategic interaction among different actors in this domain, though not from a public-private perspective.

For example, Nagurney et al. (2016) and Nagurney et al. (2019) look at competition between HOs based on a game-theoretic model, which jointly integrates both logistical and financial decisions. The model sheds light on the interesting strategic position of HOs who are competing and at the same time collaborating to share resources and reduce cost (collaboration is realized by shared constraints). Compared to public and private players, HOs are non-profit and non-governmental and therefore represent a third type of actor, which is not considered by our approach (see also Section A.1). Gossler et al. (2019) apply a similar approach to determine the optimal distribution of tasks. The authors derive the optimal distribution decisions for a long-term business perspective of disaster relief organizations. Nagurney et al. (2016, 2019) and Gossler et al. (2019) all apply the rather specific concept of a Generalized Nash Equilibrium, which allows them to deal with the strategic aspects and the complexity of the decisions (with respect to the large number of restrictions).

H. Zhang et al. (2020) analyze a cooperative scenario of two rescue teams. The authors optimize both actors' vehicle routing strategy, using a non-cooperative approach first and comparing the results to a cooperative approach. They argue that the cooperative scenario always outperforms the non-cooperative scenario. One of the main differences to our approach is that the analyzed actors cooperate on a horizontal level and share the same objective functions. The same argument applies to M. Zhang et al. (2019), which deal with a collaborative multimodal approach to finding the optimal allocation proportion to optimize coverage, construction costs, and rescue time.

Moreover, Kang et al. (2013) investigate PPP projects and the bargaining process related to them. They elaborate on the government's bargaining power in the bidding process of a specific project with different companies. While the authors give valuable insights into the general functioning of logistics processes in PPPs, they do not explicitly deal with emergency logistics.

Coles and Zhuang (2011) model a multi-actor collaboration game to establish a decision support framework in the context of emergencies. The model evaluates and selects the most valuable relationships for the emergency manager considering resource restraints. In addition to the assumption that every company is a profit maximizer, the authors also look at non-financial benefits that accrue value to the business model of a private company. Taking a similar focus on preferences and goal alignment, Carland et al. (2018) analyze the potential for collaboration between humanitarian organizations and the private sector based on a decision support framework (multi-attribute value analysis). From an HO's perspective, the objective is to engage private actors, to elicit their preferences, and to align the objectives of both sides.

The following game-theoretical model primarily serves illustration purposes and is therefore deliberately kept simple. We assume two players, the public sector and the private sector. The objective functions of both players correspond to the roles of both players in emergency logistics as discussed in Sections A.1 and A.2.

In the model, we assume two reasons for the firm to engage in a collaboration: reduction of disaster-related cost and reputation. These two variants of motivation primarily serve to illustrate the interplay of state and firm incentives in a basic model. Albeit not part of our analysis, it is promising to extend the firm's motivation in a dynamic setting. For example, one could imagine a private company that learns from the emergency context, where it collaborates with the public sector and thus ultimately establishes a more sustainable and crisis resilient business model, which improves the company's internal BCM processes. The aspect of reputation is also touched upon only briefly to highlight the incentive effects. A detailed analysis of reputation effects requires a dynamic model that goes beyond the objective of this contribution.

The advantage of our approach to choose a basic model is that two central solutions of the game can be derived in closed form and thus directly compared: The Nash equilibrium (NE) as an individually rational solution of the game on the one hand and the loss-minimizing result, which the state primarily strives for. This raises the important question whether the outcome envisaged by the state can also be implemented by a so-called *incentive-compatible* contract. A simple *mechanism-design* approach describes the conditions under which this solution is feasible. The application of contract theory and mechanism design is important for a game-theoretic account of a PPEC because the collaboration between state and company is ultimately intended to improve crisis management, i.e. to transfer relief supplies more efficiently to people in need. As mentioned above, the main advantages of collaboration in emergency logistics are the increased resource availability and capacities, leading to a higher overall service level (Bealt et al., 2016).

A.5.1 The model

We now illustrate the potential for collaboration by choosing a basic game-theoretic framework. As outlined in the previous sections, "collaboration" means that the firm and the state jointly prepare for the disaster by coordinating their planned activities.

Many measures are conceivable for such joint planning. These measures include, among other things, the provision and sharing of storage capacity, agreements on the coordinated use of truck capacities, or the company's promise of preferential deliveries to the state (in return for which the former receives certain regulatory relief). A quite apt example of such cooperation is the Freight-Transport-Pact (FTP) agreed upon in Germany during the Corona crisis between state authorities and freight carriers, together with transportation and logistics associations. The pact provides 24/7 supply in the event of a crisis, whereby both night-time driving and weekend deliveries are permitted.

Collaboration can avoid cost and provide the requirements for more efficient crisis management. In a first step, we describe the objective functions for the state and the firm. Based on the objective functions and the strategies, we derive the *NE* of the game. As a solution concept, the NE provides us with the individually optimal outcome of each player given that the co-player plays its NE-strategy, too. Thereafter, we compare the individual optimization result with the strategy combination, which minimizes under-supply in the form of (non-material) losses of the population such as suffering and deprivation. In the context of a disaster, this is the overriding goal of state crisis management. We therefore consider this *loss-minimizing*-outcome (LM) as the first-best solution out of the state's perspective as the ruling disaster management authority. Finally, we discuss under which conditions the loss-minimal solution can be implemented in an incentive-compatible way and to what extent company reputation can support a collaborative solution.

A.5.1.1 Basic structure

Assume that a disaster strikes with a probability ε and that the disaster causes a damage of size $D > 0$. We assume that ε is an independently Bernoulli-distributed random variable on the interval [0,1]. In this model, damage is understood as "deficit quantity", i.e. the quantity of essential goods that is missing to supply the population. To be able to supply the population with these goods, the state needs to acquire them on the market together with the "logistical capacity", which is needed to store, transport, and distribute the goods. As the difference between goods and logistical capacity is of secondary importance for our analysis (what matters is the fact that the state has to purchase these resources from the company), we summarize both with the variable x which stands for "resources". These resources could be freight capacities for trucks, as in the example of the FTP.

The state can acquire these resources at two points of time: It can procure *before* the crisis occurs (ex ante) and thus create an emergency reserve of x^N where the index N stands for "No crisis" or "Normal times". Procuring in normal times implies that the state has to pay the regular market price p for the resources. Alternatively, the state can wait until a crisis occurs and try to acquire the goods "ad hoc" from the firm (ex post). In most countries, such an intervention comprises confiscation and a subsequent compensation of the company (Daniels and Trebilcock, 2006; Deflem, 2012). We use the variable x^C for the confiscated items where the index C stands for "Crisis". The state compensates the firm at arm's length prices q per unit. The variable q (compensation payment) is determined by competition law and by the type of contract between the firm and the state. The compensation level can be equivalent to the market price p but don't need to be. Besides the uncertain price conditions during a crisis, the complete availability of goods during a crisis, even if the price does not rise, is uncertain. For example, in most countries, the state compensates the companies for seized goods with the market price which was observable $before$ the crisis occurred.

Furthermore, since the confiscation occurs ad hoc, it causes transaction costs to both the state and the firm, which can be substantial if the intervention is not coordinated (Pelling and Dill, 2010; Wood, 2008). As explained at the beginning of this section, pre-crisis collaboration reduces these transaction costs because a PPEC reduces frictions at the company due to otherwise unprepared and abrupt changes in the business procedures. This excessive increase in transaction-cost reflects the difficulty – or even impossibility – of procurement processes under enormous time pressure for all actors and extreme stress conditions on the markets. If, however, the joint use of capacities has already been planned and operationally prepared in peacetime in such a way that only an emergency plan needs to be activated in the event of a crisis, then the transaction costs for both sides are considerably reduced. For the state, a high degree of collaboration will accelerate the availability and usability of the firm's resources. The transaction costs are given by $T_{S,F}(\theta_S\,\theta_F) = \frac{c_{S,F}}{\theta_S \theta_F}$ for the state (S) and firm (F) respectively. The variable $c_{S,F}$ denotes the combined transaction cost factor of the state (or the firm, respectively) as occurring during a crisis.

The strategy variables $\theta_S \in [0,1]$ and $\theta_F \in [0,1]$ are at the center of this analysis because they capture the investment in collaboration of the state θ_S and the company θ_F. Both actors choose their strategy on a continuous spectrum between full collaboration ($\theta_S = 1$ and $\theta_F = 1$) or no collaboration at all ($\theta_S = 0$ and $\theta_F = 0$). High collaboration implies that both, the company and the state, prepare the legal, technical and procedural conditions of a confiscation and hence face lower cost. For $\theta_S\,\theta_F = 1$ (bilateral full collaboration) the transaction cost for an intervention are on a minimal (but nonnegative) level c_S for the state and c_F for the firm. However, with decreasing levels of collaboration, the transaction costs increase exponentially and would even become infinitively high if one partner preferred no collaboration at all ($T_{S,F} \to \infty$ for $\theta_S\ \theta_F = 0$). We assume a multiplicative effect of collaboration, since it is not possible to collaborate unilaterally. For both actors we assume a linear cost function for collaborative investment of the form θ_S, θ_F, $\kappa_{S,F}$ ($\kappa_{S,F} \geq 1$).The variable $\kappa_{S,F}$ denotes the transaction cost of collaboration, occurred by the state or the firm.

The loss-function of the state is given by (1):

$$L(x^N, x^C) = \varepsilon\,[\mu|D - x^N - x^C| + \bar{B}^C] + B^N, \quad x^N \geq 0, \quad x^C \geq 0 \tag{A.1}$$

The term $|D - x^N - x^C|$ captures the loss of the state due to a deficit of goods, which can be reduced either by the emergency stock x^N or by ad hoc confiscation x^C. The weighting parameter $\mu \geq 1$ takes into consideration that the losses, which result out of uncovered need in the population (deprivation) have a different unit than all other cost components, which are expressed in monetary units. By increasing μ, the state can give more weight to the distribution of goods compared to budget concerns; for $\mu \to \infty$ it gives absolute priority to people's needs and completely ignores budget restrictions. The terms $\bar{B}^C$ and B^N are budgets and hence monetary components of the loss function. The indices N and C again refer to "normal times" and "crisis", i.e. there is a budget B^N available in normal times and a budget for exceptional crisis situations $\bar{B}^C$. Whereas the former corresponds to the regular annual budget, which can be spent by the crisis management authorities the latter represents a highly up-scaled budget released by the government only in an emergency situation. Although $\bar{B}^C$ will certainly be a larger budget than $B^N(\bar{B}^C > B^N)$, the exact volume is unknown before the onset of a crisis, which is indicated by the expectation-bar. Before a crisis occurs, the state plans to spend the budgets as follows:

$$B^N = x^N p + \theta_S\,\kappa_S \tag{A.2}$$

$$\bar{B}^C = x^C q \, \frac{c_S}{\theta_S \, \theta_F} \tag{A.3}$$

The normal-times budget is spent for the procurement of emergency stock under regular (market) conditions and for investment in collaboration (budget equation (2)). The crisis-budget (budget equation (3)) has to cover the (expected) compensation payments for confiscated goods and the (expected) transaction cost for having emergency supply available. This way, the state's objective function represents a social cost function as outlined in Section A.4: the undersupply corresponds to the deprivation cost and the budgets reflect the financial constraints. If we solve both budget equations for the quantities of goods x^N and x^C and insert these quantities into (1) we get (4) as a modified version of the state's loss function, which now depends explicitly on the strategy variables θ_S and θ_F.

$$L(\theta_S,\, \theta_F) = \varepsilon\, [\mu\, |D - x^N(\theta_S) - x^C(\theta_S,\, \theta_F)| + \bar{B}^C] + B^N \tag{A.4}$$

The firm's profit function is given by (5):

$$\pi_F(\theta_S,\, \theta_F) = \pi + (p - c_F)\, x^N(\theta_S) - \kappa_F \theta_F + \varepsilon\, [q x^C(\theta_S,\, \theta_F) - \frac{c_F}{\theta_S\, \theta_F}] \tag{A.5}$$

The expression π represents the "profit in normal times" and the second term is the profit for the provision of resources for the state in normal times. The content of the square brackets $\varepsilon[\cdot]$ reflects the changes in profit due to confiscation and compensation in the case of a crisis. If there is no crisis (which is expected with a probability of $1 - \varepsilon$), these profit changes are zero. The cost term $\kappa_F\, \theta_F$ represents the effort in time and money for engaging in collaboration ("collaborative investment"). Note that these costs have to be incurred already in "normal times" and that the firm's collaboration cost just depends on its own effort θ_F whereas the cost reduction requires a joint collaborative effort $\theta_S\, \theta_F$.

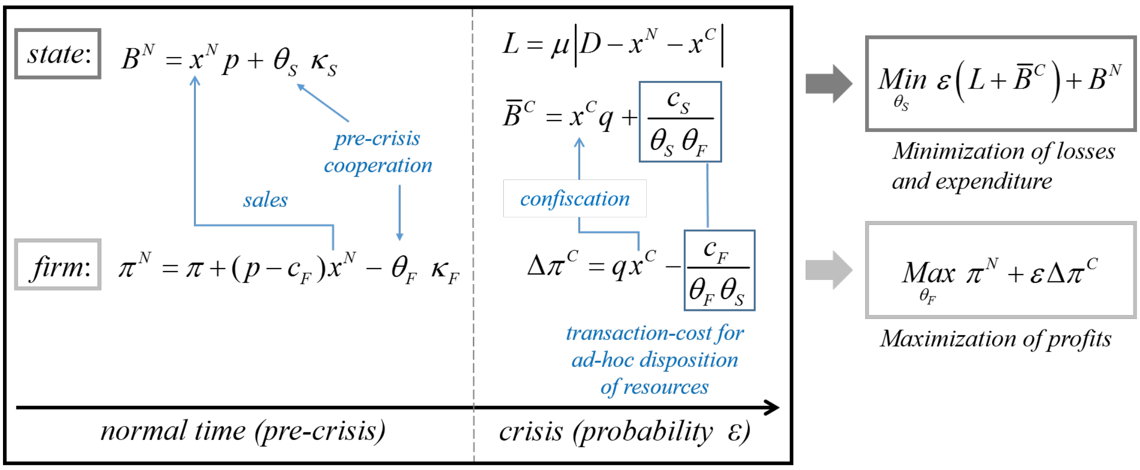

Figure A.4: Overview on model components.

Figure A.4 provides an overview of the model's components. The left column shows the payoff-components, which are relevant for the normal times conditions; these are the budget of the state – spent for the purchase of commodities and for cooperation expenditures - and the profit function of the firm. Both actors invest in cooperation in normal times as part of their contingency planning. The middle column represents the payoff-components of the state and the firm, which occur in a crisis. The provision of goods and resources is realized by confiscation. The transaction cost of this provision depends on the level of cooperation implemented prior to the crisis. The right column shows the optimization-problem of each actor.

A.5.1.2 Nash-equilibrium

In a Nash-equilibrium, both actors pick their optimal strategy given their co-player's strategy. Formally, the Nash-equilibrium is the intersection point of the best response profiles of both players. We get the best-response functions $BR_{S,F}$ by taking the first derivative of the objective functions with respect to the strategy variable of each player and considering the first-order condition (FOC) for a minimum (the state minimizes losses with respect to θ_S) or maximum (the firm maximizes profit with respect to θ_F). Expressions (6) and (7) give the best-response functions of the state and firm (the star indicates Nash-equilibrium-strategies):

$$\frac{\partial L}{\partial \theta_S} \stackrel{!}{=} 0 \Rightarrow \theta_S^* \left(\theta_F\right) = \sqrt{\frac{c_S\, p}{\kappa_S\, q\, \theta_F}} \qquad 0 \leq \theta_S^*, \theta_F \leq 1 \tag{A.6}$$

$$\frac{\partial \pi}{\partial \theta_F} \stackrel{!}{=} 0 \Rightarrow \theta_F^* \left(\theta_S\right) = \sqrt{\frac{\left(c_F + c_S\right) \varepsilon}{\kappa_F\, \theta_S}} \qquad 0 \leq \theta_F^*, \theta_S \leq 1 \tag{A.7}$$

The state has a higher incentive to increase θ_S if the transaction cost parameter c_S and the price for resources p increase. The first effect is due to the fact that collaboration reduces transaction cost and a larger p increases the cost of an emergency stock, which makes confiscation of items during a crisis more attractive. However, as collaboration reduces the transaction cost of confiscation, the state has an incentive to increase θ_S. Inversely, larger values of κ_S, q and θ_F reduce the incentive for collaboration. The effect of κ_S as the cost parameter of collaboration is straightforward. If the compensation cost q is high, the state is reluctant to rely upon confiscation and rather builds an emergency stock of resources for which collaboration is not necessary. Perhaps the most interesting effect refers to θ_F. There is a clearly negative effect of θ_F on θ_S^*: the larger the firm's contribution to collaboration, the larger the incentive for the state to *reduce* its collaborative effort. Hence, the collaborative investments of both actors are strategic substitutes. Roughly speaking, games in which the players' strategies are substitutes (as the opposite of complements) are called *submodular* games (Fudenberg and Tirole, 1991).

It is mainly this feature of the game that makes the NE-outcome inefficient.

Some effects of the model's parameters are similar for the optimal collaboration strategy of the firm. The firm increases collaboration if the transaction cost parameter c_F is high and if the collaboration cost parameter κ_F is low. Furthermore, the collaboration level of the company θ_F^* also acts as a substitute for the collaboration level of the state θ_S, i.e. the more (less) the state collaborates, the less (more) the company invests in collaboration.

However, three differences in the optimal strategies are striking: first, the firm's collaboration level is not only increasing in its own transaction cost parameter but also in the transaction cost parameter of the state c_S. Hence, the firm is partially internalizing the transaction cost of the state, which leads to a higher level of collaboration. The reason for this is that a high value of c_S increases the need for collaboration for the state but reduces the amount of resources x^C the state can acquire in times of a crisis. By increasing θ_F complementary to the increase of θ_S, the firm can keep the number of resources high and the state's frictions for use of these resources low.

Second, in contrast to (6) the influence of the transaction cost parameters are merely probabilistic, i.e. they only influence the optimal strategy of the company as an expected value. However, the disaster probability ε does not influence the state's collaboration level, because the entire first-order condition is multiplied with ε so that this parameter cancels out. Finally, while both resource prices (q and p) influence the optimal strategy of the state, they do not appear in the best-response function of the firm. This is because these parameters are linked to the state's collaboration level via the budgets whereas they are independent from the firm's collaboration level (collaboration reduces cost but does not alter prices).

Figure A.5 depicts the best-response functions of both actors. The chosen parameter-values are D=100, ε=10%, c_S=1, c_F=1, p=2, q=1, $\kappa_S = 10$, $\kappa_F = 10$. Both response functions have a negative slope and are convex which reflects the submodular property: The less (more) one actor contributes the (higher) lower the contribution of the other actor.

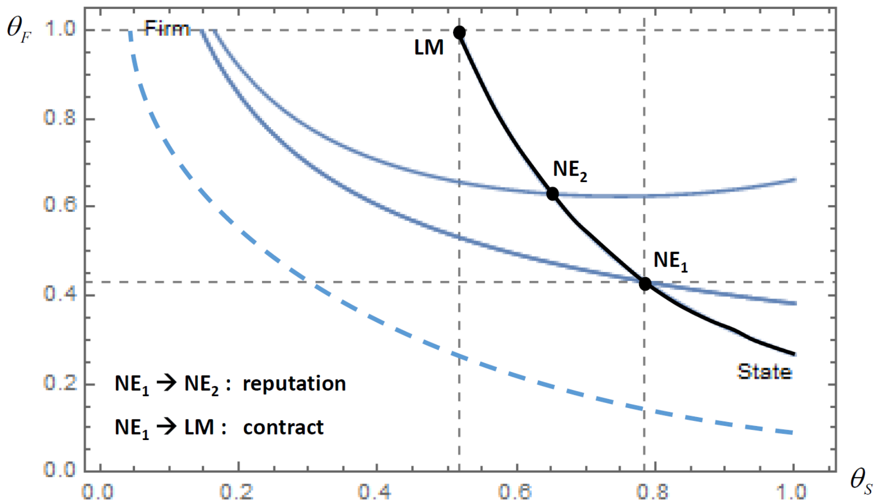

Figure A.5: Best-response functions.

The NE (NE_1) can be found at the intersection of both curves. For this example, the collaboration levels are $\theta_S^* = 0.79$ for the state and $\theta_F^* = 0.43$ for the firm, i.e. the state provides a larger contribution than the firm. Formally, we determine the optimal collaboration levels in equilibrium (8) and (9) by equating the best-response functions:

$$\theta_S^* = \sqrt[3]{\frac{(p^2\, c_S^2\, \kappa_F)}{(q^2\, \varepsilon(c_F + c_S)\kappa_S^2)}} \tag{A.8}$$

$$\theta_F^* = \sqrt[3]{\frac{(\varepsilon^2\, q\, (c_F + c_S)^2 \kappa_S)}{(p\, c_S\, \kappa_F^2)}} \tag{A.9}$$

Inserting the optimal levels for θ_S^* and θ_F^* into the loss function of the state and the profit function of the company gives the individually optimal outcomes in terms of loss L^* (θ_S^*, θ_F^*) and profit π^* (θ_S^* θ_F^*). However, there is still one important note at order. The derived solutions (8) and (9) characterize the equilibrium provided the existence of a NE. A NE for this game exists if (and only if) inequality (10) is fulfilled. If expression (10) is violated, there is no intersection of the best-response functions:

$$\theta_S \geq \sqrt{\frac{\kappa_F}{(\varepsilon(c_F + c_S))}\, \frac{c_S}{\kappa_S}} \tag{A.10}$$

This case is illustrated in Figure A.5 for the constellation where the best-response function of the firm corresponds to the dotted line. In this case, the company's curve is so low that it passes under the curve of the state. Such a failed-collaboration scenario is possible if, for example, the collaboration cost κ_F of the firm is very high (numerator of the right-hand side of (10) increases), the disaster probability ε is extremely low or the firm's frictions due to lack of collaboration (c_F) are not high enough (denominator of the right-hand side of (10) decreases). We can conclude that the first and most important obstacle for collaboration is a parameter and incentive constellation in which a company has no self-interest in a collaborative agreement at all.

A.5.1.3 Firm reputation

In this basic model, the firm has an incentive to invest into collaboration if pre-crisis collaboration with the civil protection authorities reduces the cost for an ad-hoc transfer of resources to the state in the moment of a crisis. In other words: If one is inevitably confronted with the crisis anyway, then it is better to approach the operations in an orderly and planned manner.

In addition to this motive, it is also possible that a company is willing to contribute due to a sense of responsibility or reputational concern. As explained in Section A.3.2, the latter is similar to the motivation of firms to establish a positive reputation for CSR. The firm can expect a positive percussion of its (publicly visible) activities if customers take note of the company's efforts and perceive these activities in a way which increases their loyalty towards the firm or their willingness to pay (Besiou and Van Wassenhove, 2015). This way, the firm's contribution to public crisis management can be regarded as an investment into higher future returns.

To illustrate this effect formally, we add the reputation-term $R = \delta\, \bar{r}\, \theta_S\, \theta_F$ to the profit function of the firm where $\bar{r}$ represents the expected return of reputation and $0 < \delta < 1$ is the discount factor. For $\bar{r} > 0$, an anticipated reputation has a positive effect on the company's willingness to collaborate. The second Nash equilibrium NE_2 in Figure A.5 illustrates this effect: The integration of the reputation term increases the reaction curve of the company and leads to higher collaboration rates of the firm. However, as collaboration rates are (imperfect) substitutes, the state will slightly reduce its level of collaboration and can use the saved resources to increase the emergency stock x^N.

Just as in the case of CSR, reputation does not automatically increase, but actions must be credible from the customer's point of view. Since reputation is a long-term mechanism, the company must be able to provide the externally visible resources and competence on a long-run basis. However, if customers have the impression that a company pretends to play a supportive role in humanitarian operations for tactical reasons only, this critical perception can backfire and seriously damage the firm's reputation (Stewart et al., 2009; Donia et al., 2017). In the area of crisis management, a particularly high level of sensitivity on the part of the public can be expected, as human lives are at stake here.

A.5.1.4 Loss minimal solution and mechanism design

We focus on mechanism design as a last example to illustrate how the state can lever the collaboration level in a PPEC. Mechanism design is a branch of game-theory and deals with the question on how the incentives of institutional rules influence the outcome of a group (e.g. welfare on a market or in society) and how these rules should be designed in order to improve these outcomes (Jackson, 2014; Maskin and Sjostrom, 2002; Myerson, 1989). Accordingly, the question is now, whether the individually optimal NE-outcome of the PPEC-game can be Pareto improved. In economic policy and welfare economics, an important reference solution is the so-called social-optimal outcome, which maximizes the players' joint utility (Green and Laffont, 1979; Sen, 1982).

However, the purpose of a PPEC is not to find a balanced improvement between firm and state but to minimize the undersupply, which is caused by the crisis. It is straightforward to realize that the loss-minimal outcome implies the maximal contribution level of the firm $\theta_F = 1$ (an increase of $\Delta\theta_F$ unambiguously lowers L because the cost of $\Delta\theta_F$ just affects the firm, not the state). Consequently, the loss-minimal solution θ_S^{LM},$\theta_F^{LM} = 1$ can be found at point LM in Figure 4. However, a higher level of collaboration reduces the firm's profit (otherwise a PPEC would also be feasible in absence of any additional incentive). To motivate the company to participate, the state has to guarantee an outcome equal to the individually optimal position $\pi^*\ (\theta_S^*, \theta_F^*)$ to the firm. To achieve this, the state must compensate the company in monetary terms, say by a monetary transfer t. One aspect that favors the use of mechanism design in the context of a PPEC is the fact that the party to be compensated (the company) is also primarily interested in monetary payments. In order to seek an agreement with the company that comes as close as possible to the preferred target level $\theta_F = 1$, the state solves the minimization problem (11):

$$\min_{\theta_S, \theta_F} L \quad s.t. \quad B^N = x^N p + \theta_S \kappa_S + t, \quad \pi(\theta_S, \theta_F) + t = \pi^*(\theta_S^*, \theta_F^*) \tag{A.11}$$

According to (11), the state looks for the optimal solution that minimizes the undersupply. The company must be compensated with the transfer t for its additional expenditures. The transfer must be chosen in such a way that the company receives at least the profit of the individually optimal solution π^* and that the state can finance this transfer from the regular (normal-times) budget B^N. If a solution exists, the state can offer the contract $\langle \theta_S, \theta_F, t \rangle$ to the company, which should have no reason to reject it.

Note that for the state to be able to finance the transfer t, it must either reduce the emergency stock x^N or its collaboration level θ_S. Both have problematic implications. The reduction of the emergency stock increases the dependence on the company and requires a high degree of confidence in the willingness of the company to actually implement the concluded contract in an emergency. Since this trust – as in any collaboration – only develops over a longer period of time, the readiness for such a measure will already require a certain depth and duration of the collaboration (Gintis, 2000; Hardin, 2002). In this case, the formal contract would be supplemented by a relational contract between the company and the state, which is primarily stabilized by the long-term nature of the collaborative relationship.

If, however, the state reduces its own collaboration level, this could be viewed with suspicion by the company. Discussions between the authors and company representatives (as part of the NOLAN project on public-private collaboration in Germany (IIP, 2019)) revealed that under certain conditions, companies are prepared to support the state in emergencies. Nevertheless, they also see the danger that the state could misuse such collaboration to delegate governmental tasks to the companies. These arguments show that the practical implementation of derived solutions requires an intense stakeholder dialogue.

The model and analyses provided in this last Section quantitatively validate public-private collaboration in emergency logistics, considering the parties' different objectives and incentives to engage in a PPEC.

A.6 Conclusion

Public-Private Emergency Collaborations provide tremendous opportunities for public and private actors in disaster relief. However, no study on logistical or game-theoretical models exist, which explicitly deals with this specific form of collaboration in disaster management. Therefore, we developed a logistical modeling framework that defines the context of logistical PPEC models.

In the framework, we discuss the different logistical characteristics of public and private actors in relief logistics, regarding their strategy and motivation, the way they interact with each other, and their capabilities and resources. By that, we provide a base for quantitatively modeling emergency logistics problems considering both public and private actors.

Moreover, we developed a basic game-theoretic PPEC model that gives more precise insights into the motivation and incentives of the partners. Inspired by game-theoretic accounts of conventional PPPs, this model sheds light on the partners' participation constraints (which define the scope of collaboration), the effects on the outcome if the partners' contributions are strategic substitutes, and on reputational effects. Finally, it was illustrated how a mechanism design approach can be used by the state to transform the firm's incentives into lower levels of undersupply or deprivation.

With the present paper, we are able to define a variety of opportunities for future research. However, the developed framework and model could work as an orientation for upcoming research. Especially with the help of real world data and case studies, the modeling framework can be further tested, extended, adapted, and optimized.

In a nutshell, it can be concluded that, with the help of well defined PPEC-concepts, processes in relief logistics can be understood better, supply chains can become more resilient, and public actors can ensure that the population is supplied as good as possible. Therefore, research on PPECs promotes the shift from fighting the symptoms of the population's undersupply during crises towards fighting the course of the problem, leading to an increase in resilience of public and private actors.

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B How to enhance company engagement in public-private emergency collaborations in the supply of essential goods

Abstract

Natural disasters and crises like the COVID-19 pandemic, climate change, and the war in Ukraine can significantly disrupt supply chains. In extreme cases, public actors might have to take over responsibility for the population's supply of essential goods as the market can fail to meet demand. Naturally, from the centralized view of public actors, companies in supply chains can be valuable collaboration partners when addressing crisis management challenges. However, conditions and prerequisites under which companies are willing and able to support public crisis management are poorly understood. To better understand the motives which lead companies to participate in public-private emergency collaborations, we empirically investigate expectations and motivation. We analyze the replies of 398 German companies from food, healthcare, and logistics sectors to a questionnaire of 25 closed questions and find that most companies have already been active in crisis management and are willing to engage collaboratively. While their preferred contribution to collaborative crisis management is providing resources (e.g., goods or equipment) instead of coordination tasks, they also want to ensure that their business processes are sustained. Among the most promising incentives to increase company engagement are monetary compensation for provided resources and an improved communication policy. Logistics companies are motivated more by relaxing regulations, while healthcare companies prefer reputation measures. Our insights provide the basis for fostering further public-private collaborations and raising awareness of their potential during crises. Moreover, the study promotes the systematic implementation of public-private emergency collaborations instead of short-term, spontaneous forms of support.

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B.1 Introduction

B.1.1 Motivation

Sudden-onset disasters like floods or hurricanes, or long-term, ongoing events such as climate change or the COVID-19 pandemic confront supply chains with serious challenges. They can disrupt demand or supply in abrupt and persistent ways and go far beyond what companies are typically prepared for (Sodhi and Tang, 2021; Ye et al., 2020; Hecht et al., 2019; Chopra et al., 2021). When disruptions within different supply chains threaten to endanger the supply of essential goods, like food or pharmaceuticals, to the population, it is the responsibility of the government and related public actors on a state or regional level to step in and manage the crisis.

However, at the same time, these public actors do not and can not have knowledge of how complex supply chains operate and the challenges they face. This outlines the strong need for collaboration between public actors and companies to address the challenges of crises affecting supply chains of essential goods. Companies in supply chains of essential goods can take on a unique role in public crisis management (Sodhi and Tang, 2021). They control large amounts of products needed for basic supply and operate in established communication structures. This makes them valuable partners for collaborative crisis management.

B.1.2 Lessons from the field

In an ideal world, one would expect collaborations between public actors and companies to be the standard operating procedure in (public) crisis management, or at least very common. Examples of voluntary engagement in relief operations prove companies' fundamental willingness to support and collaborate (Johnson et al., 2011; Fontainha et al., 2016; Binder and Witte, 2007). Corporate help is tracked by the U.S. Chamber of Commerce Foundation (2021), which established the Disaster Corporate Aid Tracker and aimed to track business-related assistance within relief and recovery efforts. Some companies prefer to act and react to crises on their own. As an example, Walmart successfully supplied the population with essential goods on its own during hurricane Katrina. Although the company highlighted the need for stronger relationships with public actors and did emergency training with them, it rejected contract offers to become public actors' emergency merchandise supplier. Maintaining large stocks that are possibly unnecessary would not fit Walmart's business model (Horwitz, 2009; Rosegrant and Leonard, 2007). According to Horwitz (2009); Rosegrant and Leonard (2007), it can be suggested that Walmart's faster lower-level and local decision-making, together with the demand for stronger public support in crisis preparedness, were further reasons not to formalize collaboration with public actors.

Generally speaking, few collaborations between public actors and companies in crisis management exist in reality, especially in the long term (Diehlmann et al., 2021). An explanation could be that participation in public actors' crisis management is typically not within the scope of a company's duty or business model, as it was the case for Walmart. Furthermore, there can be perceived differences in power when collaborating with public actors, as they have the authority to make legislative decisions that impact the company's operations (Diehlmann et al., 2021; Fontainha et al., 2016).

Throughout this paper, we will use the concept of public-private emergency collaboration (PPEC), which was proposed by Wiens et al. (2018); Diehlmann et al. (2021) and is defined as coordinated public and private crisis management. It combines the goals of managing resources like finished goods or trucks, sharing information and competencies like production and transportation planning and designing legislation for more effective and efficient supply of essential goods. This type of collaboration needs to be executed on a planned-committal long-term basis, so that public actors can reliably include company contributions in their crisis management plans (Wiens et al., 2018).

B.1.3 Interaction with the practice motivating our study

What initially motivated us to research incentives and barriers of collaboration between private and public actors are first-hand experiences gathered throughout previous years. We had the opportunity of being involved in several national research projects that touched upon crisis management of supply chains. In this context, the collaboration of public actors and companies during crises had always been a concept that seemed logical and almost self-enforcing from the outside. However, workshops and interviews conducted over the years have gained us insights from different perspectives into why that is not (yet) the case in practice. We consulted a large food producer, a logistics service provider, a food retailer and German public actors responsible for emergency food supply and transportation infrastructure, namely *Baden-Württemberg Ministry of Rural Areas and Consumer Protection*, *Baden-Württemberg Ministry of Transport*, *German Federal Agency of Civil Protection and Disaster Assistance* and *German Federal Office for Agriculture and Food.*

Most recently, exchanges with experts and practitioners who were at the same time associated partners of a research project on PPEC took place. Expert workshops and individual interviews were both conducted regularly, with additional spontaneous, bilateral communication occurring as well. The bilateral exchanges were often initiated by public actor representatives, who were interested in a close exchange of data (e.g. on available resources), and company representatives, who were keen on information (e.g. on regulation) and contacts (single point of contact) during particularly difficult phases of the COVID-19 pandemic.

During the projects that took place several years before the pandemic, the perceived general interest in collaboration from both sides had, naturally, not been as high, but the sentiments collected in workshops and interviews had been about the same. The public actors would welcome any input and especially data from companies, but were unsure how to stimulate a collaboration that reached further than providing simple statistics on an annual basis. In other cases, they just outright expected companies to make the first step. The companies on the other hand often noted they were of course willing to provide spontaneous help on a short-term basis during crises, but were hesitant towards long-term collaborations. They saw the responsibility for coordinating actions during crises with the public actors (rightly so), as well as the initiative for designing and setting up long-term collaboration efforts. They further implied that collaborations like these would need rule-sets, compensations and oversight.

From theory, we know that the voluntary involvement of companies in long-term collaborations can be supported by identifying the required conditions and the right incentives (Tomasini and van Wassenhove, 2009). A specific example for an incentive to collaborate mentioned by representatives during a workshop was clarification regarding the affiliation of critical infrastructure during the COVID-19 pandemic. It seems that companies saw collaboration with public actors as a way of accessing crucial information more quickly than otherwise. This could lead to better (informed) planning, as being part of the critical infrastructure entails several potential advantages such as exception from certain regulations. This was directly verified by participants from practice in another workshop that was held during the pandemic: A logistics service provider and a producer of beverages both stated that they would expect to benefit from establishing communication structures with public actors. They referred explicitly to gaining better transparency of public crisis measures and legal restrictions, to be able to implement them more efficiently.

Data privacy concerns are an example of a possible barrier keeping companies from engaging in collaborations, which were mentioned multiple times during different interactions with practitioners. On the one hand, the companies saw the risk of increased direct costs due to additional tasks, surrender of resources, and increased planning effort due to a collaborative contribution. On the other hand, it became clear that they would be willing to collaborate under certain conditions, e.g., if they were compensated for their efforts and if their internal processes were considered.

Our discussions with public actors' representatives revealed some general skepticism about the reliability of company contributions. However, they admitted a lack of profound knowledge on how to reliably incentivize and engage companies. Furthermore, they expressed their interest in gaining general insights into what might motivate companies to collaborate with them.

Based on first-hand exchanges and experiences like these, we conjecture that the lack of (long-term) collaborations between public actors and companies in crisis management at least partly results from a gap in the understanding of what could motivate companies to take part in such a collaboration and further, what actively keeps them from doing so.

B.1.4 Outline of the study and findings

A collaboration such as a PPEC touches on two usually mutually exclusive areas of responsibility. With its primary focus on civil protection, the crisis context makes public-private collaboration a sensitive and ethically challenging issue. This may be one reason why research on durable and established collaboration between public actors and companies regarding crisis management is scarce, as of yet. As mentioned before, such forms of collaboration are also still relatively rare, if not even non-existent, in practice. To leverage the potential for PPECs, requirements for successful collaboration like motivation, opportunities, and limitations need to be further investigated. In particular, existing research lacks a systematic empirical study that identifies drivers for companies to engage in a PPEC.

With this research, we want to address the following research questions: (1) What are incentives and barriers to collaboration from a company's perspective? (2) What can be done to enable and promote more PPECs? (3) Which are efficient contributions of companies in PPECs?

We investigate these questions using a survey that yielded 398 responses from German producers, logistics service providers, and retailers from supply chains of essential goods.

The design of our survey is based on qualitative interviews and workshops with representatives of both public actors and companies from essential good supply chains. Topics discussed with the practitioners in the survey included for example possible areas of company involvement, areas in which companies are able to support and the areas which companies expect public actors to need support. The survey was pre-tested with 20 supply chain professionals from different industries and revised based on their feedback.

Overall, this study contributes to the existing literature and crisis management in three ways: First, it empirically carves out requirements as well as favorable and unfavorable conditions for companies to participate in a long-term collaboration with public actors. While we find that the willingness to participate in collaborations is generally high among companies, they also assign a high priority to maintaining their business processes. Additionally, further clarification and commitment from public actors is needed to pave the way for more collaborative crisis management. We show that providing resources, physical or informational, is the preferred way of companies to collaborate. However, the results also indicate that companies wish to receive monetary compensation for supplied resources. Moreover, an improved communication policy of public actors is perceived as important. Second, these insights can be used to design and operationalize PPECs in an optimal way with respect to the companies' incentives. Third, our study raises awareness for the potential of public-private collaborations during crises and promotes the systematic implementation of PPECs in contrast to rather spontaneous forms of public-private interworking.

The remainder of this paper is organized as follows. The next section provides the theoretical background on public-private collaborations in crisis management from a company perspective. From that, we derive research questions and underlying hypotheses for our survey. This is followed by the presentation of the study design. The section after that presents our results. Next, we discuss the results and derive theoretical and managerial implications for the implementation of PPECs. Finally, we look into limitations of our study, suggest further research directions in this area and conclude with the main findings.

B.2 Theoretical background

B.2.1 Crisis management

B.2.1.1 Public crisis management

In crises, public actors' primary objective is to avoid or reduce negative effects on the population. Especially in unexpected large crises, proactive preparations for different crises become more important. For example, public actors can set up communication structures, share crisis information and physical resources like stocks of goods or transport equipment to ensure the population's supply with essential goods or apply legal resources to adapt laws when necessary (Moline et al., 2019; Kovács and Spens, 2007; Diehlmann et al., 2021).

An additional direct approach of public intervention in existing commercial supply chains can occur through financial support (Hofmann et al., 2023), formulation of sector-wide regulations or policies (Sodhi and Tang, 2021; Quarshie and Leuschner, 2020) and political initiatives (Chopra et al., 2021). These interventions can happen both in anticipation of or during an event. If the legal situation allows, even confiscation of critical private resources can become possible (Wendelbo et al., 2016).

However, in contrast to companies, public actors hardly possess sufficient production and logistics capacities as well as the technological know-how to supply the population with essential goods (Diehlmann et al., 2021). Therefore, they rely on companies and would thus primarily coordinate and support them to maintain commercial supply chains. Such support can happen, for example, on an economy-wide level or, more specifically, on a company level. For more specific support, public actors require more detailed insights into complex and dynamic commercial supply chains, which they would often lack.

B.2.1.2 Company crisis management

During a crisis, a company's first motivation is to protect, maintain or recover business processes (Palin, 2017; D. Elliott et al., 2010). The goal of keeping the business running is at the center of business continuity management (BCM) (Craighead et al., 2007). However, protecting staff and customers also arises from corporate social responsibility (CSR).

Due to this study's focus on supplying essential goods to the population, we focus on supply chain risk management and BCM (Kumar and Park, 2019). Supply chain risk management (SCRM) is defined by Tang (2006) as 'the management of supply chain risks through coordination or collaboration among the supply chain partners to ensure profitability and continuity'. We use the term company crisis management covering supply chain-related BCM and CSR in the following.

In response to more and more large-scale crises recently, Sodhi and Tang (2021) introduced the term *extreme supply chain management* (ESCM) for supply chain management for severe crises, which goes beyond supply chain risk management. It is applied in severe demand or supply increases or drops.

In non-crisis and crisis times, companies in commercial supply chains can produce the necessary physical resources to produce and distribute essential goods (e.g., raw material, production sites, trucks, warehouses), and rely on established communication structures with other supply chain members. Companies use advanced technologies to monitor demand and use track-and-trace systems and industry standards for information flow (Bealt et al., 2016).

However, the companies' scope of action in a crisis outside established supply chains is limited compared to public actors. Setting up new business processes takes time, and collaboration with competitors may be forbidden by competition law. Despite concepts of SCRM and ESCM being known, companies typically lack preparedness for disruptions or events of high impact and low probability (Izumi and Shaw, 2015a; Scala and Lindsay, 2021). Recent crises have led to a stronger focus on SCRM among companies though (R. Elliott et al., 2021). There is however evidence that larger companies are better prepared than smaller ones, which can lack formal emergency plans due to lack of time or expertise (Hecht et al., 2019).

We conclude that the roles and strengths of public and private actors complement each other in terms of resources, coordination opportunities, and preparedness.

B.2.2 Company collaboration in crisis management and the concept of PPECs

Companies can increase their resilience through collaboration with other companies, including their competitors (Scholten and Schilder, 2015). Collaboration in general and information-sharing in particular can lead to greater visibility and flexibility and thereby improve resilience along the whole supply chain (Sodhi and Tang, 2019; Scholten and Schilder, 2015; Kleindorfer and Saad, 2005). Many possible collaboration measures are known, such as resource-sharing, collaborative communication, goal congruence, decision synchronization, incentive alignment, and joint knowledge creation (Scholten and Schilder, 2015).

Collaborative relationships in crisis management are increasingly encountered between companies and non-governmental organizations (NGOs) (Bealt et al., 2016). Madsen and Rodgers (2015) found that companies collaborating with an NGO in their crisis-related CSR activities would receive more stakeholder attention than companies not collaborating with an NGO. However, in the case of logistics service providers, CSR activities like donations of free capacity or employee volunteering are only one way to engage.

Formal collaborative relationships between companies and the public sector are, however, rarely observed (Diehlmann et al., 2021). Such a relationship is defined by Wiens et al. (2018) as a PPEC. It combines commercial supply chains for essential goods with public relief supply chain management and includes joint supply chain planning, knowledge management, and the use of resources. Moreover, it is 'designed for improved crisis management by joint coordination and collaboration between private and public representatives. A PPEC additionally requires thorough and joint preparation of both parties' (Diehlmann et al., 2021), which distinguishes it from spontaneous collaboration.

Some research exists about collaboration between public and private actors supporting the current relevance of PPECs. For example, Sodhi and Tang (2021) suggest several similar research streams with public actor involvement in commercial supply chains in the context of crisis management: public actor subsidy and support schemes, joint coordination of an exit from a lockdown, and programs about re-shoring production of essential goods. Based on public-private collaboration observed during the COVID-19 pandemic, Scala and Lindsay (2021) argue that supply chains should be seen as critical infrastructure and be managed collaboratively by government and companies. de Moura et al. (2020) propose further research on public-private collaboration and the type of resources shared as well as how much know-how from both parties could be used to improve response to emergencies.

Furthermore, little is known from practice about companies' motivation to engage in these collaborations nor the collaborations' success and potential benefits from a company perspective.

Existing research provides some suggestions for designing PPECs and some assumptions about companies' motivation. Stewart et al. (2009) suggest that companies become involved in a public-private collaboration for disaster response mainly for two reasons: The first reason is to fulfill a public actor contract and the second reason is to protect their assets, customers, suppliers, or other interests in the disaster area. Breitbarth et al. (2021) propose a PPEC for coordination of vehicles across logistics service providers for last-mile delivery during pandemics. The authors name intrinsic motivation and compensation of additional expenses as incentives for companies to collaborate with public actors. Further, companies could, next to financial compensation for their services, benefit from improving resilience by getting up-to-date crisis information about demand or supply through established communication channels (Wiens et al., 2018; Mehrotra and Schmidt, 2021).

However, barriers for companies to join a PPEC might be similar to those to collaborating with humanitarian organizations. Often public actors are skeptical of companies and their willingness to provide help (van Wassenhove, 2006). Steyer and Gilbert (2013) claim that companies would rarely take over the responsibility to prevent society's risks. Large companies would be more proactive, but on the other hand, large multinationals would be 'insensitive to local concerns' and often lack legitimacy (Steyer and Gilbert, 2013).

There is no comprehensive empirical research about the benefits and risks that companies see in engaging in a PPEC as well as the incentives required to make a PPEC attractive to companies to the best of our knowledge. Since the issue has been recently raised more and more in literature, a deeper understanding of the companies' perspective, in particular also classified into individual industries and company sizes, is needed.

B.3 Research questions and hypotheses

B.3.1 Research questions

Research and practice need to understand better why and under which conditions companies would want to collaborate with government agencies to support crisis management. Information about the companies' incentives enables both parties to establish a realistic and thus stable collaborative relationship.

Furthermore, with improved knowledge, public actors can better motivate companies to join a PPEC and design PPECs, in which companies find incentives to act as reliable partners.

To this end, we set up three main research questions (RQ) (see Figure B.1) which focus on various aspects of a PPEC that both public actors and companies need to understand in order to make such collaboration stable and reliable.

The first research question is derived from the identified research gap as detailed in Section *Theoretical Background* and was raised by public actors in workshops on several occasions.

RQ 1: *What are incentives and barriers for companies to collaborate with public actors?*

Within this research question, we will first examine a record of incentives and barriers for companies to participate in a PPEC. RQ 1 refers to a company's whole business model. Hence, we look at all relevant areas in which companies can assist in the emergency context (provision of goods, logistics services, storage capacities, personnel, coordination, and information exchange). For example, a potential barrier to a company's willingness to support in a crisis is that companies' business models need to be protected or stabilized. This was well illustrated during the COVID-19 pandemic, where an extreme demand and supply volatility overwhelmed most preemptive measures enacted by companies to mitigate disruptions in their supply chains (Dohmen et al., 2022). In such a situation, setting up a spontaneous collaboration is more time-intensive and less effective than using an existing collaboration framework where players know their roles and aligned emergency strategies may be rolled out immediately.

We ask the companies questions around the importance of different business-related actions, relationship-management, profit and reputation considerations as measures and motivators for a particular crisis reaction.

RQ 2: *What can be done to enable and promote more PPECs?*

In RQ 2, we focus on measures of public actors as options to make a PPEC more attractive to companies. In particular, public actors have a number of measures at their disposal to facilitate companies' participation in a PPEC. These measures comprise e.g. regulatory relief, financial compensation or an official testimony of a company's engagement. How should public actors deploy their bundle of measures and thus design attractive and acceptable framework conditions for companies?

We asked questions concerning the type of emergency help, the financial conditions, and the time frame for the intended help. In particular, we want to find out how companies weigh financial reimbursements and positive public recognition and, if at all, in which phase of a crisis they would prefer to collaborate.

RQ 3: *Which are efficient contributions of companies in PPECs?*

The third RQ deals with companies' contributions to PPECs. Assuming that companies are willing to participate in a PPEC: In what role and function do they believe they can make the most meaningful contribution? We differentiate three ways companies could contribute during a crisis: by providing goods, transportation resources, or participating in emergency planning (e.g., co-development of operational plans with public actors).

We ask questions on these three types of emergency measures regarding willingness to provide them and under which financial conditions. Moreover, we investigate the companies' perception of how the private sector can best complement public crisis management and the other way around: What do companies believe public actors need most within the categories presented? From the company's point of view, it is essential to know how a PPEC is designed and which tasks and responsibilities need to be fulfilled.

Within RQ 3, we also want to identify the strengths of different companies: Which type of company (e.g., concerning a specific sector) sees itself as particularly well suited for participation in a PPEC? This knowledge helps public actors to identify more specific fields of collaboration and better understand companies' perceptions of their contribution.

B.3.2 Hypotheses

To answer the research questions above, we developed six hypotheses (see Figure B.1). Clues and prior knowledge that led to these hypotheses were derived from literature and expert workshops with practitioners from the public and commercial fields. For example, regarding the COVID-19 pandemic, practitioners from companies struggled with the unavailability of business critical information and point of contacts with the public actors. Furthermore, it was added that assistance offered in the past could not be provided most efficiently due to legal requirements or excessive bureaucracy. Public actors also missed the lack of linkage with logistics companies.

The first hypothesis refers to a fundamental motivational tension, which companies have to face when they are confronted with a supply crisis. On the one hand, companies need to run profitably in the long run to withstand competition. On the other hand, it is harder to balance different priorities in times of high uncertainty in their supply chains (Wu and Pagell, 2011). Given that managers show some genuine concern about the distressed population and consider providing assistance: Are they willing to sacrifice daily business obligations for it? Even though it is clear that a company can never sustain such prioritization of postponing daily business in the long term, the short-term willingness to do so is an essential prerequisite for voluntary contributions to crisis management.

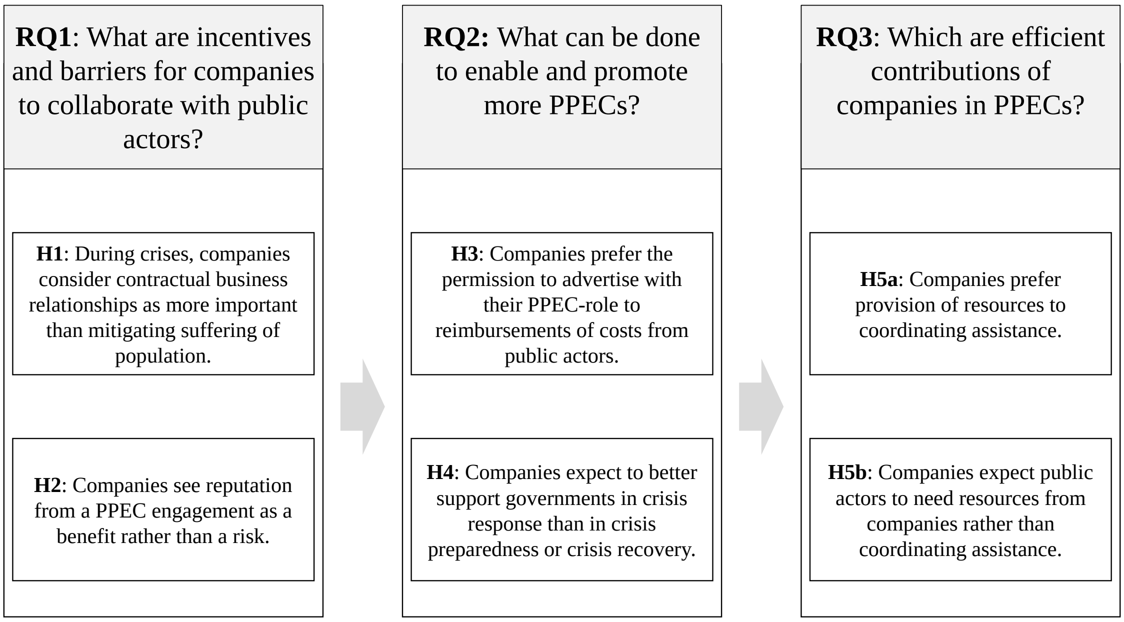

Figure B.1: Research questions and corresponding hypotheses

According to Porter and Kramer (2011), corporate rewards for private sector involvement in PPPs go beyond tax savings and immediate profit and that CSR should be considered an important motivational factor for a sustainable value chain. It increasingly is an integral part of companies' objectives (Madsen and Rodgers, 2015; Dahlsrud, 2008). Therefore, it can be assumed that such companies, for which CSR goals are critical, also show a higher motivation for private sector involvement in crisis management. von Behr et al. (2022) found indicators for altruistic behavior during the COVID-19 pandemic in companies, contradicting - or at least complementing - the standard paradigm of pure profit orientation.

For our first hypothesis, H1, we expect that companies follow their business priorities even in a crisis and that they put social concerns aside.

H1: *During crises, companies consider contractual business relationships as more important than mitigating suffering of population.*

A company's reputation is a precious asset. A positive reputation is reflected in a premium on the valuation of the company (Arora et al., 2020; Donia et al., 2017). It is a decisive factor for young talents to join a company (Donia et al., 2017), which is among the most important factors for running a successful business model in the long-run.

Social and humanitarian engagement are essential components of CSR activities for an increasingly large number of companies (Dahlsrud, 2008; Johnson et al., 2011). Bealt et al. (2016) identified three key drivers of corporate engagement in disaster relief operations: internal ethical drivers, external stakeholder drivers, and internal corporate drivers. By providing aid to society in times of a crisis, a company protects its staff and customers or can create new business opportunities (Izumi and Shaw, 2015b). Hence, by investing in societal resilience, companies can improve their corporate reputation, which could pay off in the long term. In contrast, humanitarian activities are not always easy to assess in public perception. They can be risky for a company for at least two reasons: First, promoting corporate involvement can appear incredible from the public's point of view creating suspicion that the company in question is seeking to make a profit at the expense of those affected (crisis capitalism). Interestingly, this opportunity of "crises gains" has vehemently denied being in consideration of any emergency engagement by some of the practitioners we talked to. Second, uncoordinated crisis involvement without experience can also be risky for companies in that mistakes (e.g. distributing goods to the wrong recipient group) can happen easily, which in turn damage their reputation.

As the evidence hints at a preponderance of potential reputation benefits we assume that companies expect positive net reputation effects (H2):

H2: *Companies see reputation from a PPEC engagement as a benefit rather than a risk.*

Contributing resources during a crisis comes at potentially high cost, comprising delivery of goods, staff involvement, and equipment usage. These cannot be used for ongoing business activities at the same time. However, the proper promotion and the role of a company in the eyes of (possible) customers is of high importance to the financial performance of the company as well (Green and Peloza, 2015). If the expected positive reputation effects of H2 are confirmed, then the question arises for public actors whether they should also explicitly allow companies to promote with a PPEC participation towards their stakeholders (involving potential employees, members of their own SC, and customers). Possibly, this option could already be incentive enough for some companies to participate in a PPEC. In H3, we have explicitly formulated this conjecture:

H3: *Companies prefer the permission to promote with their PPEC-role to reimbursements of costs from public actors.*

According to the United Nations Disaster Cycle, disaster management has four phases - mitigation, preparedness, response, and recovery (Seaberg et al., 2017; van Wassenhove, 2006). Since each of these phases requires different tasks and resources, it is important for civil protection agencies to know which phase companies can best be deployed in and, more importantly, at what stage they are most likely to engage in a PPEC?

According to Swanson and Smith (2013), in the past, the private sector has responded to disasters more efficiently and effectively than government agencies. Based on these findings from the literature, we see three reasons why the response phase should be the phase that companies would most prefer for a PPEC contribution:

(I) Preparedness measures require lengthy ex-ante coordination and involve high uncertainty about the actual need. However, in immediate crisis response, companies can quickly adapt to the need that becomes apparent relatively soon during an acute crisis. (II) As they have to be raised on a continuous level before a potential crisis, preparedness measures imply a durable cost factor. Hence, these measures will most probably be too expensive and more difficult to justify internally from a company's point of view. (III) Focusing on the response phase is the more effective way to gain attention for the engagement because it is visible and in urgent need (promoting effect). For example, Madsen and Rodgers (2015) argues that disaster relief activities that promptly address disaster-created needs receive more stakeholder attention. Based on these considerations, we formulate our fourth hypothesis:

H4: *Companies expect to better support governments in crisis response than in crisis preparedness or crisis recovery.*

The basic idea behind a PPEC, as outlined in Diehlmann et al. (2021); Sodhi and Tang (2021); Wiens et al. (2018) is that companies are specialists in their respective fields of work and have the appropriate resources and know-how. As discussed above, companies can in principle contribute to a PPEC in a number of ways, but some of these options will be more attractive to them than others. On the other hand, in a crisis, governmental actors have to coordinate numerous companies and establish a suitable distribution of tasks in a PPEC. These crisis-related coordination efforts are time-consuming. Company participants at the workshop feared that a PPEC could be characterized by too much bureaucracy and too little flexibility. In contrast, providing resources (e.g., delivery of goods) should be a comparatively easy way to contribute, making companies more independent.

We argue that it is easier for a company to divert resources (companies can decide on their own about resources which are under their control) than to coordinate prioritization, information exchange, and action planning with public actors. Concerning companies' role in humanitarian operations, Diehlmann et al. (2021) identify ownership of physical resources and their control as a key factor in crisis management. Given these considerations, it is reasonable to conclude that companies see their role in a PPEC as a resource provider rather than a coordinator of relief efforts. In general, making monetary or product donations is common for companies themselves or in collaboration with NGOs (Bealt et al., 2016).

Hence, we propose our fifth hypothesis regarding two different perspectives on the nature of willingness to help:

H5a: *Companies prefer provision of resources to coordinating assistance.*

Furthermore, in a change of perspective in H5b, we want to find out whether companies also *believe* that they are *expected* to contribute resources or whether the state requires them to provide coordinating planning support. Therefore, hypothesis H5b takes this second perspective on the nature of willingness to help:

H5b: *Companies expect public actors to need resources from companies rather than coordinating assistance.*

B.4 Survey design and data collection

The survey contains 13 questions that are based on the hypotheses. Additionally, 12 characteristics of the respondents and their company, such as revenue, industry, and the number of employees, were surveyed. The survey's target were companies from the following industries: food retail (including wholesale), food production, healthcare retail (including wholesale), healthcare production, and logistics.

The survey was developed with the research institute Allensbach (IfD Allensbach). The institute took over the final implementation, and data collection was carried out in July and August 2021.

From a sample which is representative for German companies from the targeted industries, about 9,000 companies were randomly selected and contacted online. This yielded 398 valid replies, which corresponds to a low response rate of 4.5%. However, a low response rate is common for large-scale surveys solicited from CEOs and top managers, in particular for small companies and in the sectors of logistics, food and retail (Dora et al., 2014; Ellis et al., 2010). In general, company response rates lie frequently between 5-10% (Sroufe, 2003; Alreck and Settle, 1995), e.g. 6% in the study of Testa et al. (2018) or 7% in the survey of Choon Tan and Wisner (2003). However, the response rate can also be very low, like 1.7% (Porteous et al., 2015) or 2.6% (Li et al., 2010). Therefore, we see this issue as tolerable, in particular because the population consisted of the entire company database and not a random sample. Nevertheless, we are aware of the implications (especially the higher risk of a non-response bias). The survey was conducted in German and translated into English for publication.

We used closed questions with predefined possible answers and assumed the answers to be metric data (de Campos et al., 2020). A Likert scale with the number of options dependent on the content of the possible answers was used. The development of variables and items was partially self-constructed. We validated the relevant topics and related questions in several workshops with experts. Among other things, we defined the various categories of business support options, such as support with warehousing, goods, or personnel. Other variables were set up based on literature, such as the question on the different phases of helpfulness, which are based on the four phases classified within the *the disaster management cycle* (Coppola, 2011). Additionally, participants were asked to select options from a given list.

We asked questions within the areas of: (1) behavior in the event of a crisis, (2) lessons learned from the COVID-19 pandemic, (3) willingness and ability to provide assistance in a PPEC, (4) requirements to engage in a PPEC, (5) communication with public actors in the event of a crisis.

The characteristics of the sampled companies are shown in Table B.1.

B.5 Results

We evaluated our main research questions using a confidence interval of $\alpha = 95\%$ for directly testable hypotheses, if not stated otherwise. To increase readability, we shortened most of the items within the text passages.

We also conducted correlation analysis concerning SC stage (retail or production companies), different industries (food, healthcare, and logistics), and the company revenue for each hypothesis. Based on Moore et al. (2013), we interpret a correlation of two variables up to $|0.3|$ as low, between $|0.3|$ and $|0.5|$ as medium, and $| > 0.5|$ as strong, and correlations as statistically significant with ρ-values < 0.05.

Variable	Sample companies	
	Number	Percentage (%)
Industry		
Grocery	146	36,7
thereof: Production	*91*	*22,9*
thereof: Retail	*55*	*13,8*
Healthcare	125	31,4
thereof: Production	*46*	*11,6*
thereof: Retail	*79*	*19,8*
Logistics	97	24,4
thereof: Grocery	*9*	*2,3*
thereof: Healthcare	*7*	*1,8*
thereof: Others	*80*	*20,1*
No answer	30	7,5
Employees		
$1-10$	41	10,3
$11-20$	183	46,0
$21-100$	136	34,2
> 100	37	9,4
No answer	1	0,3
Annual revenue		
$<$10 Mio €	256	64,3
10Mio - 50 Mio €	90	22,7
$>$50 Mio €	36	9,0
No answer	16	4,0
Family business		
Yes	334	83,9
No	55	13,8
No answer	9	2,3
Area of responsibility of respondent (multiple answers possible)		
(Top-)Management	301	75,6
Business Continuity Management	140	35,4
Logistics or SCM	131	32,9
Corporate Social Responsibility	94	23,6
Other	34	8,5
No answer	16	4,0

$n = 398$

Table B.1: Companies' characteristics

B.5.1 Incentives & barriers

H1: *During crises, contractual business relationships are considered more important than mitigating suffering of population.*

We asked the respondents to rate the importance of several requirements in case of a crisis on a likert scale from one (*very important*) to five (*not important*). The sequence of the items corresponds to the sequence in the questionnaire.

Contrary to our expectation, the respondents rated *reducing suffering of the population* ($Mean = 1.43$ and $SD = 0.68$) higher in importance than *not endangering contractual business relationships* ($Mean = 1.73$ and $SD = 0.85$) (see Table B.2). A one-sided t-test for the opposite direction even revealed a highly significant difference with a p-value of 0.000.

If you needed to react to a crisis, how important would the following aspects be for your company?	Mean	SD
Maintaining operational business processes	1.28	0.62
Not endangering short-term profit	2.96	1.05
Not endangering long-term profit	1.79	0.8
Not endangering contractual business relationships	1.73	0.85
Avoiding disadvantages for customers	1.63	0.78
Avoiding loss of reputation	1.97	0.96
Improving reputation compared to competitors	2.87	0.97
Reducing suffering of the population	1.43	0.68

$n = 372$, $1 =$*very important*, $5 =$*not important*

Table B.2: Priorities in company crisis management

Hence, we reject H1, which points to companies having an altruistic motivation in crisis management, or at least, to have a coherent and credible CSR strategy. Nevertheless, at least part of this motivation can be profit-oriented, too, as healthy customers and employees are an important requirement for companies to perform business.

Looking at all items of Table B.2, it can be concluded that in a crisis, to protect processes ($Mean = 1.28$), help people (customers ($Mean = 1.63$), and citizens in general ($Mean = 1.43$)) are seen most important. Profit concerns appear to be only subordinate while *long-term* ($Mean = 1.79$) considerations are significantly more important than *short-term* ($Mean = 2.96$) considerations (p-value of a t-test is 0.000).

As expected, we can further observe a stronger correlation between *long-term profit* and *not endangering contractual business relationships* ($r = 0.21, p = 0.000$) than between *short-term profit* and *not endangering contractual business relationships* ($r = 0.14, p = 0.006$). This finding points to the fact that contractual business relationships are seen as a long-term commitment, an essential contribution to the long-term success of the company. Short-term, deviations from obligations from contractual business relationships may be possible.

In addition, a significant and medium degree of correlation exists between *short-term* and *long-term* profit ($r = 0.36, p = 0.000$). Hence, it can be suggested that the more sensitive respondents are to long-term profit, the more sensitive they are to short-term profit and vice-versa. This result could indicate a general profit-sensitivity among some respondents.

We additionally performed regression analyses at various points in the statistical analysis. The results were not significant with a low value of R^2=0.13 (target coefficient $>$0.2) in each case. In contrast to the highly significant correlation analyses, no significant relationships could be identified in any of the regression analyses performed.

In principle, *endangering companies' operational processes* and *long-term* profit can be seen as universal barriers to companies engaging in crisis management. Interestingly, the importance of *reducing the suffering of the population* and *not endangering contractual business relationships* does not differ significantly between industries, supply chain stages, and company size (in terms of revenue), and no significant correlation exists among both questions.

H2: *Companies see reputation from a PPEC engagement as a benefit rather than a risk.*

To test H2, we asked the respondents about the advantages and disadvantages of collaborating with public actors. In terms of reputation, we asked whether they see a *positive reputation effect* vis-a-vis the wider public and whether they rather fear a possible *damage to reputation*. Both questions could be answered with *yes* or *no*. From all $N = 398$ respondents who answered both questions, the approval rate for *increase of reputation* yields a $mean = .41$ ($SD = .493$). A one-sided t-test reveals that this is significantly higher ($p = 0.000$) than for *damage to reputation* with a $Mean = .28$ ($SD = .451$). Although these findings show that reputation is not the predominant concern for companies in both directions, with the comparative result we do not reject H2.

Somewhat surprising at first glance, we find a low but significant positive correlation between both variables with $r = 0.231, p = 0.000$. One explanation for this finding might be the general relevance of reputation for the companies. A company that possibly recognizes a positive reputation in collaborative emergency management is at the same time aware of the possible negative consequences of wrongly perceived or failed relief efforts.

When it comes to the question of *damage to reputation*, differences in the answers of retail companies ($Mean = 0.36$, $SD = 0.481$, $n = 134$) and production companies ($Mean = 0.25$, $SD = 0.434$, $n = 137$) are noteworthy: The risk of possible reputation damage is rated higher by retail than manufacturing companies, which is plausible. Retail companies are more in the focus of the public eye and are therefore exposed to greater risks in terms of possible reputation losses towards private customers. By contrast, manufacturing companies do business rather in a B2B context and therefore do not focus on the reputation aspects of a PPEC to the same extent.

B.5.2 Enabling factors

H3: *Companies prefer the permission to promote with their PPEC-role to reimbursements of costs from public actors.*

To test H3, we asked the respondents on a likert scale from one (*very important*) to five (*not important*) how important several conditions would be if they collaborated with public actors. *Incurred costs need to be reimbursed* was rated higher than the *Permission to promote* ($Means$ 1.95 vs 2.97, see Table B.3 for further details). A one-sided t-test shows a significant difference with $p = 0.000$.

How important would the following conditions be in a collaboration with public actors?	Mean	SD
Operational processes must not be endangered	1.42	0.71
Competitors must not have access to internal corporate information	1.46	0.79
Incurred costs need to be reimbursed	1.95	0.83
Permission to promote with the relief	2.97	1.05
Public actors need to take over some of the risks associated with the company's investments in crisis management	2.02	0.92
Willingness of public actors to grant special rights (e.g., opening or driving times)	1.51	0.71

$n = 375$, $1 =$*very important*, $5 =$*not important*

Table B.3: Conditions for collaboration with public actors

Hence, we reject H3 for respondents from every industry, supply chain stage, and company revenue. Moreover, a weak positive correlation exists between responses to both questions ($r = 0.172, p = 0.001$): The more important cost reimbursement, the more important the permission to promote and vice-versa. This may be due to the fact that for most companies, basic requirements for a PPEC are decisive, such as protection of processes or company data, but only a subgroup of these also requests explicit benefits like compensation for costs and the opportunity to present themselves in a favorable light in public, which may be part of their CSR strategy.

Respondents rate *Cost reimbursement* and *Risk sharing* on a similar level. We further find a significantly higher rating of reimbursement of investments among small companies ($Mean = 1.91$) than among large companies ($Mean = 2.31$) through a t-test with $p = 0.048$. This finding could be explained by the fact that large companies generally possess a higher liquidity and more options for financial diversification (Soboleva et al., 2018).

In alignment with H1, respondents rated *Operational processes* highest within this question, followed by *No internal information to competitors* and *Public actors grant special rights*. Compared to the general importance they attach to operational process continuity, they rate its importance in a PPEC slightly but significantly lower (t-test: $p = 0.000$, $Means = 1.28$ vs 1.42). When collaborating with public actors, one could interpret it as goodwill, sacrifice, or increased tolerance towards operational interventions.

From these findings, we conclude that public actors should focus on designing compensation regulations and providing a high degree of confidentiality rather than enabling mere publicity. Moreover, public actors might have to pay even more attention to the continuity of companies' operations, e.g., by relaxing regulation, which is valued higher than monetary compensation.

H4: *Companies expect to best support governments in crisis response rather than in crisis preparedness or crisis recovery.*

We asked companies during which crisis phase their company could best support public actors. In these questions, we applied a likert scale from one (*we can support public actors very well*) to four (*we can barely support public actors*).

The respondents significantly prefer *immediate crisis response* to *permanent crisis preparedness* and *preparedness during an emerging crisis* (see Table B.4). For both comparisons, one-sided t-tests reveal statistical significance of the difference in means ($p = 0.000$). Hence, we do not reject H4.

When do you think your company could best support public crisis management?	Total		Food		Healthcare		Logistics	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Permanent crisis preparedness	2.39	0.89	2.56	0.85	2.16	0.89	2.36	0.85
Preparedness during an emerging crisis	2.30	0.83	2.51	0.82	2.09	0.79	2.2	0.77
Immediate crisis response	1.99	0.77	2.14	0.81	1.81	0.69	1.99	0.7
Recovery from long-term consequences of a crisis	2.34	0.81	2.48	0.84	2.14	0.79	2.40	0.73

$n = 373$, $1 =$*we can support public actors very well*, $4 =$*we can barely support public actors*

Table B.4: Support in different crisis phases

In addition, we find that respondents from healthcare companies show a significantly higher preference for all four queried disaster phases (*permanent*, *preparedness*, *immediate* and *recovery*), in particular for the *immediate crisis response* phase, than respondents from the food industry (t-test: $p = 0.000$). This indicates that the healthcare industry more strongly believes in a successful collaboration with public actors than the food industry. A reason for this could be the experiences of the healthcare sector with public actors during the COVID-19 pandemic. A statistically significant difference between logistics and healthcare companies can only be found for the *recovery* phase (t-test: $p = 0.012$), which might be due to less urgent logistical activities in the last phase.

From the answers of the companies (see Table B.4), we conclude that companies prefer to avoid intense, long-term involvement. Interestingly, the correlation analysis shows a strong and significant correlation between the companies' assessments concerning support in all four phases of a crisis (see Table B.5).

This indicates that some companies are willing to help at all stages, while others are generally less willing to help (regardless of stage). The more companies prefer to provide immediate support, the more they would also prefer to help in preparation and recovery. Hence, supportive companies tend to provide contributions and commitment throughout the disaster cycle.

B.5.3 Efficient design

H5a: *Companies prefer the provision of resources to coordinating assistance.*

When do you think your company could best support public crisis management?	Permanent crisis preparedness	Preparedness during an emerging crisis	Immediate crisis response	Recovery from long-term consequences of a crisis
Permanent crisis preparedness	1			
Preparedness during an emerging crisis	0.721**	1		
Immediate crisis response	0.563**	0.564**	1	
Recovery from long-term consequences of a crisis	0.453**	0.474**	0.501**	1

$n = 398$, ** Indicates significance at $p < 0.05$

Table B.5: Correlation analyses of support in crisis phases (H4)

To answer H5a, we developed an index of *Resources* and an index of *Coordination* (for the exploratory factor analysis, see Table B.7). The same variable composition per index was used for both H5a and H5b. *Mean* values and *SD* from the different types of assistance are provided in Table B.6.

Type	For each type of assistance mentioned, please indicate the conditions under which you would be willing to provide it.	Mean	SD
Resources	Providing goods	1.75	0.512
Resources	Providing transportation capacity	1.70	0.594
Resources	Providing storage	1.62	0.696
Coordination	Tactical planning	1.93	0.883
Coordination	Strategic planning	1.59	0.608

$n = 381$, 1 =*free of charge*, 2 =*against reimbursement*, 3 =*no willingness at all*

Table B.6: Contributions in a PPEC

Regarding the question whether companies would prefer provision of *Resources* to engaging in *Coordination*, the willingness to provide *Resources* is significantly higher than to partake in *Coordination* activities ($Mean = 1.69$, $SD = 0.43$, $n = 381$ compared to $Mean = 1.76$, $SD = 0.63$, $n = 381$; one-sided t-test with $p = 0.016$). Hence, we do not reject H5a.

Among the listed resources of Table B.6, *Providing Storage* is underpinned with the highest willingness to contribute ($Mean = 1.62$, $SD = 0.696$). Looking into different industries, using an ANOVA mean comparison, we find only slight differences, which are not significant ($\rho = 0.357$). Healthcare companies responded with a $Mean = 1.56$ and a $SD = 0.69$, Logistics companies with a $Mean = 1.59$ and a $SD = 0.66$, and Food companies with a $Mean = 1.68$ and a $SD = 0.71$. These results may be surprising as one could assume logistics companies have the largest storage capacities and thus should display a higher willingness to share them in a PPEC. One explanation for this observation might be that it is exactly because providing warehousing services is the core of their business model. A lower availability would seriously affect these companies if they had to provide these capacities without reimbursement. Interestingly, *Strategic Planning* is the most preferred relief measure by respondents. This shows that companies' willingness to support *Coordination* assistance varies concerning the time horizon. While tactical planning is closely linked to the companies' operational processes, which they consider particularly important and untouchable, strategic planning can improve ex-ante coordination. With *tactical planning*, we refer to, for example, capacity planning for production and logistics in the next weeks and months. *Strategic planning* comprises, for example, planning of emergency stockpiling of certain essential goods. Although we can confirm H5a, the extensive range between *Tactical Planning* and *Strategic Planning* indicates the need for evaluating carefully the way how companies should support in a PPEC. The relatively high SD for *Strategic Planning* also indicates a controversy among respondents.

Coordination also includes the exchange of information. To deal with this topic, which requires substantial discretion and trust on the part of the companies, we asked additional questions. It became apparent that *Information exchange with public actors* ($Mean = 1.27$, $SD = 0.55$) correlates significantly ($\rho < 0.01$) and on a high level of 0.64 with *Information exchange with companies from own SC* ($Mean = 1.28$, $SD = 0.54$; $n = 380$). Both answers are significantly ($p = 0.000$) different from the companies' willingness to do *Information exchange with competitors* (the willingness here is smaller with a $Mean = 1.62$ and a $SD = 0.79$). From these findings, we conclude that during a crisis, companies would share information with public actors with the same high willingness as with actors of their own SC and therefore trust public actors.

H5b: *Companies expect public actors to need resources from companies rather than coordinate assistance.*

The same way as analyzed in H5a we shifted the perspective: We asked the companies about their expectations, and whether public actors are more likely to need resources than coordinating support.

Exploratory factor analysis was conducted to examine whether the measurement items correlate with deriving a meaningful index for further analysis. As the analysis revealed, the Kaiser-Meyer-Olkin (KMO) criterium was 0.594, and Bartlett's test of sphericity was significant ($\chi^2(15) = 356.941, p = 0.000$) (Backhaus et al., 2016). According to the results of these indicators, the sample was considered adequate, and all five items suitable for conducting an exploratory factor analysis.

For the complete set of items, the calculation of factor analysis yielded two factors explaining a cumulative sum of 48.810% of variance. Factor 1, comprising the equally weighted items of '*production of goods*', '*transportation of goods*' and '*storage capacities*', explained 28.724% of the variance with factor loadings from 0.797 to 0.487 (the statistical results of the exploratory factor analysis using maximum likelihood and varimax rotation are presented in Table B.7). This Table also shows the mean values and standard deviations of the responses to the different items. Factor 2, which comprises the equally weighted items '*tactical planning*' and '*strategic planning*', explained 20.086% of the variance with factor loadings from 0.775 to 0.698.

For Factor 1, we obtain a Cronbach's α of 0.684 ($n = 398$) and for Factor B 0.702 ($n = 398$) respectively. Both values are acceptable to proceed (Grau, 2007). We conclude that both perspectives, what companies want to provide (H5a) and what they think that public actors need

Type	Where do public actors need support from private companies in crisis situations?	Mean	SD	Factor Loadings	
				Factor 1	Factor 2
Resources	Providing goods	0.69	0.465	0.487	
Resources	Providing transportation capacity	0.69	0.464	0.797	
Resources	Providing storage	0.54	0.499	0.675	
Coordinating	Tactical planning	0.40	0.490		0.775
Coordinating	Strategic planning	0.50	0.501		0.698

$n = 398$, $0 =$*No support needed*, $1 =$*support necessary*

Table B.7: Factor analysis for *Resources Index* and *Coordinating Assistance Index*

from them (H5b), go into the same direction and thus appear consistent. When asked about the needs of public actors, companies responded with a $Mean = 0.639$ and a $SD = 0.373$ ($n = 398$) in favor of the *Resources*, which is significantly higher (one-sided t-test with $p = 0.000$) than *Coordination* ($Mean = 0.451$, $SD = 0.436$; $n = 398$).

Again, no significant correlations are observable in SC stage, industries, or company revenue.

All in all, we do not reject H5b. To sum up the results from H5a and H5b in order to answer RQ3 (*Which are efficient contributions of companies in PPECs?*), public decision-makers need to consider the preferences of companies when it comes to the type of relief measure. We found in H5a that companies prefer to support with *Resources* rather than with *Coordination*. Given the fact that companies expect public actors to need support in *Resources* rather than in *Coordination*, one can conclude that rather little compensatory regulation might be necessary by public actors. However, depending on the actual need of public actors, for individual support measures like e.g., *Providing goods*, companies correctly expect a relatively high need but for their part show a rather low willingness to support in this area, at least free of charge. This indicates a greater need for compensatory regulation in *Providing goods*.

B.6 Discussion and conclusion

B.6.1 Theoretical implications

Our sample of 398 surveyed companies showed a high willingness to contribute to crisis and humanitarian operations. However, the companies need clarification and commitments from public actors to design and implement PPECs. Regarding the division of tasks (cf. indices of resources and coordination) and the type of contribution, we found differences in the willingness to engage in possible tasks as well as different ideas regarding the preferred contribution. The results of this study complement the now pervasive literature on humanitarian logistics. Companies' involvement in this field is often limited to a few "big players", such as DHL, UPS or FedEx, which have specialized in global emergency operations with a logistical focus (Binder and Witte, 2007). In local crises, however, spontaneous assistance is also often provided by regionally based SMEs, which is rarely documented in the literature due to its case-by-case nature, and of which civil protection authorities and researchers just learn about by chance through their network (Hunt and Eburn, 2018). As our study showed, also among small and medium companies, there is a clear and measurable willingness to get involved in a PPEC. A large survey like this thus provides a more comprehensive picture of the pattern of this important motivation.

It is also evident that many requirements for a collaboration between the humanitarian and private sectors are also highly relevant to public-private collaboration (Fontainha et al., 2016). This applies, for example, to the frequent problem of unspecified (or insufficiently specified) needs, as well as attention to the core competence of the companies with which they are involved in the collaboration. As our study showed, companies not only have a clear idea of what they can best deliver, but also of what is likely to be needed in an emergency. Tomasini and van Wassenhove (2009) propose a metrics system (similar to a scorecard) for this purpose, which can help to better match partners' fit in terms of motivation, needs, and competencies. Although it is impossible to predict the exact needs of the next crisis event in advance, even rough categories are beneficial. The categories used for our survey can serve as an initial orientation and contribute to the basic concept of such a scorecard. In general, companies have fewer reservations about entering into collaborations with humanitarian organizations compared with public actors (Binder and Witte, 2007). Hence, just as in NGOs' collaboration with private companies, public-private collaboration can benefit from close coordination, organizational learning and reputation capital (as part of an innovative CSR strategy) (Fontainha et al., 2016; Johnson et al., 2011).

B.6.2 Managerial implications

When asked for preconditions to engage in a PPEC, companies put the highest priority on the protection and stabilization of their business processes. In particular, the continuity of their processes and the protection of internal data towards competitors are most important to companies. Going beyond that, companies wish to be granted special rights in a PPEC.

This need for law adjustment and regulatory relief was highlighted particularly by logistics companies, which might indicate that they perceive their operations as especially regulated by governments. Relaxing these regulations thus offers public actors leverage for collaboration with logistics companies in times of crisis. Moreover, especially logistics companies do not want to endanger contractual business relationships in a crisis. Reasons for that might be the prevalence of performance-related payments in the logistics sector together with contract negotiations with customers, and the competitive transportation market in Europe. This lack of flexibility can impede short-term collaboration with public actors. Therefore, the latter should either set up specific, flexible contractual agreements with logistics companies or find gentle ways of collaboration that do not endanger the logistics company's business relationships. A possible scenario would be for a public actor to provide a driver for a logistics company's truck that is not in use, as it was observed recently in the UK during the Brexit-induced shortage of fuel and truck drivers, where soldiers were used to drive trucks (Kennedy, 2021).

The same applies for large companies of any industry, which are more afraid to endanger existing business relations through a PPEC than small companies. Hence, if public actors aim to collaborate with large companies, they should focus on ways of collaboration that minimize the risk of undermining the partaking companies' other business relationships. Although small companies are likely to possess less resources, they are more flexible in adapting their operations to the needs of public actors.

These aspects underline the importance of business continuity. Furthermore, public actors should prefer collaboration with companies with robust operations to less robust ones. Although it will be difficult to identify such companies, this aspect indicates that there are two reasons at the same time to favor companies with an already high competence in crisis management: First, these companies could most effectively contribute to a PPEC and second, these companies have comparatively low opportunity cost for their engagement due to robust and agile operations. Due to more and more large-scale crises and a growing application of supply chain risk management, it is quite plausible to expect that more robust supply chains lead to greater acceptance of a PPEC being part of companies' operations.

Regarding potential contributions to a PPEC from the company's side, our results generally meet public and private characteristics described in Section *Theoretical Background* and show that companies of all types would see themselves in a PPEC as a provider of storage and transportation resources and goods rather than coordinating assistance. However, we conclude from Table B.4 for companies in the food industry that more clarification from public actors might be necessary about potential fields of collaboration, what can be done by the companies, and how the companies may benefit from such collaboration. For such support, companies demand monetary compensation. Especially for small companies, it is important that a PPEC is financially compensated. Hence, public actors should realistically plan for these costs from the outset and be willing to pay up - even for such things as provided data as part of a long-term collaboration.

However, we observed that the more benefits respondents see in a PPEC, the less monetary compensation they expect for their contribution to a PPEC. This suggests that public actors' communication of a PPEC's benefits to the public can lower companies' compensation claims. Therefore, a dual strategy is recommended for the public sector. On the one hand, it should optimize the non-financial conditions for the most suitable companies and communicate their contribution extensively. On the other hand, it should be made possible by law to reimburse the particularly costly activities and contributions as quickly and with as little bureaucracy as possible.

Besides monetary compensation, companies also perceive an increase in reputation as an opportunity from a PPEC. Although this is of comparably low importance to companies, it provides a lever for public actors to approach certain company types.

For healthcare companies, it is more important than for others to avoid a loss of reputation in crises. In line with that, a potential increase of reputation through a PPEC is a stronger incentive for them. Moreover, retail companies are more concerned about a reputation damage from a PPEC than production companies. When approaching healthcare and retail companies, public actors could therefore develop strategies for public communication with society to satisfy these demands by for example positively highlighting a company's involvement. Due to the great importance of a professional communication strategy in times of social media and the possible negative consequences of mistakes, the close collaboration with communication and media experts is recommended. Companies could take advantage of this consulting service free of charge if they participate in a PPEC.

One major insight of the study is that 91% of the respondents replied to the question, under which circumstances they would exchange information with public actors in a crisis (H5a), with *free of charge* or *against reimbursement of costs*. Companies would be willing to share information with public actors to a larger extent than with competing companies (77%) and to the same extent with companies from their own supply chain (91%). This openness is high across industries, supply chain stages, and company sizes. However, according to public actors, there is currently no such format in which companies could transfer their data. Consequently, public actors need to build upon this potential and show ways and initiatives for structured and safe data transfer.

The general preference of companies is to keep their effort in a PPEC low in non-crisis times and become active in immediate crisis response. Therefore, public actors should set up a PPEC framework of low effort for companies in non-crisis times (e.g., establishing data transfer and developing communication networks but reducing or avoiding crisis exercises and extra resources), which becomes logistically active in crisis response. Since companies fear legal risks and unclear consequences of participating in a PPEC, public actors should additionally be precise and transparent about the company's tasks and obligations.

On the business side, corporate managers can use the implications of the study as support for their own decision whether to collaborate with public actors, and interpret them as a benchmark attitude of companies. When presented with a summary of our results and findings, experts from public actors and companies generally validated them. They were in strong agreement especially regarding the areas that companies expect public actors to need support in (H4) and companies' preferred ways of contributing to a PPEC (H5a). Insights from Table B.2 about general priorities in a crisis can be used by corporate managers to better coordinate a company's crisis management with its suppliers, customers, and logistics service providers. The high willingness to share data in a crisis across all companies (with companies from their own supply chain and public actors) should encourage them to intensify data exchange with other companies to increase resilience along their supply chains.

B.6.3 Limitations and future research

We faced a relatively low response rate of below 5%, leading to a possible self-selection bias and non-response bias. The non-response bias, meaning to have in a sample a relevant difference between respondents who answered and those who chose not to answer, could be investigated with Bonferroni adjustments to test statistical power of data (Clottey and Grawe, 2014). Besides that, self-selection with companies exceptionally committed in this area in one way or another is less of a problem for our study since our goal is precisely to identify suitable company candidates for such a collaboration. Self-selection thus supports the identification task.

The responses were mostly homogeneous across company sizes, type of industry, and supply chain stage (see Section *Results*). However, with regards to reputation aspects, especially the healthcare industry results have to be carefully evaluated, as this industry was and is in the focus of public attention during the COVID-19 pandemic. This might imply an increased importance of the topic for the healthcare industry.

We cannot exclude a social desirability bias, especially when it comes to the aspects of humanitarian engagement, reputation, promotions, and other related fields, which we consider in our study. While we fully believe the answers of our participants to be honestly given, the mere conviction, opinion or attitude on a subject is ultimately only of limited reliability, since entrepreneurial decisions of this kind have to be made under strong restrictions (competition, cost pressure, etc.). We have tried to minimize this problem, as the survey was conducted completely anonymously by a neutral third party (IfD Allensbach). In this way, we motivated participating companies to give honest answers without being afraid of receiving bad publicity.

B.6.4 Conclusion

Summing up our main results: First, we found that most queried companies have already been active and are willing to engage in humanitarian actions. Second, companies prefer to help when a crisis has occurred and not in a preventing manner. Third, these companies were open to discussing and implementing PPECs to improve crisis management. Fourth, when it comes to concrete actions, companies prefer spending resources to coordinate tasks and are open to sharing data which is not yet the case. Public actors need to consider the financial hurdles and provide compensation for any resources and coordinating tasks that arise for the respective companies.

Thereby, our study is the first to provide an overview of the perspective of companies operating in the fields of logistics, food, and healthcare industries towards PPEC.

B.7 References

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C Public-private collaborative re-routing of commercial transports in crisis situations

Abstract

With an increase in natural hazards and human-made crises, supply chain management needs to adapt to extreme conditions. In response to sudden-onset large-scale crises associated with a lack of time-critical goods like bottled water, it is crucial that public authorities activate relief logistics within the shortest time. However, taking responsibility and gathering physical resources can take valuable time. Though officials from public authorities and companies in food supply chain emphasized a high demand for decision-support in this area, there is a lack of scientific literature on relief collaboration between public authorities and companies. To contribute to closing this gap, we propose public-private collaborative re-routing of commercial transports based on real-time data supporting immediate crisis response. We apply our approach to a case study representing a large-scale tap water failure in a German city. To allow joint re-routing of retailers' trucks loaded with bottled water, state authorities lift competition law for the three retailers investigated. We model different crisis extents in terms of increased demand as well as different scenarios related to the crisis striking at different times of the day. Public-private collaboration is most effective with very strong demand increase and proves to be beneficial for public authorities and companies across most modeled settings. However, the effectiveness of collaborative re-routing varies strongly, dependent on the time of the day at which the crisis occurs. Additionally, the degree of retailers' delivery performance and contributed resources vary among different crisis timings, which reveals the need for flexible compensation schemes. Thereby, our study provides valuable insights about the importance of crisis timing as well as different retailers' distribution network structure and processes for re-routing. We conclude with both practical recommendations on relief logistics and opportunities for further academic research.

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C.1 Introduction

Due to a significant increase in natural hazards and human-made crises, the need for efficient humanitarian operations and related research is more extensive than ever (Besiou and Van Wassenhove, 2020). Given that around 80% of all crisis relief efforts are related to logistics (Van Wassenhove, 2006), many authors have transferred and applied existing operations research and supply chain management approaches, such as location, routing, or inventory models, to a humanitarian setting that is often more dynamic and uncertain. However, in order to be able to respond to more complex crises, humanitarian problems can no longer be addressed by simply applying best practices from the commercial sector (Besiou and Van Wassenhove, 2020). As stated by Holguín-Veras et al. (2022) as well as Sodhi and Tang (2020), extreme conditions require existing practices to be revised in order to go beyond mere supply chain risk management.

In general, there are three important aspects to address in crisis management research going forward. First, researchers need to ascribe more importance to the real-life features of a specific crisis context. Developing algorithms for generalized problems introduces a strong research bias on highly mediatized crises and a lack of empirical validation (Besiou and Van Wassenhove, 2020). Second, despite the prominent opinion stressing the importance of multiple actors in crisis management and the advantages associated with collaborative humanitarian logistics, most of the studies in the field of humanitarian supply chain management focus on a single actor (Behl and Dutta, 2019). More specifically, the government's role in humanitarian supply chains and its interaction with the private sector requires more attention (Akomea-Frimpong et al., 2023; Sodhi and Tang, 2021; Quarshie and Leuschner, 2020). Finally, in line with the importance of partnerships and the sharing of resources in improving resilience, research on humanitarian operations needs to conceptualize interventions from a holistic, system-focused view. Thereby, interventions can comply with the complex requirements in humanitarian operations, namely reduction of suffering, speed of crisis response and efficient use of resources (Besiou and Van Wassenhove, 2020; Holguín-Veras et al., 2013). We took care to design our research approach in this paper accordingly.

As part of a German government-funded research project, we investigated several types of crisis scenarios. Among them a large-scale tap water failure is considered which would have severe impacts on population and supply chains and requires immediate response to limit the damage. In the course of the research project and in exchanges with government officials from the *German Federal Agency of Civil Protection and Disaster Assistance*, the *German Federal Office for Agriculture and Food* and the *Baden-Württemberg Ministry of Rural Areas and Consumer Protection*, these public parties emphasized their strategic goal to involve the private sector more in emergency food supply. For this purpose, they highlighted the need for research on how public authorities can partner with companies to supply the population with water in response to a large-scale tap water failure. Accordingly, in this study, we include both public authorities' and companies' perspectives in the development of a crisis response concept as well as its evaluation. For the latter, we make use of several KPIs to interpret the dynamics determining effectiveness and efficiency of the collaboration concept.

In Germany, as in many industrialized nations, tap water is the primary source for the population's drinking water. Other essential functions and activities of daily life such as cooking, washing, or cleaning are often depending on the same source of water as well. However, the immediate reaction of public authorities to an outage of tap water is mostly undefined. Even though the importance of the water supply and its susceptibility to failures and outages has been highlighted often and recently in Germany (Bavarian Environment Agency, 2022; Bross et al., 2019), there are currently no detailed procedures as to what a structured response in the direct aftermath of a tap water outage would look like (Bross et al., 2019). Our discussions with officials from state authorities point in the same direction. The concepts in place to deal with shortages in general are remnants of the Cold War or meant for completely different applications. Public authorities and NGOs manage various types of warehouses to offer goods to beneficiaries (e.g., the German *Zivile Notreserve* or the European Humanitarian Response Capacity). It is evident that these concepts were neither designed for tap water outages nor for quick and immediate response. Humanitarian operations, especially in industrialized countries that have rarely or never faced any crises so far, cannot be activated in a heartbeat. For example, in the current setting, driving capacities have to be acquired externally and volunteers have to be activated – both activities would take time and hence cannot be part of an immediate response.

Given a sudden outage of the tap water supply, the population will turn to bottled water as the next logical choice. Although public authorities keep emphasizing the importance of a private safety stock of various goods (German Federal Agency of Civil Protection and Disaster Assistance, 2023; National Sanitation Foundation, 2023), people's stocks of drinking water are negligible (Sandholz, 2019; Menski, 2016). Demand for bottled drinking water is usually satisfied by simply purchasing it in a retail store. Consequently, this is where peaks in demand can be expected, following an outage – as has been observed in several instances (Heidelberg24, 2019; LZ.de, 2016; Menski, 2016). However, retailing companies and their supply chains are highly optimized constructs. As part of efforts to save costs and become leaner, inventories have been constantly decreasing over the last decades (Vlajic et al., 2013). This poses a problem in the face of a sudden, large increase in demand for any product. There simply will not be enough stock at retail stores to satisfy all demand, should people turn to retail stores to satisfy their demand for drinking (and even cooking) water. As the recent COVID-19 pandemic has shown, empty shelves and the subsequent customer reactions can pose additional challenges to retailers. There are many reasons for a retailer to satisfy as many customers as possible in the scenario of a tap water outage and the public authorities being the agent of the people pursue the same objective.

Accordingly, the question we set out to answer is the following: How can retailing companies and public authorities work together to improve the reaction to a tap water outage? We started our investigation by interviewing representatives of one of the leading global producers and distributors of bottled water, with the original goal of discussing and evaluating direct and immediate actions which the company could take. However, it was quickly pointed out that any reaction from the producer would fall outside our intended scope of an immediate reaction, which was preferably within one or very few hours. Producing, packaging and delivering new replenishment of bottled water would simply take too long, especially since production sites are often located far away from retailers' warehouses. An alternative solution was proposed by indicating that, with high and steady demand as well as frequent deliveries, a lot of the stock of bottled water is actually continuously on the road. In inventory management, this is often referred to as *pipeline stock* (Silver et al., 2016). Even though these deliveries are not meant for crisis applications, we argue that these on-road inventories can play an essential role in relief logistics, reducing the population's burden in the direct aftermath of the outage of an essential good. Furthermore, there is no need to set up new humanitarian supply chain structures as supply chain collaboration between the public and private sector can help move commercial goods fast and efficiently during crisis.

The overarching objective of the study is showcasing the benefits of a collaboration between public authorities and retail chain companies for the population and the companies for a short-term decision horizon. For this purpose, we developed a case study in which tap water fails in the German city Stuttgart. We define the failure of the provision of water as a sudden-onset event, in which the supply of water is either cut off (e.g., as due to an accident at a construction site in South Korea (KoreaTimes, 2009) or malicious damages (Jurica et al., 2019)) or contamination (e.g., as in the Flint (USA) water crisis (Ruckart et al., 2019)), rendering it unusable for drinking and other uses without treatment. Even if the water can eventually be purified for consumption, it is likely that the population will increasingly turn to other sources to satisfy their demand for water. Consequently, we treat both cases, a total cut-off and a contamination of the tap water supply, as different degrees of the same scenario – an actual shortage of the essential and often time-critical good of drinking water in households.

A typical reaction of the population is to substitute the required tap water with bottled water by purchasing it at supermarkets and other retail stores. Thus, the resulting demand for bottled water at retailers' stores will largely exceed a normal day's demand and is likely to also deplete their safety stocks. This sudden rush for bottled water has been observed in several real-life situations (wetter.com, 2020; Heidelberg24, 2019; LZ.de, 2016; Menski, 2016). Many customers trying to buy as many products as they can and even more than they might need can hit retail supply chains unprepared and cause disturbances throughout entire supply networks, as was showcased for several products during the COVID-19 hysteria (e.g., pasta, flour, or toilet paper). Therefore, the effects of the actual event on supply chains may become amplified in terms of severity, duration and extent. As such, it is crucial that such a shortage is addressed quickly and efficiently.

Depending on the extent and duration of the outage of tap water, the public authorities could and should step in, using drastic measures such as supplying bulk water from trucks or using national emergency supplies. However, both the extent and the duration might not be clear in the beginning of the event. Moreover, as confirmed by public authorities, official procedures often take time or might not be defined specifically enough, which means that such help cannot be deployed instantaneously. Additionally, the described situation suffers from a central dilemma of crisis management: public authorities need to wait to act until a certain severity of a situation is officially declared and it becomes responsible (Diehlmann et al., 2021). However, until then, valuable time for action will have passed.

In our exchanges with public authorities, the finger has often been pointed at companies which are deemed “responsible” for the supply of bottled water during normal times. On the other hand, discussions with company representatives have indicated that companies expect guidance from public authorities in such cases. Commercial companies are not responsible for services of public interest and emergency supplies. Consequently, managing large-scale crises is not part of their daily business. However, companies are often willing to act and help in crisis situations for multiple reasons, such as contributing to their corporate social responsibility strategy or simply because it aligns with their business goals (Izumi and Shaw, 2015). We argue that the collaboration of companies, which are not used to dealing with crises, with public authorities, which do not have the infrastructure and resources in place to act, is key to effectively improve the overall response to crises. To put it more bluntly: the public authorities have the responsibility and the mandate to react to crises, while the companies control the supply chain and infrastructure to react quickly.

By investigating collaboration between public authorities and companies in re-routing commercial trucks based on real-time data, this paper’s main academic novelty lies in bringing an innovative supply chain concept into the scientific discussions about extreme supply chain management (Sodhi and Tang, 2020) and public-private emergency collaboration (PPEC) (Diehlmann et al., 2021; Wiens et al., 2018). Both fields have received increasing academic attention with recent crises. Moreover, we address two research needs for humanitarian operations formulated in Besiou and Van Wassenhove (2020): investigating multiple stakeholders’ changing roles in the course of a crisis as well as opportunities in using modern technologies (through leveraging real-time data from track and trace systems).

Within our paper, we compare the performance of different responses to a sudden tap water failure and assess it using measures that capture the overall supply of bottled water to the population via retail stores in terms of speed and quantity. As a starting and benchmark solution, which was discussed with experts from practice and research, we model a retailers’ conventional response to a drastic increase in demand: sending more trucks into the affected region carrying excessive (safety) stock available at the warehouses (Heidelberg24, 2019; LZ.de, 2016; Horwitz, 2009). The alternative approach of re-routing trucks was discussed with several supply chain managers and considered as a possible response to disruptions, interestingly not only for severe crises but also to better cope with demand fluctuation. Hence, we evaluate the performance of re-routing trucks that left the warehouses into the affected region. Next, the idea of collaboration between retailers, fostered and moderated by public authorities, is introduced into the context, employing re-routing across the networks of multiple retailers. The collaboration was deemed challenging, yet possible by practitioners from public authorities and companies.

Utilizing commercial resources for humanitarian goals by solving a dynamic routing problem is a complex task. First, re-routing bottled water to crisis areas might create a demand in the good’s prior destination area. Thus, it is necessary to account for potential unmet demand when optimizing this routing problem. Second, the change from "normal" to "crisis" setting leads to the emergence of additional problem characteristics. For instance, traffic might be different during the crisis or the preparation of re-routing within or across companies may become challenging (e.g., in the IT system). Third, retailers operate stores in efficient time processes built up on opening times, customers' expected purchasing behavior, inventory and replenishment, which determine retailers' potential operational contribution at any point in time. Fourth, in order to be able to solve this dynamic re-routing problem, real-time data is required. Frequently, at the start of crisis response, sufficient information about the number of beneficiaries, their locations or quantity of relief goods required is not readily available (Maghfiroh and Hanaoka, 2018). While accessing this real-time data is a challenging task, both companies and the German government aim towards more sophisticated use of real-time data in the near future (German Federal Government, 2021; Sodhi and Tang, 2021; Monserrat et al., 2020). Moreover, Lüttenberg* et al. (2023) found that many companies would be willing to share their data with public authorities for crisis management.

For the purpose of showcasing the benefits of collaborative re-routing, we aim to orient towards the research methodology proposed by Baharmand et al. (2022) and include qualitative insights from the field and real-life characteristics for evidence-based modeling. We introduce our proposed re-routing approach consisting of vehicle selection and route planning and apply it on the developed case study with state authorities as well as three retailers jointly responding to a tap water failure within the same day. Additionally, we model the crisis striking at different times of the day and different crisis extents (i.e., demand increase). The results show that retailers re-routing individually can lead to better results than sending additional trucks from warehouses. Particularly, public-private collaboration proved to be beneficial for public authorities and companies across most modeled times and crisis extents. From a public authority perspective, coordinating collaborative re-routing pays off most if the impact of the crisis on demand is very high and retailers share supply. In other terms, collaborative re-routing is the most scalable approach with respect to crisis extent. However, overall performance of re-routing, both individually and collaboratively, varies with different times of the day. Additionally, not all companies benefit the same way. Their degree of involvement varies significantly among different crisis timings and extents which reveals the need for flexible compensation schemes. Thus, our study provides valuable insights about crisis timing as well as different retailers' distribution network structure and processes when applying collaborative re-routing, resulting in both practical recommendations on relief logistics and opportunities for further academic research.

C.2 Theoretical background

The routing problem considered in this study can be classified as a multi-depot split-delivery vehicle routing problem (MDSDVRP). Water is transported from multiple trucks and warehouses at different positions to stores, accounting for collaboration and re-routing opportunities based on real-time information. The general goal of the model is to obtain an overall distance-minimizing distribution of goods while satisfying demand in the crisis region by routing the freight through the network and allocating the stores to the trucks. In the Split Delivery Vehicle Routing Problem (SDVRP), a fleet of capacitated vehicles serves a set of customers. Contrary to the assumption of the classical Vehicle Routing Problem (VRP), each customer can be visited more than once and the demand of each customer may be greater than the vehicle capacity (Archetti and Speranza, 2018). While split delivery VRPs have been extensively studied within a humanitarian setting, Anuar et al. (2021) point out that we have yet to see more dynamic and real-time problem parameters being addressed simultaneously.

Compared with commercial models, humanitarian routing problems are subject to additional complexities such as emergency response time, limited resources and traffic interruption (Y. Wang et al., 2021). In this light, multiple authors have developed mathematical optimization models for dynamic vehicle routing and resource distribution applicable to various emergency situations. In general, a distinction can be made between two approaches for dynamic re-optimization. On the one hand, periodic re-optimization solves static problems periodically corresponding to the current states (Pillac et al., 2013). Papers that can be classified within this category are, amongst others, Alem et al. (2016), Cao et al. (2018) and Maghfiroh and Hanaoka (2018). On the other hand, continuous re-optimization updates the routes in real-time whenever new information is acquired (X. Wang and Kopfer, 2015; Pillac et al., 2013). Papers addressing the real-time adjustment problem during the progression of relief distribution are, amongst others, Najafi et al. (2014), Lu et al. (2016) and Sakiani et al. (2020). Our study is a special form of the latter, as the dynamic routing decision arises from one new demand situation and only in rare cases. Following Bektas et al. (2014) and Pillac et al. (2013), our MDSDVRP can moreover be considered as dynamic and deterministic, as the route optimization is executed based on the demand increase resulting from the sudden-onset crisis (Van Wassenhove, 2006). No anticipation of the new planning situation prior to the crisis (Bektas et al., 2014) applies.

When involving food retailers in crisis response measures with very short warning time, public authorities need to take into account retailers' intra-day time dynamics caused by store opening times, customers' purchasing behavior, perishable goods and route schedules (Seidel et al., 2016; Osvald and Stirn, 2008). For earthquakes, it is known that a strike at night can increase damage and impede crisis response measures (Gu et al., 2019; Srivastava and Gupta, 2004). It can take at least 24 hours until medical assistance from outside arrives in an affected region since it might be more difficult to activate volunteers if a crisis occurred during the night than during daytime (Stratton and Tyler, 2006). However, studies considering crises often assume a specific time the crisis strikes (e.g., the time a relatable earthquake happened (Baharmand et al., 2019; Özdamar et al., 2004)), or consider it as part of a stochastic optimization variable (Tofighi et al., 2016).

Regarding routing in crises, intra-day developments often relate to the demand-side in multi-period settings (M. K. Li et al., 2022; Gökçe and Ercan, 2019). For example, Abdelgawad and Abdulhai (2010) consider hourly distribution of evacuees in emergency evacuation planning and Rathore et al. (2022) conduct hourly demand forecasting of emergency medical services calls and real-time routing. In this context, Rathore et al. (2022) also address re-routing of emergency vehicles depending on patients' criticality. In addition, intra-day developments are considered in the time-dependent VRP, where travel times between nodes depend on distance and the time of the day (Donati et al., 2008; Wohlgemuth et al., 2012; Osvald and Stirn, 2008). However, although routing decisions in the response phase in humanitarian logistics are extensively researched (Anuar et al., 2021), research on the impact of a crisis' timing on relief logistics and routing decisions in the response phase is scarce to the best of our knowledge. Regardless the timing, Kucharska (2019) classifies both available vehicles and demand as common drivers of dynamics in vehicle routing and Al Theeb and Murray (2017) stress the challenge to balance dynamic supply and demand in a crisis situation (see also Xu et al. (2023)). Hence, we contribute to existing literature by linking crisis timing with dynamic routing decisions in which both vehicle availability and demand depend on the time of the day.

Optimizing crisis relief planning in real-time is crucial to reduce the burden on the population and companies. However both humanitarian and commercial goals would better be reached with greater supply chain collaboration and coordination (Tukamuhabwa et al., 2015; Nurmala et al., 2017; Wankmüller and Reiner, 2020). While multiple researchers analyse the potential of partnerships between humanitarian and commercial organisations (Nurmala et al., 2017), crisis relief models based on the coordination between public authorities and companies are rarely considered in literature (Diehlmann et al., 2021). As the COVID-19 pandemic has clearly shown, higher resilience provided by public and private actors collaboratively involved in the crisis life cycle, can, however, help to prevent the shift from a critical situation to a catastrophic crisis (M. K. Li et al., 2022; Müller et al., 2022; Blackmon et al., 2021; Nikolopoulos et al., 2021). Thereby, from a company perspective, participating in PPEC can contribute to companies' extreme supply chain management (Sodhi and Tang, 2020). In general, PPECs are built on the idea that partnerships with firms facilitate the transfer of knowledge and skills on collaborative logistics and supply chain management, leading to efficiency gains in humanitarian logistics (Diehlmann et al., 2021). To the best of our knowledge, only three studies approach PPEC from a quantitative logistics perspective. Diehlmann et al. (2021) provide a modelling framework using logistical and game-theoretical concepts. Additionally, S. Wang and Huang (2022) propose a VRP for public and private vehicles considering time windows and Breitbarth et al. (2021) develop a collaboration concept for tactical last-mile delivery planning during pandemics. This paper extends the work on PPECs by analysing the opportunities associated with public-private collaboration in a dynamic routing context. Given the uncertain nature of the extent and duration of the crisis situation, the analysis of collaboration between public and private partners provides significant added value in the development and implementation of real-life PPECs.

To sum up, our main contributions to existing research are in (1) proposing collaborative re-routing as a supply chain concept for PPEC and extreme supply chain management and (2) incorporating the timing of a crisis into relief logistics planning.

C.3 The proposed re-routing approach

C.3.1 Scope

We propose a supply chain concept for the re-routing of commercial transports in response to a sudden demand increase of essential goods like food and drugs. Destinations of the re-routing are retail stores or points of distribution set up by public authorities. Our re-routing approach is applicable for the immediate response phase within the same day after a crisis has hit. This requires real-time information about demand, trucks' positions and loads and warehouse safety stocks to be transparent to the decision-maker. The approach can be applied by retailers on their own to increase flexibility in their distribution network, which is becoming a more and more viable option in view of increasing applications of track-and-trace systems, as well as in a collaboration between public authorities and multiple retailers for crisis management. Special characteristics of the collaborative re-routing are presented in Section C.4.3.

The developed re-routing approach consists of demand assessment, vehicle selection and route planning, which are presented more in detail in the following. Since decision-makers would face time pressure, we first plan vehicle load and the routes, so that while planning the routes, vehicles can be loaded.

C.3.2 Vehicle selection

Our concept takes an estimate of the remaining demand of every affected store as input, which depends on the time when the crisis happens. Demand can be given in for example pallets or packages.

On the supply side, there are two options to supply affected stores short-term with commercial resources (see Figure C.1): The maximum supply volume is determined by loaded trucks on the road which are positioned at many different locations (X. Wang and Kopfer, 2015) and can change their direction immediately. Re-routing these trucks, however, causes supply gaps in the stores they were originally meant to supply. Moreover, retailers maintain safety stock at their warehouses. Increases in unexpected demand are the only reason why safety stock is being held. However, the fact that trucks need to be provided and loaded first as well as the distance between warehouse and affected stores impede quick response.

For trucks on the road being re-routed, the decision-maker needs to determine the radius around the crisis area from which trucks are selected. The greater the radius, the more trucks can be re-routed short-term, but the greater the resulting supply shortages at non-affected stores. Trucks within the radius can be in two different states at the time of the crisis: they can be driving on the road or unloading at a store. We assume that, if a truck is unloading, the earliest departure time is when unloading is finished as planned. For both states, the load can differ depending on the tour progress. Trucks can be fully loaded, partly loaded or empty.

Due to the focus on short response time, we assume that retailers preferably select trucks on the road. Hence, if the amount of water loaded on trucks on the road (within the range) exceeds demand, only the closest trucks are re-routed. In this case, only the entire truck-load is re-routed, which means that supply can slightly exceed demand.

If the amount of water on the road is not sufficient, trucks at the nearest warehouses are loaded with safety stock until the required amount of water is reached or until the warehouse is empty. If a warehouse is empty but demand is not yet met, safety stock from the next closest warehouse is loaded on trucks. If total available supply, from trucks on the road and safety stock from all

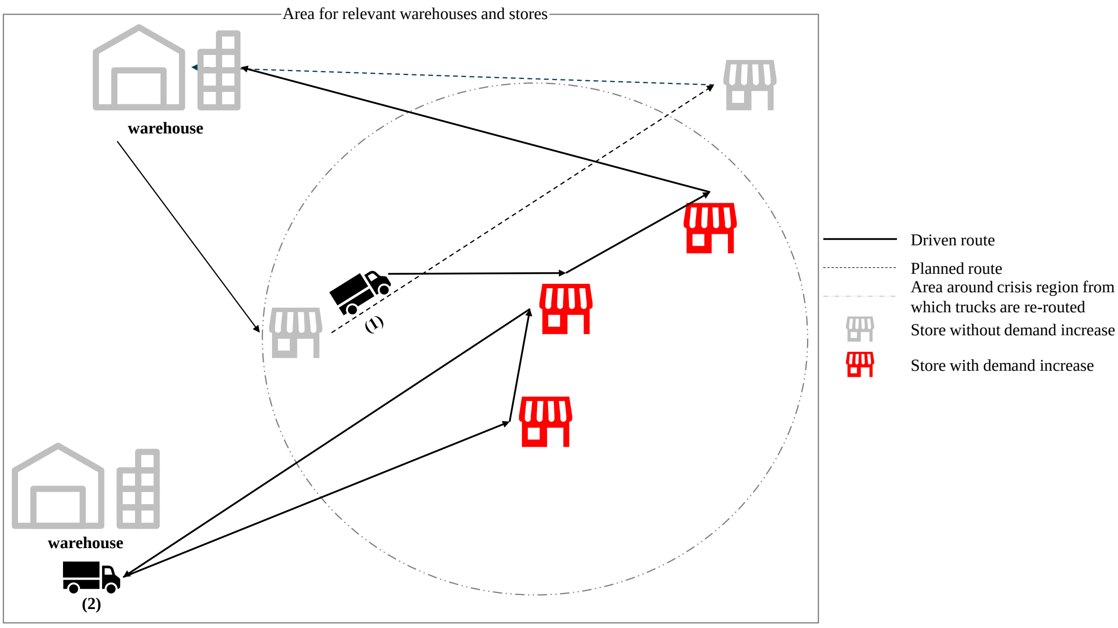

Figure C.1: Trucks on the road (1) and additional trucks with warehouse safety stocks (2) are routed to affected stores. A store can be supplied by more than one vehicle.

warehouses, is below demand, all the available supply is transported into the crisis area and supply shortage is equally distributed among stores.

Thus, the problem arises to efficiently route the loaded vehicles from different positions with different load volumes to the affected stores.

C.3.3 Route planning

We formulate the routing of loaded trucks according to the new demand situation as a Vehicle Routing Problem. Since store demand is likely to exceed vehicle capacity in a crisis, stores can be supplied by more than one vehicle. In other terms, split deliveries are possible (Khorsi et al., 2020; Dror and Trudeau, 1989).

The following formulation of the route planning can be considered a variant of the Multi-depot split-delivery vehicle routing problem (MDSDVRP) and is based on Ramos et al. (2020); Ray et al. (2014) and Cordeau et al. (1997). Compared to the classical MDSDVRP, our route planning does not include the load split across multiple vehicles at one depot, but takes loaded vehicles as input. We introduce the following notation (Table C.1).

Symbol	Details	Explanation
Sets		
$s \in S$		Retail stores in crisis area
$v \in V$		Vehicles
$V^r \subseteq V$		Vehicles on the road
$V^w \subseteq V$	$V^w \cap V^r = \phi, V^w \cup V^r = V$	Vehicles starting from a warehouse
Parameters		
C_{ij}	$i, j \in S \cup V$	Distance between position i and j where i and j represent vehicles and stores
D_s	$s \in S$	Demand of store s
L_v	$v \in V$	Load of vehicle v
N		Maximum number of stores on any vehicle's tour
Variables		
$x_{ijv} \in \{0, 1\}$	$v \in V, i, j \in S \cup V, i \neq j$	Boolean indicating if edge (i, j) is taken by v
$z_{vs} \in \mathbb{N}$	$s \in S, v \in V$	Integer amount unloaded by vehicle v at store s
$u_{vs} \in \mathbb{N}$	$v \in V, s \in S$	Integer indicating a store's rank on v's tour

Table C.1: Notation

$$\min \quad \sum_{i \in S \cup V} \sum_{j \in S} \sum_{v \in V} C_{ij} \cdot x_{ijv} \tag{C.1}$$

s.t.

$$\sum_{j \in S} x_{vjv} = 1 \quad \forall v \in V \tag{C.2}$$

$$\sum_{i \in V \setminus \{v\}, j \in S \cup V} x_{ijv} = 0 \quad \forall v \in V \tag{C.3}$$

$$\sum_{i \in S \cup V, v \in V} x_{ijv} \geq 1 \quad \forall j \in S \tag{C.4}$$

$$\sum_{i \in S \cup v, j \in S} x_{ijv} \leq N \quad \forall v \in V \tag{C.5}$$

$$\sum_{v \in V} z_{vs} \geq D_s \quad \forall s \in S \tag{C.6}$$

$$\sum_{s \in S} z_{vs} = L_v \quad \forall v \in V \tag{C.7}$$

$$z_{vs} \leq \sum_{i \in S \cup \{v\}} x_{isv} \cdot L_v \quad \forall v \in V, \forall s \in S \tag{C.8}$$

$$\sum_{v \in V^r} x_{vjv} \geq 1 \quad \forall j \in S, \text{if} |V^r| \geq |S| \tag{C.9}$$

$$\sum_{v \in V^r \cup V^w} x_{vjv} \geq 1 \quad \forall j \in \{1, 2, ..., min\{|V^r \cup V^w|, |S|\}\}, \text{if} |V^r| < |S| \tag{C.10}$$

$$\sum_{i \in S \cup \{v\}} x_{ihv} - \sum_{j \in S \cup \{v\}} x_{hjv} = 0 \quad \forall v \in V, \forall h \in S \cup V \tag{C.11}$$

$$u_{vi} - u_{vj} + |S| \cdot x_{ijv} \leq |S| - 1 \quad \forall v \in V, \forall i, j \in S, i \neq j \tag{C.12}$$

The objective function (C.1) reduces the distances travelled, which under constant truck speed equals total travel time. Thereby, both the distance-dependent transportation effort and the time on the road are minimized. The latter is an especially crucial parameter in the immediate aftermath of a crisis in an urban area, where traffic disruptions pose a threat to smooth transportation. The section back to the original position of the vehicle is not crucial for the supply of beneficiaries at stores. In order to prioritize a sooner arrival at the stores, the objective function excludes the tours' last section. Every vehicle can only start a tour from its original position and not pass through other vehicles' positions (Constraints C.2 and C.3). Constraints C.4 ensure that every store is supplied by at least one vehicle and that stores can be supplied by more than one vehicle. Since vehicles with more load than in non-crisis times can depart from the warehouses, we limit the maximum number of stores on a tour (Constraints C.5) in order to avoid long-lasting tours with more fragmented unloading. Every store demand must be met and since trucks are only completely re-routed and unloaded, it is possible that the combined supply of several trucks (slightly) exceeds store demand (Constraints C.6). Every truck needs to be fully unloaded (Constraints C.7). Constraints C.8 state that a vehicle can only unload at a store if the vehicles passes by that store. Further, we argue that, in a situation where time is crucial, both commercial and public decision-makers aim to distribute its available bottled water in a balanced way (Xu et al., 2023). Constraints C.9 and C.10 ensure that, if there are sufficient trucks on the road, every store is the first stop on any tour. If not, as many stores as there are vehicles on the road are supplied by them as a first stop on their tour. The remaining vehicles departing from a warehouse moreover supply as many different stores as possible as a first stop on their tours. Constraints C.11 contains standard route continuity constraints. The Miller–Tucker–Zemlin constraints (Ramos et al., 2020) eliminate subtours for every vehicle in Constraints C.12.

According to this problem formulation, all vehicles return to their initial positions, which can be on the road. This last section of tours is not part of the objective function. For building tours and interpreting the results regarding distance travelled, all tours' last section is replaced with the section back to the vehicle's original warehouse.

C.4 Case study

We use a case study to showcase the potential benefits of a collaboration during a crisis which comes in form of the sudden shortage of an essential good. It is assumed that companies possess the digital means to track the locations of their vehicles on the road. Furthermore, both companies and public authorities engage in coordination efforts beforehand, to make a re-routing of trucks from a centralized perspective possible.

To account for the specific nature of food retailing with fixed delivery times, we investigate the impact on different indicators such as effectiveness and efficiency for different timings of the crisis.

C.4.1 Setting

C.4.1.1 Distribution network design

The case deals with a tap water failure or contamination in the German city of Stuttgart. As was observed in many cases, this will most likely lead to, at times irrational, runs for bottled water at food retailers, where the additional demand can exceed that of the unavailable drinking water (from the tap) by multiple folds. The scope includes three food retailers operating in the state corresponding to Stuttgart, Baden-Württemberg (BW) (see Figure C.2). The location data for Retailers 1-3, warehouses and stores, are real data (see Table C.2). Based on historic consumption data (Senn-Kalb et al., 2022) and discussions with a food retail supply chain professional, we developed a simplified quantity structure which assumes that every store has a daily demand of three pallets of bottled water and is supplied every day. Based on this information, we set up a distribution network for every retailer using a variant of the Multi-Depot Capacitated Vehicle Routing Problem which minimizes total distance, builds tours and allocates them to warehouses. In other terms, to satisfy daily store demand, every retailer achieves this in the most distance-minimizing way. This results in tours of mostly three stops, which is in line with evidence from practice.

Characteristic	Retailer 1	Retailer 2	Retailer 3
Total number of stores in BW	775	347	124
Number of stores in crisis region	8	12	1
Number of warehouses	5	3	1

Table C.2: Retailers' characteristics

We assume retail store opening hours are from 8:00 to 20:00. Other than fresh products, which usually arrive early in the morning, bottled water and other beverages can arrive at any time during the day. Moreover, according to discussions with practitioners, the choice of departure times for deliveries should allow the retailers (1) to reach all stores before store closure time and (2) to use a truck and driver twice per day.

Consequently, trucks either depart in the morning or early in the afternoon. For Retailer 1 and Retailer 2, we randomly assign tours to departure times (8:00, 8:30 and 9:00 in the morning, and 13:00, 13:30 and 14:00 in the afternoon) so that tours are equally distributed among the potential departure times. Since the network structure of Retailer 3 requires long tours, we distribute longer tours among the morning departure times and shorter tours among the afternoon departure times.

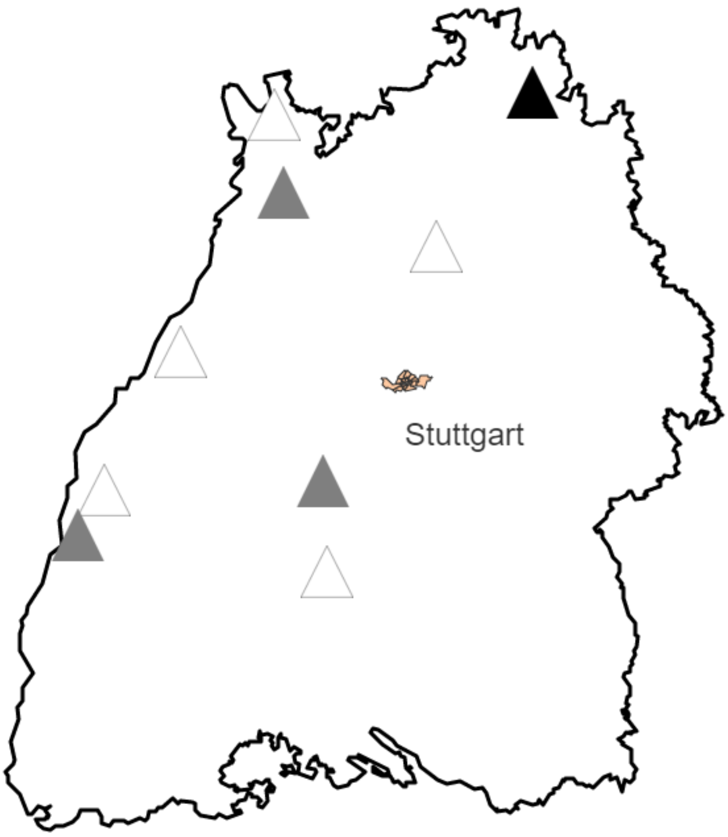

Figure C.2: The German state of Baden-Württemberg, retailers' warehouses (white: Retailer 1, grey: Retailer 2, black: Retailer 3) and crisis region Stuttgart (orange)

For all road connections between locations, we assume distance to be 30% greater than direct distance. On average, a truck is assumed to travel with a speed of 60 km/h including both highway and urban transport portions (Çankaya et al., 2019; German Federal Ministry for Digital and Transport, 2021). The unloading time at a store is set to 30 min. This results in departure times, arrival times and unloading times for every section of a tour and arrival times back at the warehouses.

For the crisis region, this means that the number of trucks in range for re-routing varies over the course of a day and among retailers (Figure C.3).

The retailers account for daily fluctuations in demand by keeping a safety stock at stores and warehouses each of 10% of daily demand or throughput respectively. Before the crisis happens, every store's inventory level is sufficient to meet demand at any time. Moreover, we assume store sales to be equally distributed over the day and, therefore, unloading times determine the daily development of inventory. Consequently, the regular schedule of unloading times determines the inventory level at any given time and, hence, also for the timing of the crisis.

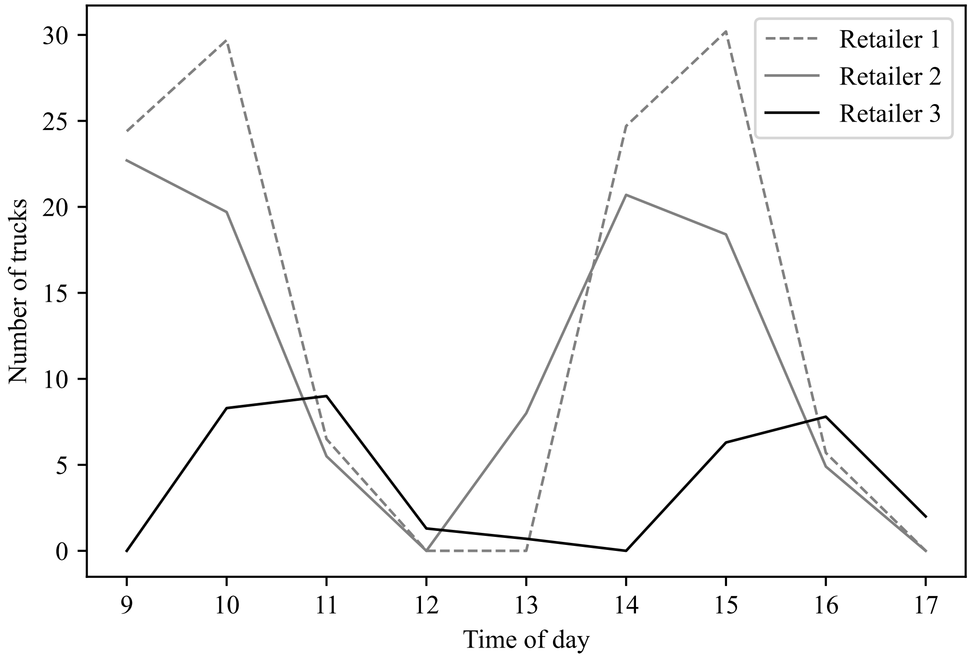

Figure C.3: Partially or fully loaded trucks within range of 40 km around the crisis area (average values over ten departure time distributions)

C.4.1.2 Crisis event: demand assessment and vehicle selection

After the tap water supply has failed, there is a strong increase in demand in all stores in the crisis region for the remaining opening hours. People turn to retail stores and are likely to purchase as much bottled water as they can. Consequently, we assume that, in terms of demand, any retail store could sell all of its bottled water to its customers immediately. However, recent years have shown that if retail stores cannot meet demand, due to a demand increase or a supply shortage, they limit the number of goods sold per person (Reuters, 2023; Heidelberg24, 2019). This is done for several reasons, one of them being to lower the risk of panic (buying). Moreover, sales capacity at stores can be a limiting factor in selling bottled water fast during crises (Schätter et al., 2019).

Given these constraints, both retailers and public authorities aim to satisfy as much demand as possible. Retailers have economic incentives to sell more goods than originally supplied (Schätter et al., 2019) and additionally, a successful crisis response underlines the retailers' general expertise and competency to the public (as in the case of Wal-mart, Horwitz (2009)). For public authorities, greater demand satisfaction means better public crisis management. Beyond this, public authorities need to satisfy demand without disadvantaging any customer group and therefore, a distribution of the available resources among stores which is balanced in the sense of Constraints C.9 and C.10 is desirable (Xu et al., 2023). Similarly, retailers are likely to aim to treat their stores in a balanced way due to contractual relationships. Uncertainty regarding crisis extent and duration can lead stores to order more than they actually need. Hence, retailers need to take countermeasures to balance unmet demand across stores.

Under these circumstances, decision-makers need to quickly decide how much of the bottled water in the system of the retailers they send to every store in the crisis region. Under time pressure, private and public decision-makers are likely to apply the *push/pull* principle described in Swanson and Smith (2013) and Kovács and Spens (2007). First, one pushes supply into the crisis region with vague demand information. At the same time, the situation is assessed further once more information is available.

In our setting, we concentrate on the *push* part of this concept for the immediate assessment of demand for the remaining opening hours. Therefore, we simplify demand dynamics by equally distributing remaining demand among all remaining opening hours. A stores' remaining demand is calculated by deducting the stores' inventory level at the crisis time from the total demand over the remaining opening hours, rounded to full pallet loads.

In order to re-route tours, every truck's position needs to be determined. If a truck is *unloading* at the time of the assessment, the truck finishes unloading first and is available for re-routing with the remaining load. Its starting position is the store and the earliest departure time is when unloading is finished. If a truck is *on the road*, retailers' ability to collect, analyze and leverage real-time data make the truck immediately available for re-routing with its current load and starting from its current position. In the case study, the route and position of a truck are modeled using the HERE API.

Trucks carrying safety stock from warehouses do, other than in non-crisis times, not carry other beverages and can therefore be fully loaded with bottled water. They have a capacity of 16 pallets. It takes 60 minutes until these trucks are operationally ready to depart from their warehouse, as they need to be provided and loaded first. We assume that trucks and drivers transporting safety stock from warehouses are unlimited.

C.4.2 Setup and performance measures

We modeled three responses to the crisis: retailers send warehouse safety stock with additional trucks (scenario A), retailers re-route individually (scenario B) and public-private collaborative re-routing (scenario C). The scenarios were implemented in Python and the re-routing scenarios B and C were solved using Gurobi 9.5.2 on a 1.80 GHz Intel (16 GB RAM). We conducted 10 runs in total, each with randomly generated departure times, built the respective newly planned tours and interpreted the results. For every run, we modeled scenarios A, B and C. In order to simulate a near real-time application of our re-routing approach for fluctuating problem sizes, we defined 30 min and a MIP gap of 2% as stop criteria for the optimization in scenarios B and C.

In different settings, we vary timing and extent of the crisis. Crisis response is executed at 10:00 (when morning tours are on the road), 12:00 (when morning tours are nearly finished and afternoon have not yet started) and 14:00 (when morning tours are finished and afternoon tours have started). Demand increases by 300%, 600% and 900% and indicates units sold per time period and target supply. In scenarios B and C, the radius from which trucks are re-routed is set to 20 km, 30 km and 40 km. In non-crisis tours, the maximum number of stores on a tour is three. In crisis times, trucks can carry more load. Therefore, we relax this constraint by setting $N = 4$ in Constraints C.5. In practice, the maximum tour length should be determined (collaboratively) in the preparedness phase.

We introduce three performance measures to evaluate different crisis responses: service level, number of additional trucks and driving distance.

Service level: For every store, the service level is measured as the share of remaining time periods before store closure in which customers can fully fulfill their demand for bottled water. It is tracked across all stores and retailers and can be used as an indicator of how well the absence of tap water and the resulting increase in demand for bottled water can be absorbed by the retailing system. The better the system absorbs the demand, the less likely panic-driven behavior among the population will become. This is especially interesting from a public authority perspective.

Number of additional trucks: The number of additional trucks needed to transport safety stock from warehouses into the crisis region serves as the main indicator for efficiency.

Distance: Re-routing affects tours and thus the distance traveled in different ways, which makes the comparison of the total distance in the network hard to interpret: some tours are disrupted and hence altered, while others are added and hence completely new. Therefore, we evaluate the efficiency by measuring only the distance of tours which are part of the re-routing. This includes re-routed tours starting from their position at the time of the crisis and ending at their original warehouse, and additional tours starting and ending at their warehouse.

Both commercial and public decision-makers are likely to consider the service level as the most important performance measure to evaluate crisis response. In addition, we argue that the number of additional trucks are critical resources, followed by the distance travelled. Since the proposed crisis response would be executed on very rare occasions, we argue that the number of trucks is more crucial for the concept's success than the distance travelled on one specific day.

The question arises of when an improvement in service level pays off and is worth the effort of re-routing and establishing a collaboration. This question might be answered very differently by both actors. In commercial contexts, it is common practice to design supply chains in a way that represents an economic trade-off between profit and offered service. Consequently, service levels below 100% are acceptable for retailers – even more in abnormal times. On the other hand, public authorities' primary objective is to supply the whole population to minimize deprivation cost, while logistic cost is only a secondary objective. Therefore, public authorities should keep in mind that they value service level improvements higher than companies which may well require compensation payments as an incentive.

C.4.3 Results

As a starting point, Table C.3 shows the effect of retailers not taking any countermeasure. All store inventory is used to satisfy the increase in demand, but no more units are sourced from warehouse or stock on the road. In this case, the number of trucks used and travelled distances remain unchanged, but the service level drops sharply for every retailer. No retailer performs significantly better than others in the crisis region. The low service level indicates that many people cannot buy (enough) bottled water to satisfy their urgent demand. A direct consequence are lost sales, as people need to turn to other retailers' stores, but also negative reputation of the retailer and riots at stores can harm the retailers' business. Hence, retailers need to take countermeasures.

Time of the crisis	Demand increase [%]	No response [Service level in %]	Scenario A [Service level in %]
10:00	300	33.39	88.12
	600	18.45	65.64
	900	12.36	56.22
12:00	300	38.60	87.92
	600	21.70	68.21
	900	13.87	54.34
14:00	300	43.14	86.43
	600	22.30	68.85
	900	14.25	52.86

Table C.3: Impact on service level if retailers do not respond to the demand increase or send additional trucks (scenario A)

Scenario A: Companies ship warehouse safety stock into the crisis region

One often observed response by retailers is to send safety stock with additional trucks to the affected stores (Heidelberg24, 2019; LZ.de, 2016; Horwitz, 2009). We use this as a reference scenario for the proposed re-routing approach. Retailers do not re-route trucks and do not collaborate.

Every retailer tries to satisfy demand in the crisis region by using safety stock from the nearest warehouse. Only direct tours from warehouse to store are possible and every tour delivers to exactly one store, to keep the response time short. If a store's estimated demand exceeds the capacity of one truck, additional trucks are used.

For every warehouse from which safety stock is sent into the crisis region, stores are prioritized by their distance to the warehouse. Stores which are closest to the warehouse are assigned first. In this sequence, complete store demands are loaded on separate trucks. If safety stock from the nearest warehouse is not sufficient, safety stock from the remaining warehouses in order of ascending distance to the crisis region is used until demand is met or all warehouses' safety stocks are run out.

Table C.3 shows how scenario A can lift service levels significantly. However, despite the resource-intensive direct transports between warehouses and stores (note that scenario A is designed to use up to 21 additional trucks), stores run out of inventory as they have to bridge the loading, driving and unloading time of trucks. Hence, if every retailer has sufficient safety stock to satisfy demand (e.g., demand increase of 300%), delivery speed causes that the service level cannot be fully recovered to 100%. If demand increase is even higher and it cannot be fully satisfied by retailers' warehouse safety stock, stores are without inventory again before closure time.

Scenario B: Companies re-route individually

In Scenario B, every retailer performs the re-routing approach presented in Section C.3 for its own stores using its own trucks and warehouse safety stock. Retailers do not collaborate.

In all settings at 10:00, re-routing individually achieves a better service level than sending additional trucks (see Table C.4). This is due to faster supplies and increased amount of bottled water in the retailers' system. Re-routing individually can reduce the number of additional trucks considerably compared to scenario A. The greater the radius from which trucks are considered to be re-routed, the more trucks are re-routed and the less additional trucks are needed.

The only setting in which scenario A exceeds individual re-routing's service level (87.92% vs. 86.01%) is when the crisis happens at 12:00 and demand increases by 300%. This is because in average only slightly more than two trucks are on the road within a radius of 40 km and are possible to be re-routed. In addition, the benefit of sharing warehouse safety stock does not yet prevail. Hence, the re-routing approach mainly consists of tours starting from warehouses.

		Radius					
		20		30		40	
	Nr trucks in range	30.2		44		58.1	
Demand	Scenario	**B**	**C**	**B**	**C**	**B**	**C**
300	Service level [%]	96.85	97.86	97.62	97.93	97.71	97.93
	Nr. additional trucks	4.5	1.5	3.5	0	1	0
	Nr. re-routed tours	25.1	29.6	27.6	32.6	33.4	32.6
	Total supply [pallets]	200.5	197.2	200.9	200.1	202.5	200.1
	Distance [km]	2,358.39	2,512.83	2,493.87	2,692.71	2,871.61	2,692.71
600	Service level [%]	89.41	94.52	91.74	94.88	93.91	94.93
	Nr. additional trucks	11.2	11.8	8.8	6.1	6.9	1.4
	Nr. re-routed tours	28.2	30.2	37.2	44	45.5	57.1
	Total supply [pallets]	310.4	350.9	324.5	350.9	350.2	351.7
	Distance [km]	3,619.86	3,869.03	4,303.8	4,617.22	4,928.46	5,569.6
900	Service level [%]	73.9	91.69	76.76	93.07	84.17	93.31
	Nr. additional trucks	15.4	24.4	12.5	17.3	10.3	12.2
	Nr. re-routed tours	29.2	30.2	39.3	44	53.4	58.1
	Total supply [pallets]	380.5	511.5	394	511.5	432.1	511.5
	Distance [km]	4,286.11	6,610.07	4,940.27	6,455.89	6,283.22	7,073.67

Table C.4: Results for crisis time 10:00 from ten simulation runs

Scenario C: Companies and public authorities re-route collaboratively

In Scenario C, retailers and public authorities collaborate by sharing information and resources (Scholten and Schilder, 2015) and apply the re-routing approach as follows. To enable the collaboration, public authorities on state level lift competition law. Public authorities manage the transports.

Real-time information-sharing is done in several ways: retailers share their information regarding demand, warehouse and store locations, safety stocks and truck loads as well as truck positions with public authorities. It has to be highlighted that retailers do not share information with competitors. In public-private collaboration, especially demand assessment is where companies can contribute to public crisis management through their experience in market dynamics and demand patterns (Diehlmann, 2022). This is underlined by Swanson and Smith (2013), who surveyed logistics professionals and found that *push/pull* (see Section C.4.1.2) was among other supply chain concepts considered the most appropriate one to be transferred from commercial into public relief supply chain management.

Moreover, retailers jointly use several resources. Resource-sharing includes first the joint pooling of bottled-water. For re-routing, the nearest trucks on the road are chosen across retailers. If the combined truck load is not sufficient to meet demand across retailers, safety stock is retrieved from the nearest warehouse, regardless of the retailer. Additionally, the collaboration allows using one retailer's trucks and goods to supply them to another retailer's store, and to sell them.

Consequently, collaborative re-routing includes joint vehicle selection and joint route planning, which comes along with joint prioritization of stores (Constraints C.9 and C.10). If not all stores can be a first stop on any tour, stores for which this applies are randomly selected across retailers.

The results for the crisis time at 10:00 (Table C.4) show that collaborative re-routing (scenario C) achieves a greater service level than individual re-routing (scenario B) and sending warehouse stock (scenario A) in every demand and radius setting. This also accounts for settings in which demand is manageable by all retailers, i.e., every retailer has enough bottled-water to meet its own demand. For these cases, collaborative re-routing even requires fewer additional warehouse tours.

With increasing demand and if at least one retailer cannot fully meet its demand by itself, the joint access to other retailers' trucks and warehouse safety stock contributes to even greater benefits of collaborative re-routing. Accordingly, re-routing trucks from a wider range further increases total supply and service level, which makes the collaborative re-routing scalable for greater demand increases than scenarios A and B.

Moreover, we can observe in several settings in which trucks on the road carry sufficient load to satisfy demand that collaborative re-routing requires less re-routed trucks than individual re-routing to achieve the same service level. Thereby, collaboration reduces the resulting supply gaps outside the crisis area. Furthermore, note that there is no obvious link between distance, service level and supply within one demand scenario. Sometimes, distance and supply increase through collaboration, and sometimes distances increases while supply decreases. One reason is that distance calculation includes trucks returning to their original warehouse.

At all three modeled crisis times, collaborative re-routing achieves a higher service level than individual re-routing. However, at 12:00, overall responsiveness is lowest across all modeled times. For a demand increase of 300%, the service level in scenario C is below the reference scenario A, though higher than individual re-routing. At 12:00, the lowest service levels can be achieved because very few trucks are available for re-routing. This is also reflected in scenarios of greater demand increase, in which results from 10:00 show much sharper increases in service level through collaboration.

If the crisis happens at 14:00, the remaining demand is consequently lower than as if the crisis strikes at 10:00 and 12:00. This means fewer additional tours across all settings, since more often on-road stock is sufficient to meet demand. Even in case of a demand increase of 900%, collaborative re-routing needs no additional tours (using the largest radius) to achieve a service level of 87.94%. Therefore, despite the fast supply using only re-routed trucks, the unmet demand immediately after the crisis leaves comparably little room for improving the service level. Hence, for large demand increase, the earlier the crisis happens and the re-routing decision is made, the greater the potential of a higher service level through collaborative re-routing.

Additionally, retailers benefit differently from collaborative re-routing. In general, Retailer 1 has most trucks on the road and compared to Retailer 2, Retailer 1 operates even less stores in the crisis region (Table C.2). Consequently, when re-routing collaboratively, Retailer 1 is the retailer which most often faces a lower service level across its stores compared to re-routing individually. Retailer 2 barely faces a worse service level from collaboration. Due to the fact that Retailer 3 operates only one remote warehouse and thus drives longer tours, Retailer 3 operates most trucks around the crisis area at 12:00 (Figure C.3). Consequently, Retailer 3 performs well in re-routing individually at this time of the day and therefore especially suffers from a lower service level in collaborative re-routing.

For both Retailer 1 and Retailer 3, we observe in several settings two different effects when they contribute with their trucks on the road. An increasing radius can cause that the retailer with the highest probability to suffer from a worse service level either increases even further or decreases this probability. Among others, at 14:00 with a demand increase of 300%, service levels in scenarios B and C are almost constant with increasing radius. Increasing the radius in this case can be a measure to reduce the burden on Retailer 1: For a radius of 20 km, the retailer faces a lower service level in eight out of ten runs – for a radius of 40 km, only in five out of ten. However, such a measure needs to be carefully evaluated as it depends on the trucks' positions on the road and the retailer's own performance in re-routing. At 14:00 and with a demand increase of 900%, the opposite effect is the case: with increasing radius, the probability increases that Retailer 1 would be better off from re-routing individually.

On the one hand, Retailer 2 is the one which benefits most often from collaborative re-routing. On the other hand, in line with more urban stores, Retailer 2 operates the nearest warehouse to the crisis region. Hence, in collaborative re-routing with high demand increase, this warehouse's safety stock and the retailer's additional trucks are used first.

In summary, collaborative re-routing always achieves a higher service level than individual re-routing. However, at 12:00, when very few trucks are on the road, the reference scenario achieves a higher service level than collaborative re-routing, though with using more additional trucks. In addition, distribution network structures and tour schedules cause that retailers contribute and benefit differently at the different times of the day.

C.5 Discussion

The proposed re-routing approach is based on exchange with public and private practitioners who confirm the feasibility of re-routing and consider it a worthwhile immediate crisis response to demand increase. Our results support decision-makers from public authorities and companies in assessing re-routing's most suitable preconditions and operational strategies. The presented collaborative re-routing adds a real-time based supply chain concept to the research streams of PPEC and extreme supply chain management. Moreover, showing the varying performance of a relief logistics concept with regards to the time of the day when the crisis strikes, is novel, to the best of our knowledge.

C.5.1 Implications for public authorities

To steer collaborative re-routing in the most effective and efficient way, it is indispensable for public authorities to design a collaboration in non-crisis times in which they gain transparency about real-time dynamics in retail distribution networks. Due to their responsibility for population supply, public authorities are the ones who should build up and maintain such collaboration in preparation for crises. Public authorities should initially involve large retailers with many points of sales, trucks and larger safety stocks and which are likely to possess a more sophisticated (real-time) data infrastructure. This is beneficial since, as highlighted in discussions with food supply chain professionals, it is (yet) time-consuming to collect and analyze real-time data and to inform truck drivers.

However, this is expected to accelerate with rising supply chain digitization and transparency and enhanced use of real-time data in supply chains. Among others, this is supported by the fact that applications of track-and-trace systems are becoming more affordable and common in commercial supply chain management (Sodhi and Tang, 2020; Dahl and Derigs, 2011). Moreover, public authorities even have the opportunity to impose the use of track and trace systems in supply chains. Examples are obligations for ocean carriers to electronically share shipment data like arrival date and bills-of-loading with United States' customs agency (Prieto, 2006) and for companies in international agri-food supply chains to have traceability systems in place, as required by the European Union in response to incidents which compromised public health (Hallak and Tacsir, 2022). Hence, existing technological, organizational and legal starting points can support the application of traceability systems for public-private re-routing of commercial transports in crisis situations.

Beyond the provision of transparency, IT infrastructure needs to be prepared to sell other retailers' goods. In addition, public-private emergency plans should be developed which prepare for a fast provision of retailers' warehouses with additional trucks and drivers. Thereby, overall crisis response can be improved if demand increases sharply.

Re-routing commercial transports can be a promising measure for public authorities to enable supply until large-scale public emergency supply becomes active. Our results show that the effort for implementing a collaboration including lifted competition restrictions pays off most in case of a very sharp demand increase (900%). If demand increases by 300%, the benefit compared to individual re-routing is lower. Furthermore, the earlier the crisis happens and public authorities coordinate re-routing, the higher the leverage to recover continuous supply in the remaining store opening time. Nevertheless, when integrating re-routing into their crisis management, public authorities need to be aware of time dynamics. Supply quantity, need for transportation resources, demand satisfaction and retailers' contributions and compensation claims can vary significantly. Especially, time windows with few trucks around a crisis region jeopardize sufficient store supply. As a consequence, when public authorities assess the severity of a crisis and plan a set of countermeasures, they need to incorporate time dynamics for applying re-routing. Considering these time dynamics, public authorities might also pick only the most suitable retailers, i.e., retailers with many trucks around the crisis area at the time of crisis and with many stores, for collaboration.

The more trucks are on the road around a city, the more effective is re-routing for immediate crisis response. Consequently, public authorities can strategically shape transportation flows of essential goods. Positions of warehouses and logistics clusters (Chopra et al., 2021; Sheffi, 2012) of food retailers can enhance benefits of (public-private) re-routing in surrounding areas. Public authorities can support and reward such location selections in accordance with public crisis management. Thereby, re-routing can particularly be prepared for remote areas to which supplying public emergency stocks is more time-consuming. In such cases, continuous food transports complement costly public emergency stocks.

C.5.2 Implications for companies

In line with recent years' disruptions in transportation networks, food retail supply chain professionals highlighted the increasing value of flexibility in transportation. In order to achieve greater flexibility, re-routing in general would be a worthwhile option to cope with congestion or to increase efficiency by skipping a logistics network's handling stage. Consequently, companies can consider the proposed re-routing approach as one way to increase their distribution networks' flexibility. If companies want to consider real-time re-routing as a permanent and frequent option, our results indicate that retailers might want to align their tour schedule accordingly.

Companies can see re-routing in crises as a new business opportunity. Public authorities stated in personal discussions that they aim to involve the private sector more in emergency food supply, and past crises have revealed how retailers might strengthen the immediate response phase in public crisis management (Horwitz, 2009). As our results show, retailers with longer response times can be supported by competitors and benefit from collaboration through increased sales. Hence, in non-crisis times, companies could agree with public authorities on offering their service of re-routing into crisis regions and thereby complement public crisis management. If companies put collaborative re-routing into practice, they need to negotiate compensation schemes with public authorities already in non-crisis times. Given the uncertainties in demand increase and time of the crisis, compensation schemes need to provide enough incentive for companies to re-route collaboratively at any time of a day. This especially includes settings in which a company operates relatively more trucks than competitors, which causes that the own performance is worse than from re-routing individually. Hence, our approach can serve as a basis for running stress tests with the goal to develop appropriately tailored compensation schemes.

Furthermore, the proposed re-routing concept provides an additional option with which companies can strengthen their organizational and operational agility in the face of extreme events. The COVID-19 pandemic, for example, demonstrated how commercial structures can be transformed into flexible emergency supplies in a crisis. During COVID-19, this was most observable for production conversions (Müller et al., 2022). Our approach shows another way to transfer agility to an industry-wide logistics network. Since re-routing is likely to be an innovative concept for both companies and public authorities, retailers can try to actively shape public crisis management with regards to re-routing. As a consequence, companies can benefit from e.g., loosened competition law in favour of companies' business continuity and subsidies for warehouse location decision. Moreover, companies can jointly with public authorities develop the data-sharing infrastructure necessary for collaborative re-routing. To this end, companies might be able to (1) share data immediately in case of a crisis and (2) to share just enough data about warehouse and store locations, safety stock and trucks on the road to be meaningful for public authorities. Exemplary granularity includes number of stores in the affected area and number of trucks, their position, earliest departure time and load with the required goods.

Additionally, positive publicity from successful crisis management can improve companies' reputation. The case of Wal-Mart's fast response to Hurricane Katrina and its intensive public discussion afterwards underlines this (Horwitz, 2009; Prieto, 2006). Hence, companies should aim for communication of their collaboration together with public authorities.

C.5.3 Limitations and future research

Our study comes with limitations originating from the case study on which we apply the re-routing approach. In scope are two supermarket chains and one discounter operating in one German state and re-routing into one city. As Seidel et al. (2016) show for the case of Germany and France, the share of discounters and supermarket chains, density of point of sales and population and distribution of logistics areas differ significantly between both countries. Our results show that all these factors determine the performance of re-routing. Hence, future research should better understand the impact of different distribution network structures on re-routing.

Moreover, our study does not answer the question of how public authorities should design compensation schemes. Public authorities face the challenge to develop compensation mechanisms prior to crises, which are flexible enough to motivate companies to collaborate in numerous different settings (e.g., geographical scope, time of the day) and to supply as many essential goods as fast as possible. One option is to compensate more with increasing service level. However, public authorities must not overcompensate companies and use funds efficiently. So, collaboration might also be designed in a way that companies first use their trucks in range to supply their own stores, and contribute remaining trucks to the collaboration (Hernández et al., 2011). This would reduce companies' disadvantages in service level. Hence, one path for research is how public authorities can, under limited knowledge of companies' operations and cost structure, compensate company effort caused by trucks, drivers, distance traveled as well as supply shortages in stores outside the crisis region.

Future research should also investigate how, in different geographical settings, minimization of total distance to supply stores performs compared to other objective functions. In urban areas with short distances between points of sales, including stop time in the objective function (similarly to last-mile delivery as in Breitbarth et al. (2021)) might lead to better performance than in rural areas. Crisis-caused traffic disruptions might also be less of a concern in rural areas than in urban areas.

Finally, including non-affected stores and their demand in the re-routing decision can balance resulting supply gaps more equally among non-affected stores. Paths for future research are identification of the circumstances under which companies would amplify their planning scope as well as corresponding extensions of the re-routing approach including algorithms which can deal with even greater problem complexity.

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D Protecting vulnerable people during pandemics through home delivery of essential supplies: a distribution logistics model

Abstract

Purpose — This paper studies a concept for protecting vulnerable population groups during pandemics using direct home deliveries of essential supplies, from a distribution logistics perspective. The purpose of this paper is to evaluate feasible and resource-efficient home delivery strategies, including collaboration between retailers and logistics service providers based on a practical application.
Design/methodology/approach — A food home delivery concept in urban areas during pandemics is mathematically modeled. All seniors living in a district of Berlin, Germany, represent the vulnerable population supplied by a grocery distribution center. A capacitated vehicle routing problem (CVRP) is developed in combination with a k-means clustering algorithm. To manage this large-scale problem efficiently, mixed-integer programming (MIP) is used. The impact of collaboration and additional delivery scenarios is examined with a sensitivity analysis.
Findings — Roughly 45 medically vulnerable persons can be served by one delivery vehicle in the baseline scenario. Operational measures allow a drastic decrease in required resources by reducing service quality. In this way, home delivery for the vulnerable population of Berlin can be achieved. This requires collaboration between grocery and parcel services and public authorities as well as overcoming accompanying challenges.
Originality/value — Developing a home delivery concept for providing essential goods to urban vulnerable groups during pandemics creates a special value. Setting a large-scale CVRP with variable fleet size in combination with a clustering algorithm contributes to the originality.

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D.1 Introduction

D.1.1 Pandemics as a global disaster scenario

Pandemics and epidemics are far-reaching threat scenarios that are increasing in frequency (Nandy and Basak, 2017). The resulting crises can have serious consequences, especially from a medical, social and economic perspective, as demonstrated by the COVID-19 pandemic in 2020.

In pandemics, measures such as reducing social interaction and self-isolating aim to contain the disease and soften negative impacts of the crisis. Since grocery stores are places of close personal contact, they can cause infections. If public isolation recommendations are followed, visits should be limited (Ekici et al., 2013; Haug et al., 2007). However, the population's supply of essential goods, especially food, must be maintained at all times. In case commercial supply chains are not able to ensure smooth distribution, public authorities must intervene as part of their general duties. The long-term nature of pandemics requires a stable food supply for several weeks or months. In this way, pandemics differ from other disasters such as earthquakes that require an immediate supply of relief goods with short response times and durations (Ekici et al., 2013; Maghfiroh and Hanaoka, 2018; Toth and Vigo, 2014). Preparatory planning of a coordinated humanitarian supply chain can lead to greater efficiency and save human lives (Balcik and Beamon, 2008).

Especially vulnerable groups should limit social interactions to avoid the high risk of an infection's adverse effects. A general definition of "vulnerable groups" with regard to pandemics does not exist and should be determined on a case-by-case basis (Vaughan and Tinker, 2009). Generally, vulnerable groups are subdivided based on medical, social and economic vulnerability (Brimmer et al., 2020). From an economic perspective, entrepreneurs and employees are financially affected by shutdowns or reduced demand. Workers without formal working contracts are economically vulnerable due to the lack of furlough schemes, for instance. Social vulnerability refers to people with a high likelihood of infection due to the high rate of interpersonal contact in their living and/or working conditions (e.g. urban dwellers). Medically vulnerable population groups are very susceptible to the severe consequences of infection. Studies during the COVID-19 pandemic have shown that an individual's age and underlying health conditions affect the progression of the disease (Jordan et al., 2020; Yang et al., 2020). COVID-19 cases in Germany have shown that 86% of the deceased are over the age of 69 with median age of 82 years. In contrast, the median age of infected individuals is only 40 years old (Robert Koch Institute (2021), as of 2021-01-19). Therefore, the urban population above 69 years old is very vulnerable from a social and medical perspective. Since the food supply is essential, solutions must be developed to circumvent supermarkets as a potential source of infection for vulnerable populations. In the future, other pandemics or epidemics may reveal different vulnerable population groups.

D.1.2 Food distribution logistics for vulnerable groups

Nowadays, home delivery is an established concept for food distribution in primarily urban areas and provides an option to avoid contacts during grocery shopping. As a reaction to the COVID-19 pandemic, several grocery delivery concepts evolved to offer special protection to the vulnerable population. Some of the existing services assigned a high priority to orders of differently defined vulnerable groups. The Swiss company Farmy reserved delivery time slots for people with the verified status of medical vulnerability (Farmy, 2020). Another initiative by Mat.se, a Swedish food e-commerce company, provided pre-picked weekly food packages for vulnerable persons in the urban areas of Stockholm and Gothenburg. Due to capacity restrictions, they were only able to serve around 500 persons per week (Gunnilstam, 2020).

A first collaborative approach across companies without public authorities was established by the German food retailer Rewe and the parcel service DHL. Within the district Heinsberg with large numbers of affected people, the delivery concept regularly supplied around 37,000 households with uncooled essentials from supermarkets (Klasen, 2020). In the United Kingdom, a large-scale delivery concept was established between the government, retail companies and groups of registered inhabitants who are "clinically extremely vulnerable" and do not have personal contact to people serving them with essentials (Department for Environment, Food and Rural Affairs, 2020). The government identified all adults aged over 69 and those with previous illness as high risk, which included around 25% of the population (Jordan et al., 2020). Eligible persons were provided with a weekly parcel consisting of dry essential supplies.

These delivery concepts stress the practical relevance of home delivery for vulnerable groups during pandemics. However, while the small-scale delivery concepts in Switzerland and Sweden supplied both fresh and dry goods, the large-scale applications only offered dry goods. This brings up the question of resource requirements and operational limitations for a large-scale home delivery concept of fresh and dry goods. The purpose of this paper is to investigate the feasibility of home deliveries for an urban vulnerable population during pandemics with a collaborative delivery concept. Based on a mathematical model, we quantify the required transportation capacities. For a developed case study of a large-scale urban area and dry as well as fresh goods, we investigate resource-efficient alternatives to the regular brick-and-mortar point of sale during pandemics.

D.2 Theoretical background

D.2.1 Logistics in pandemics

Transport logistics is essential for a resilient food supply (Dasaklis et al., 2012). Huff et al. (2015) highlight that transports along the food supply chain are crucial due to long transport distances and small inventories. While food reaches the population via multiple channels, the traditional distribution via grocery stores is currently paramount. In Germany's case, online grocery in combination with home deliveries accounts for less than 2% of total grocery revenues (HDE, 2020). However, home delivery is a logistics solution, which reduces social interactions and is therefore suitable for pandemic conditions (Ekici et al., 2013; Haug et al., 2007).

Disturbances in the logistics chain can threaten supply (Dalton, 2006). Last-mile relief logistics is the final stage in relief supply chains and aims to distribute goods to affected people (Balcik et al., 2008). Balcik et al. (2008) as well as Maghfiroh and Hanaoka (2018) stress the relevance of limited transport resources for emergency supplies in last-mile logistics.

In a related study on food supply during pandemics, Ekici et al. (2013) assume a mixed supply of the population, with points of distribution (PoD) within walking distance and home delivery. The authors dynamically model the spread of a disease and solve a facility location problem to minimize the travel distance of the population. By doing so, the authors focus on the question of facility location and resource allocation, and not on the required fleet size for home delivery.

The task of determining the required fleet size can be modeled as a vehicle routing problem (VRP) (Kim et al., 2015; Renaud and Boctor, 2002), which is a well-established optimization model in literature, with many variations (Gansterer and Hartl, 2018).

VRPs can be motivated by different commercial or humanitarian objectives (Holguín-Veras et al., 2012). de la Torre et al. (2012) classify relief routing based on the objectives of cost minimization, unsatisfied demand, latest arrival, total response time and travel reliability and provide a broad overview of further VRP literature in relief logistics. While the humanitarian context requires minimizing the population's suffering, commercial settings often aim for minimal costs (Holguín-Veras et al., 2012; Toth and Vigo, 2014). In a pandemic, however, not only the immediate response but also the efficient resource utilization is crucial to cope with the longevity of such a crisis. For example, with their minimization of the total time needed to serve all customers, Wang et al. (2018) show that results differ from those that have a cost focus in routing problems.

In order to identify the required number of vehicles, fleet size minimization in VRPs can be applied. Generally, minimizing fleet size results in the smallest number of vehicles to satisfy demand while considering case-specific restrictions (Escuín et al., 2012; Figliozzi, 2011). A commercial example is the fleet size minimization of logistics service providers for economic reasons (Kim et al., 2015). When transporting food, products with different temperature requirements make distribution more complex and require different delivery vehicle types (Kuo and Chen, 2010; Renaud and Boctor, 2002). The fleet size and mix vehicle routing problem (FSMVRP) determines the required fleet size and plans the routes for different types of vehicles. Due to accessibility issues, this is a common problem in crisis situations when vehicles of different owners are used jointly (Maghfiroh and Hanaoka, 2018). Fleet size minimization can be integrated in the objective function of a VRP by minimizing total costs consisting of vehicle fixed costs and variable transportation costs (Renaud and Boctor, 2002). Another approach by Balseiro et al. (2011) optimizes the fleet size with an objective function minimizing the number of vehicles and total travel time. In Figliozzi (2011), the VRP first minimizes the number of required vehicles, and then the distance-dependent travel costs. All of the variants require vehicles with capacities and are therefore related to the capacitated vehicle routing problem (CVRP), introduced by Dantzig and Ramser (1959). Besides the use of CVRPs in operational contexts, it is also applicable for a wide range of tactical or strategic investigations, for example, determination of resource use (vehicle fleet or drivers) and network planning (Toth and Vigo, 2014). A broad overview of the variety of CVRPs was provided by Toth and Vigo (2002).

Two studies particularly relate to our research within the literature on VRPs during pandemics. Herrmann et al. (2009) model medical distribution during a pandemic with a single-commodity time-minimizing VRP and a fixed number of vehicles. However, the model distributes to PoDs and not households, which means fewer destinations and higher transport consolidation. Shen et al. (2009) minimize the unmet demand and assume a fixed number of capacitated vehicles. Hence, both studies model distribution logistics in pandemics without addressing variable fleet sizes.

The complexity of urban last-mile relief logistics leads to large-scale problems (Barzinpour and Esmaeili, 2014). Large amounts of demand points, representing, for example, households, make such VRPs complex to solve. Therefore, the development of suitable solution techniques plays a major role in reducing computation time (Arnold et al., 2019).

Resources for transportation, for example, vehicles, are usually in operation by numerous different owners, business as well as public authorities or NGOs. Collaboration between owners can increase the available logistics capacities, provide access to logistical resources and increase the provided service level. In relief logistics, collaboration between multiple actors like private or humanitarian organizations is often investigated (Gansterer and Hartl, 2018; Nurmala et al., 2018; Tomasini and Van Wassenhove, 2009). In crises, emergency legislation can allow public disaster agencies to access commercial information and to control commercial resources, for example, coordinating commercial transports (centralized collaborative planning) (Gansterer and Hartl, 2018; Wiens et al., 2018). Potentially differentiating objectives between public and private actors might complicate such a joint supply. Therefore, the concept of a public-private emergency collaboration (PPEC) can mitigate conflicting objectives between public and private actors by providing incentives for both parties (Wiens et al., 2018).

To conclude, we contribute to the existing literature by applying a CVRP with variable fleet size for a large-scale urban home delivery with food during pandemics. To our knowledge, these areas of research have not yet been combined.

D.2.2 Solution techniques for a large-scale CVRP

Existing VRPs differ in terms of variables, objective function, restrictions and suitable calculation approach selection and implementation. In most cases, the VRP can be solved by methods of linear programming. Since the problem formulation does not only deal with binary decision variables and values, it can be characterized as a mixed-integer linear program (MILP).

The literature distinguishes between exact and heuristic solution approaches (Laporte, 1992; Toth and Vigo, 2002). A literature consensus apparently exists about the solvability of VRPs, which belongs to the category of NP-complete problems. Toth and Vigo (2014) prove that exact algorithms are able to solve CVRPs with 100, and, in some cases, up to 200 customers. This outcome is verified by Pecin et al. (2017) as well as by Borcinova (2017). Further improvements in terms of algorithms, software and hardware can increase the number of customers. A comparison of exact CVRP approaches with its performance in practical applications by Toth and Vigo (2014) demonstrates that algorithms based on branch-and-cut can be regarded as the most efficient method for large-scale CVRP. Nevertheless, exact solutions can claim a high computing effort of several days (Pecin et al., 2017).

To achieve results for such large-scale problems in a reasonable time, a variety of heuristics and metaheuristics, for example, tabu search, simulated annealing or genetic algorithms, can be used (Cordeau et al., 2002; Laporte, 1992; Liong et al., 2008).

The application of different heuristic approaches to benchmark data sets has shown that, currently, heuristics are able to find a good solution for CVRPs with up to 500 customers (Laporte et al., 2014).

Another solution technique of the CVRP is continuous approximation models which replace numerical with analytical methods. This can be beneficial in case of strategic investigations and inaccurate data, but comes with disadvantages for cases where demand is not uniformly distributed and high solution accuracy is desired (Franceschetti et al., 2017; Saberi and Verbas, 2012).

Commercial MIP solvers also work with hybridizations of heuristic and exact optimization methods to combine the advantages of both solution approaches. The results are easily assessed regarding their optimization quality (gap to the optimal solution) (Laporte et al., 2014). Comparisons of different mathematical solvers show that CPLEX and Gurobi achieve the best optimization efficiency for most test instances, with Gurobi holding a small lead for memory usage (Le Bodic and Nemhauser, 2015; Mittelmann, 2018).

If the number of customers is large, the connection of the CVRP with a clustering algorithm, for example, the k-means algorithm, for partitioning areas can be suggested. With this approach, a defined number of smaller CVRP will replace the single large-scale CVRP. With a k-means-algorithm, all demand points are assigned based on the shortest Euclidean distances to a desired number of spatially distributed points in the model area. Within certain iteration steps, the centroids are moved until the sum of all assigned demand points is minimized (Faber, 1994). A two-stage procedure with clustering and CVRP optimization enables problems to be iteratively solvable within an affordable running time. A higher number of clustered regions lowers the final computation time but leads to less accuracy due to the higher probability of suboptimal routings in the overall context (Geetha et al., 2009; He et al., 2009).

D.3 Methodology

D.3.1 Model development

The proposed methodology for generating a feasible and resource-efficient home delivery concept for the vulnerable population is presented in the flow chart in Figure D.1. To adopt the

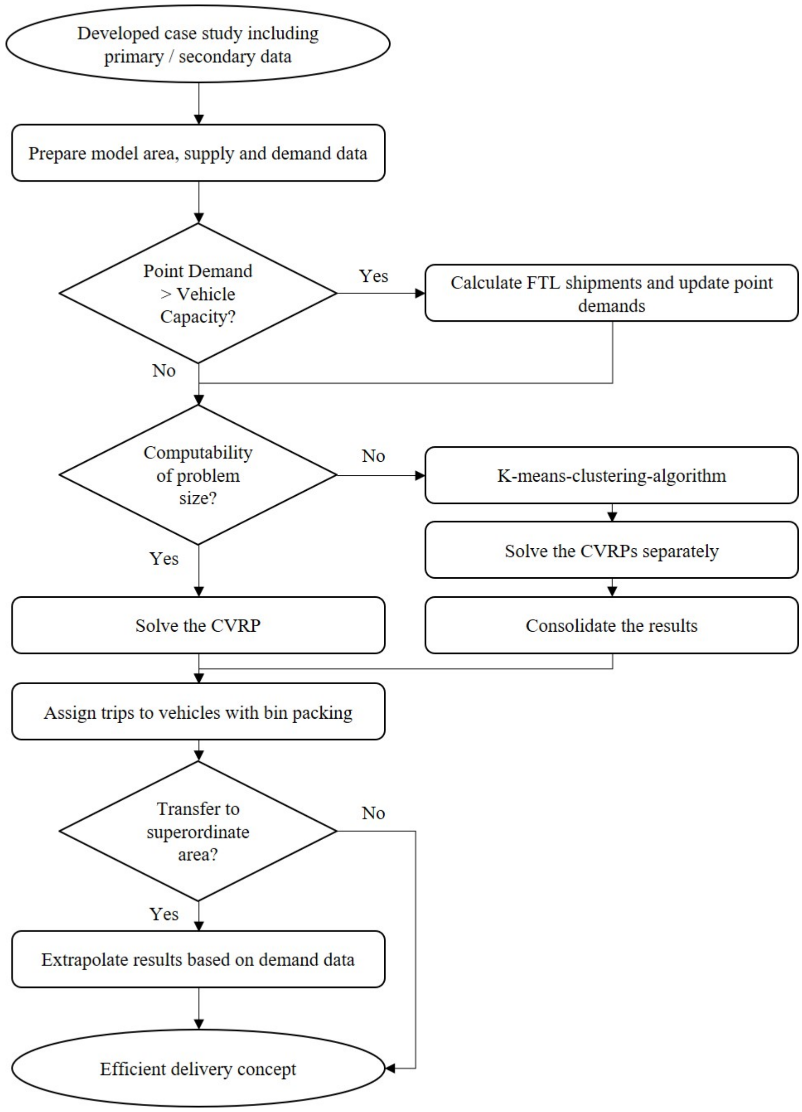

Figure D.1: Proposed solution methodology

specific application characteristics, a CVRP model is built, including suitable preprocessing and postprocessing steps. Since the vehicle fleet is investigated from a tactical perspective, the focus of the calculations lies on the quality of the results, and computation time improvements are not extensively investigated.

If the quantity of defined demand points exceeds the vehicle capacity, the delivery will be divided into multiple shipments with a certain number of full truck load (FTL) shipments and the residual amount as input for the CVRP. This preprocessing step ensures the feasibility of the CVRP regarding the vehicle capacity restriction. In a postprocessing step, bin packing tactically assigns trips to delivery vehicles (Martello and Toth, 1990). In case large-scale application with limited computability is handled, an additional step aims to divide the model area based on a k-means clustering algorithm, as discussed in 2.2. In the case of a spatially limited but representative model area, some applications appear to be predestined for extrapolating results to a larger sector.

D.3.2 Model formulation

We introduce an MIP formulation designed for a calculation with exact algorithms inspired by Borcinova (2017); Laporte (1992); Toth and Vigo (2002).

The defined CVRP is designed to serve demand points from a single origin within a limited time and with multiple capacitated vehicles assigned to numerous routes. In contrast to the basic CVRP, which aims to minimize total costs, our model purpose calculates a route plan that optimizes the total number of delivery vehicles by minimizing the time needed to serve all customers.

The main characteristics of the developed CVRP are listed in Table D.1.

Categories of an CVRP	Characteristics of the designed CVRP
Capacities	Vehicle capacities
Fleet size	Multiple vehicles
Fleet composition	Homogeneous
Route origin	Single depot
Demand type	Known deterministic demand
Demand location	In each destination node
Network type	Non-oriented or oriented
Maximum time per route	Yes
Multiple routes per vehicle	Yes
Implementation of FTL	Yes
Product type	Multiple
Time categories	Loading time, travel time, service time
Cost calculation	None
Objective	Minimize delivery time

Table D.1: Characteristics of the developed CVRP (inspired by Faulin et al. (2011))

The frequently used CVRP formulation of Laporte (1992) is based on a two-index vehicle flow formulation with one single decision variable, which indicates if an arc or edge (i, j) is passed by any vehicle or not. This kind of formulation neglects the assignment of specific routes or vehicles traversing (i, j) and is therefore "generally [...] inadequate for more complex versions of vehicle routing problems" (Toth and Vigo, 2002). To easily include the assignment of vehicles, usually a second binary variable or a three-index vehicle-flow formulation is suggested (Borcinova, 2017; Laporte, 1992).

In the present model, a binary three-index vehicle-flow formulation with the decision variable x_{rij} is defined to indicate if the route r traverses arc (i, j) in an optimal solution. This approach allows a higher degree of flexibility to incorporate additional constraints, like time or capacity restrictions (Borcinova, 2017; Rieck and Zimmermann, 2010). The binary decision variable is defined as follows:

$$x_{rij} \in \{0, 1\} \quad \forall i, j \in \mathcal{N}, i \neq j, \forall r \in \mathcal{R}$$

The mathematical model uses the following value ranges and parameters:

N Set of all nodes, $\in \{0, \ldots, n\}$
D Set of destination points, $\in \{1, \ldots, n\}$
R Set of routes, $\in \{1, \ldots, m\}$
L_r Loading time at the beginning of every route
s_j Service time at node $j, \quad \forall j \in D$
t_{ij} Travel time from node $i$to node$j, \quad \forall i, j \in N, i \neq j$
d_j Demand at node $j, \quad \forall j \in D$
C Capacity of the vehicles
T Time limitation per route

The objective function of the CVRP is formulated as follows:

$$\text{Minimize} \sum_{\mathrm{r}\in\mathcal{R}} L_r + \sum_{\mathrm{r}\in\mathcal{R}} \sum_{i\in\mathcal{N}} \sum_{j\in\mathcal{D}, i\neq j} s_j x_{rij} + \sum_{\mathrm{r}\in\mathcal{R}} \sum_{i\in\mathcal{N}} \sum_{j\in\mathcal{N}, i\neq j} t_{ij} x_{rij} \tag{D.1}$$

Subject to:

$$\sum_{r\in\mathcal{R}} \sum_{i\in\mathcal{N}} x_{rij} = 1, \quad \forall j \in \mathcal{D}, i \neq j, \tag{D.2}$$

$$\sum_{i\in\mathcal{N}} \sum_{j\in\mathcal{D}} d_j x_{rij} \leq C, \quad \forall r \in \mathcal{R}, i \neq j, \tag{D.3}$$

$$L + \sum_{i\in\mathcal{N}} \sum_{j\in\mathcal{D}} s_j x_{rij} + \sum_{i\in\mathcal{N}} \sum_{j\in\mathcal{N}} t_{ij} x_{rij} \leq T, \quad \forall r \in \mathcal{R}, i \neq j, \tag{D.4}$$

$$\sum_{j\in\mathcal{N}} x_{r0j} = 1, \quad \forall r \in \mathcal{R}, \tag{D.5}$$

$$\sum_{i\in\mathcal{N}} x_{rij} = \sum_{i\in\mathcal{N}} x_{rji}, \quad \forall j \in \mathcal{N}, \forall r \in \mathcal{R}, i \neq j, \tag{D.6}$$

$$x_{r00} = 1 \Rightarrow \sum_{i\in\mathcal{N}} \sum_{j\in\mathcal{N}} x_{rij} = 1, \quad \forall r \in \mathcal{R}, \tag{D.7}$$

$$x_{r0j} = 1 \Rightarrow \sum_{j'\in\mathcal{D}} x_{rjj'} = 1, \quad \forall j \in \mathcal{D}, \forall r \in \mathcal{R}, j \neq j, \tag{D.8}$$

With the objective function presented in D.1, the model aims to minimize the total time to serve all destination points j. It consists of the loading time L_r at the depot, which is considered to be constant for every route r, the service time s_j, which depends on the number of households assigned to the routes' destination points; and the travel times t_{ij} of all active $\text{arcs}(i, j)$ in the routing. The so-called degree constraints D.2 impose that each destination is visited in exactly one route. The capacity constraints D.3 ensure that the sum of the assigned demands per route d_j does not exceed the vehicle capacity C. Constraints D.4 represent the time constraints, which ensure that the total time per route (including loading, service and travel times) does not exceed a given time limitation T, for example, the duration of a working day. The flow constraints D.5 guarantee that all routes begin at the origin point $i = 0$. The set of routes is defined with $\mathcal{R}$, which describes a freely chosen limit in the maximum number of routes. Because of the fixed loading time per route, it is beneficial to use as few routes as possible in the time minimization. Constraints D.5 allow the definition of $\mathrm{arc}(0, 0)$ to indicate deactivated routes in the routing plan. The artificial constraints D.7 ensure that no other arcs are assigned if the route is deactivated. With the flow constraints D.6, it is guaranteed that the number of vehicles arriving at every customer and entering the depot is equal to the number of the vehicles leaving that point. Constraints D.8 introduce a calculation simplification and ensure that all active routes consist of at least two destinations.

Equations D.6 – D.8 constitute the so-called sub-tour elimination. This work presents a model with indicator constraints designed for the use in a mathematical optimization solver. Since these constraints represent a significant challenge in VRP and traveling salesman problems, there is a wide range of literature describing different ways to handle the sub-tour elimination (e.g. Desrochers and Laporte (1991) or Pferschy and Stanek (2017)).

Based on the time minimization, this model is suitable for calculating the number and length of required tours and vehicles for home delivery to vulnerable groups during a pandemic. To achieve resource efficiency, other model characteristics like selectable time windows are neglected.

D.4 Case study: vulnerable group delivery in Berlin

D.4.1 Description and data collection

The practical feasibility of our model is analyzed with a case study of the urban area of Berlin, Germany. This area serves as an appropriate modeling exercise, because urban areas incur social vulnerability due to high population density, and medical vulnerability is prevalent since all age groups share neighborhoods. In Berlin, protecting vulnerable groups from infections is a particular concern because hospital beds are relatively scarce (Federal Health Monitoring System, 2020). Additionally, an extensive base of open secondary data is available for Berlin.

D.4.1.1 Population

The data basis for this work builds on the depicted understanding of medically vulnerable groups in section D.1.1 based on pandemics like COVID-19. Because an exact geographic determination of all vulnerable persons is not available, the age of the inhabitants is used as the statistically most evident identification parameter. COVID-19 data from Germany show that protecting all people over 69 years would prevent 85% of fatalities (Robert Koch Institute, 2021). For investigating the effect of an enlarged vulnerable group, this case study also includes the Berlin population over 64 years of age. No open access to data representing the remaining quantity of younger individuals with underlying medical conditions is available, and therefore excluded from this work.

For solving the introduced model, open secondary data are used to derive discrete georeferenced points representing the vulnerable population's demand.

Berlin has a population of around 3.77 million registered inhabitants and a population density of more than 4,000 inhabitants per square kilometer (as of 2019-12-31) (Statistical Office for Berlin-Brandenburg, 2020). Based on public data, Berlin has about 715,000 senior citizens over the age of 64 and 527,000 over the age of 69 (Senate Departement for Urban Development and Housing, 2020). These population groups are the vulnerable groups for the home delivery concept.

The city is divided into 12 boroughs with a population range between 245,000 and 409,000 . The highly different areas of the districts submit to a wide population density range between 1,600 and 13,600 inhabitants per square kilometer. The city administration of Berlin provides an additional subdivision into 447 so-called LOR planning areas with a detailed age distribution of the population, which are created based on uniform building and living structures (Senate Departement for Urban Development and Housing, 2020). The most accurate open population data for Berlin are provided by the Statistical Office for Berlin-Brandenburg (2019), which divides the model region into 14,759 districts, each representing residential blocks and the associated number of inhabitants. In order to define an age distribution for these districts, the data of the 447 LOR areas are interpolated depending on the georeference by assuming the same age structure for all subordinated areas of one LOR area. The geometric center points of the districts are used for the demand representation of the model.

The contained data of the senior population (over 64 and 69 years of age, respectively) have been further enriched with Germany-wide statistical information about the proportion of pure senior households and seniors living alone or in shared accommodations (Federal Statistical Office, 2014). This allows us to specify the number of seniors and senior households for every demand point, which is the basis for the quantity of food and the number of stops per demand point, respectively. It is also assumed that all registered seniors who are living in pure senior household will use the home delivery service. About 70% of the seniors live alone or in accommodations with only seniors. On average, about two seniors live in every purely senior household.

The demand quantity per person includes the average consumption of food and beverages for the German population. Other essential goods, for example, medicines, are not considered in this model. Open sales data forecasts for food and beverages in Germany in 2020 were used to calculate an average daily demand per person (German Wine Institute, 2018; Statista Market Analytics, 2020; wafg, 2020). In this calculation, weight statistics for the packaging of food and beverages are also included (pwc, 2011; Federal Statistical Office, 2020; Stoll, 2018). This results in 1.71 kg of dry goods (0.44 kg dry food and 1.27 kg beverages) and 0.65 kg of fresh goods per person per day. This leads to a total daily demand by the in Berlin registered seniors aged over 64 of about 1.7 million kg and over 69 of 1.2 million kg, respectively.

D.4.1.2 Logistics Parameters

For our case study, we consider established food delivery service providers in Berlin, such as Amazon Fresh or Rewe delivery service, as the most suitable delivery actors. They are already familiar with the last-mile food distribution and would be able to provide convenient urban storage areas with loading zones, trained staff and delivery vans with cooling units. Therefore, the geographic location of a real urban food delivery hub is the origin point for the CVRP. Food delivery hub capacity is neglected due to the lack of information and in order to focus on the fleet size calculation.

To define the vehicle capacities of the CVRP, we assume a typical delivery van with a payload of $1,200\ \mathrm{kg}$, which is used by parcel delivery services and by food delivery services equipped with a cooling unit (Kress, 2020).

Additionally, we assume an average driving speed in Berlin of $24\ \mathrm{km/h}$ (Forbes, 2008) and a loading time per vehicle per trip of $15\ \mathrm{min}$. This necessitates prepared food packages and is therefore small compared to usual loading times of normal parcel delivery vans (Clarke and Leonardi, 2017). Travel distances between demand points and between hub and demand points are calculated based on the road distances with the help of the street layer of OpenStreetMap and the open geographic information system QGIS.

An asymmetric cost matrix helps to include the special travel characteristics in urban areas, for example, one-way directions (Toth and Vigo, 2002). To lower the combinatory complexity of the problem, only the 25 closest relations to other demand points are included for every demand point rather than the whole distance matrix. Tests have shown that computation time can be significantly reduced with negligible effects on the optimal solution.

D.4.1.3 Demand and clustering

As outlined in section D.2.2, CVRPs with thousands of customers cannot be solved with the current state of technology. Therefore, one representative district has been selected to run the calculations. For deciding for one district the criteria vulnerable population density, demand point density and average distance to the closest hub are considered. Berlin-Lichtenberg has only a very small deviation from the mean values in all these categories ($5,600$ inhabitants $/\mathrm{km}^2, 17$ points $/\mathrm{km}^2, 8$ kilometers road distance to the closest hub) and can therefore be evaluated as suitable for extrapolation to all of Berlin (Statistical Office for Berlin-Brandenburg, 2020). This district has 39,834 inhabitants aged over 64 (29,424 over 69), who live in approximately 28,000 households (21,000 over 69) and must be provided with around 94,000 kg of food (70,000 for those over 69) per day. A well-located hub of an established food delivery service is selected as the origin for the home deliveries. It is not located directly within the model district, but is the closest option with an average road distance to the customers of around $7.8\ \mathrm{km}$. The resulting 826 demand points of the model area represent a median number of 14 households with inhabitants aged over 64 years (10 households aged over 69). Due to very different demand areas, the number of households per demand point considerably vary with a first quartile of 5 and a third quartile of 37 households (aged over 69 years: 4 and 27). In practical implementation, all households per demand point need to be served successively by the deliverymen. Assuming geographically evenly distributed households within the demand areas, the average euclidean distances between households is less than $20\ \mathrm{m}$ but could reach $400\ \mathrm{m}$ in the worst case. This case study excludes a detailed routing within demand points and considers a fixed service time per household.

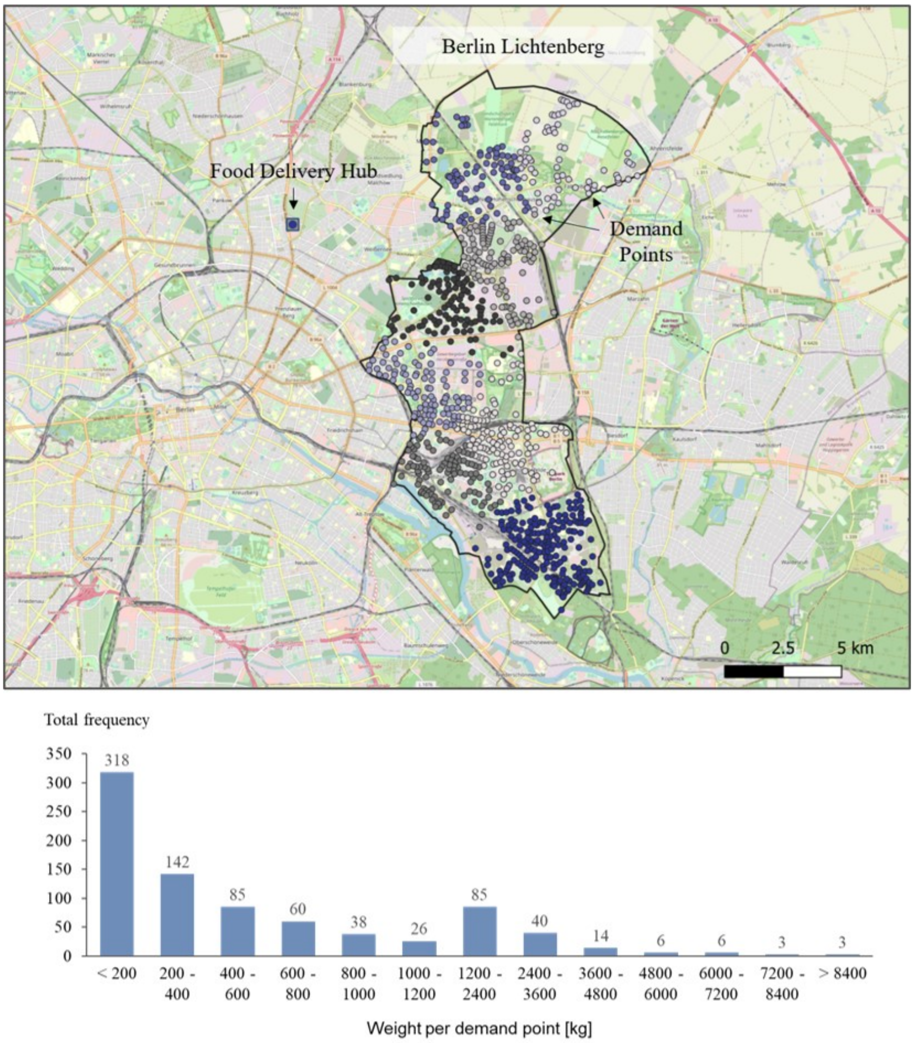

Figure D.2: Geographic distribution of the clustered demand points in Berlin-Lichtenberg (above) (OpenStreetMap, QGIS) and weight distribution per demand point for the scenario: seniors over the age of 64, delivery once per week (below)

Based on the population data collection described in section D.4.1.1, the number of vulnerable people per demand point is heterogeneous. The variance leads to high weight differences to be delivered per demand point, as shown in Figure D.2, in case all people over the age of 64 are served once per week. Because a significant number of demand points amount to a quantity higher than the vehicle capacity of 1,200 kg, FTL trips are defined in a preprocessing step. All points with a demand of $1,200\ \mathrm{kg}$ and more are assigned to the weight-based required number of FTL shipments. The remaining residual demand quantities must be served with LTL shipments and are still included in the CVRP.

On that basis, a large-scale CVRP, as explained in section D.3, is implemented. The model with more than 800 customers in Berlin-Lichtenberg is not solvable in a reasonable time. The discussed two-stage solution approach is adopted to first cluster the demand points using a k-means algorithm, and then solve smaller-scale CVRPs. In this case study, two different clustering specifications will be compared. Because the literature in section D.2.2 showed that problem sizes with 100 demand points are frequently solvable, a clustering in eight areas is applied. It results in a mean of 103 demand points per area, including two larger statistical outliers with 57 and 187 points per area. The clustered model region is illustrated with different point colors in Figure D.2. Additionally, the same process is performed with 15 clustered regions, which is the least number that results in less than 100 points in all areas. The purpose of this variation is to investigate the effects of the clustering on the total computing time and the quality of results.

The individual trips that form the solution of the CVRP are then assigned to delivery vehicles with a standard bin packing algorithm (Martello and Toth, 1990). Thus, the minimal number of vehicles that are required to fulfill the transportation task per period is derived.

D.4.1.4 Scenarios

Within this work, the two following delivery modes are tested:

1. Complete delivery by food delivery services in actively cooled vans.
2. Delivery of fresh goods by food delivery services in actively cooled vans and of dry goods by parcel delivery services.

The second collaborative mode attempts to decrease the need for actively cooled vans by using uncooled vans for non-perishable goods. The first mode represents the classical food delivery model.

Different delivery scenarios are formed by varying the parameters number of weekly deliveries per household (once, twice), service time per household (1.5 min, 3 min), daily delivery service working hours (8 h, 10 h) and minimum age of inhabitants to deliver (64, 69). A sensitivity analysis evaluates the consequences of different measures during crises on the resulting number of required vehicles and other delivery characteristics. For delivery mode A, all 16 parameter combinations, and for delivery mode B, only selected scenarios are calculated.

D.4.2 Results

All calculations are performed with the mathematical MIP solver Gurobi 9.0.1 in combination with the language Python $3.6.1$ on a standard notebook (Intel Core i5 2.5GHz processor, 16 GB RAM). A maximum computation time of three hours or a maximum gap of 10% between the lower and upper objective bound per clustered area is chosen to terminate the calculations. As presumed, the results of the smaller areas are significantly better bounded than the largerscale calculations. While in most cases the gap between the lower and upper bound is just below the desired 10% limit, smaller cases quickly achieved gaps under 1%, while larger ones only reached 30%.

The presented results refer to the clustering in eight differently sized areas. The effects of performing the calculation with 15 areas are presented at the end of this chapter. All results correspond to the extrapolated values for the entire Berlin senior population based on results from Berlin-Lichtenberg.

The results of the sensitivity analysis for the number of required delivery vehicles are graphically presented in Figure D.3 and illustrate a huge impact of the different parameter settings.

The baseline scenario A1 assumes a moderate service time per household of three minutes and a delivery frequency of twice per week, with a daily working time of eight hours. The required number of vehicles amounts to more than 900 to provide the $+64$ age group for entire Berlin with food and almost 800 for the $+69$ age group.

Figure D.3 points out appropriate strategies to reduce vehicle demand in the given setting. The relative savings per strategy are almost identical between the examined age groups.

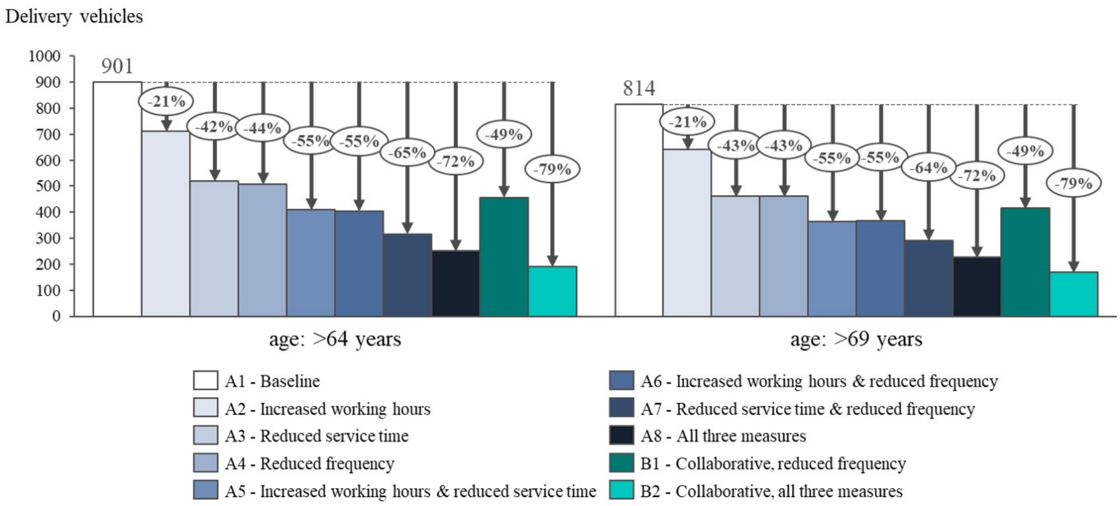

Figure D.3: Required delivery vehicles for all scenarios in delivery mode A and B

Scenarios A2 to A4 show that changing only one of the parameters in the given extent can result in up to 44% vehicle savings. The parameter changes represent different measures in the crisis. Providing the vulnerable groups with food only once per week (A4) enlarges the routing efficiency because of consolidation effects, but leads to more challenges for the households, especially regarding the shelf life of fresh produce. A second measure (A3) significantly decreases the service time, assuming that the food was not delivered right to the household's door but instead to a central pick up location, for example, the court of a condominium. Increasing the working hours of the staff to ten hours (A2) leads to a fleet size reduction of 20%.

Two measures combined in the scenarios A5 to A7 help to raise the savings. The combination of a service time and delivery frequency reduction could eventually reduce the number of vehicles by up to two-thirds. Taking increased working hours into account leads to maximum savings of 72% in delivery mode A. Therefore, in the optimistic scenario A8, 250 cooling vans would be required to directly supply all Berlin seniors over 64 years of age with food, and 226 vehicles for those over 69 years of age.

Collaborative delivery with food delivery services for fresh food and parcel services for dry food has been calculated for two selected scenarios B1 (one delivery per week, three minutes service time and eight working hours) and B2 (1.5 min service time and ten working hours) to compare with delivery mode A. The breakdown in two product categories has a negative overall effect on the efficiency of the last-mile distribution system, because all customers need to be supplied twice as much as with the collective delivery. Increase in travel, service and loading times causes an increase in the totally required vehicles of around 80% in scenario B1 compared to the reference scenario A4, and 70% in B2 compared to A8.

Assuming the cooling vehicles as a limited resource and regarding the usual delivery vans as sufficiently available, however, Figure D.3 illustrates the positive effect of the collaborative concept. The collaboration helps to achieve smaller vehicle savings between 10% for B1 and 25% for B2 compared to the reference scenario without collaboration. This results in less than 200 required cooling vans, which results in 210 vulnerable persons served per van. Section D.5 provides a discussion of the estimated supply of cooling vans and helps to better interpret the vehicle demand.

The overview of results and additional performance indicators, given in Appendix, Table D.2, helps to gain deeper insights about the different delivery modes and scenarios.

In principle, the observed cases have shown that the vehicle capacity is the critical factor for calculating routes, which becomes evident by means of the high average vehicle utilization over all scenarios of 88%. This fact also explains the huge differences in the supplied seniors per tour in Table A1. The scenarios A1, A2, A3 and A5 with doubled delivery frequency lead to about twice as many stops per tour and to a higher proportion of the travel time. Figure D.4 also illustrates this observation and provides the distribution of total time in categories for selected scenarios. The share of service time in the baseline scenario can be considerably decreased, not only with reduced time per household but also with less delivery frequency. The combination of both measures enhances this effect and cuts the service time per route by three-quarters. Age groups and working times do not influence time distribution significantly.

As shown in scenario A1 and particularly in B1, with lower food quantities per person, the time limit of the daily working hours rather than vehicle capacity presents the critical factor. This causes inefficient routings for the fresh food delivery in scenario B1 with less than half-loaded vans.

Performing the same calculations with 15 clustered districts in the model area leads to 1.4% increased target value of 914 cooled delivery vans in the baseline scenario. Computation time savings of around 5% justify the more detailed clustering if solution quality is less important.

D.5 Discussion and practical implications

To implement the proposed approach in practice, some remarks and challenges must be solved.

We assume the number of cooling delivery vans as the limiting factor for food distribution. With our model, we calculate a demand of about 900 vehicles, which can be lowered to around 200 vehicles under optimal conditions and with a lower service quality for the vulnerable population. The service time per household has a high influence on the required vehicles. Decreasing the service time is usually not only within the power of the deliverer, but is also customer-dependent. In practice, the service time could strongly vary due to different distances for deliverymen between households within demand points. A detailed routing between defined households could enhance the model, for instance with a traveling salesman problem or an additional VRP like implemented by Pureza et al. (2012).

To evaluate the resulting vehicle demands, we estimate the existing actively cooled vehicles in Berlin. Available statistics of the German Federal Motor Transport Authority (2019) suggest that around 200 vehicles in the category of vans with chilled loading bays in the suitable capacity category are registered in Berlin. This number considers the amount of cooling vehicles across all payload categories and a general proportion of appropriate delivery vans. Hence, the home delivery concept could be feasible with strong service quality restrictions. However, practical limitations can complicate the implementation and increase the number of required vehicles. The existing vehicles belong to different owners and companies, so the available number of food delivery services could be much lower in practice. Notably, these existing resources are in high demand during a pandemic, as the long waiting times for orders in the online food sector during the COVID-19 crisis showed (de Prez, 2020).

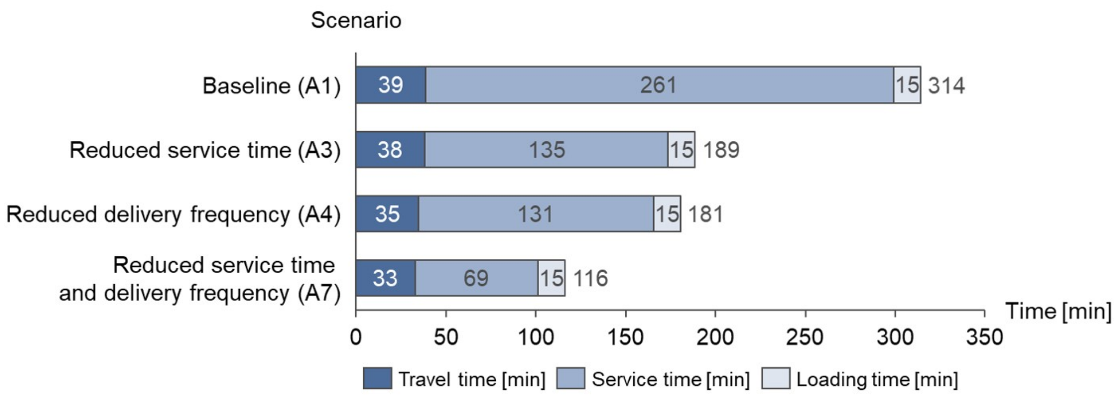

Figure D.4: Distribution of the time categories per tour in different scenarios for mode A

The presented concept requires vehicle-efficient route optimization focusing on vehicle utilization instead of customer-oriented delivery, with freely selectable time windows. Such an optimized distribution plan with a large number of customers can lead to vehicle utilization over 80% compared to primarily less than half-loaded vehicles, as observed in existing business models of food delivery services (Allen et al., 2018).

Forward-looking grocery delivery concepts often include an enhanced sustainable last-mile consolidation structure with tiny micro hubs in residential areas, only a few hundred assigned customers per day and often in connection with cargo bike delivery (e.g. Melkonyan et al. (2020); Morganti and Gonzalez-Feliu (2015). Only short route durations could make a passive cooling of perishable goods applicable, for example, in portable coolers. Thereby, the shortage of special cooling vans could be partially compensated. The micro hubs could be restocked at nighttime in order to reserve more vehicles for last-mile deliveries throughout the day (Bertazzo et al., 2016).

In practice, when public disaster response agencies manage relief supply, a collaborative home delivery would require transparency about demand, supply and especially available vehicles. To implement such a collaboration, formal cooperation agreements between companies and the government are conceivable (Holguín-Veras et al., 2014). In addition, "latent private-sector partnerships" (Gabler et al., 2017) are suggested, which can be intensified during crises. Informal cooperation can also work if partners are intrinsically motivated and economically benefit from the cooperation (Wiens et al., 2018). For that, a profound understanding of each of the participating partners' objectives and motivation is required (Bealt et al., 2016; Gabler et al., 2017). Incentives for companies to engage must be provided, since food delivery services might aim to maintain their business processes and therefore try to not compromise the delivery of existing clients. Public authorities should therefore find ways to compensate the involved companies' additional expenses and take the leading role in overall process coordination (Izumi and Shaw, 2015; Wiens et al., 2018).

An appropriate way must also be found to generate incentives for the vulnerable population to use home delivery services. Finding a good medium of communication with seniors can be a practical challenge. Smartphone apps and websites of the food delivery services mainly address a younger target group, but telephone or postal communication can lead to high staff and time expenditures.

D.6 Conclusion and future research

In this paper, we present a modeling and solution approach for protecting vulnerable populations during pandemics with home delivery of essential supplies. We model the last-mile distribution concept through a CVRP, which aims to minimize the total time for serving customers and implicitly optimizes fleet size. A developed case study based on the city of Berlin shows the model's feasibility and applicability. A two-stage approach with a k-means clustering and an MIP calculation based on the solver Gurobi is applied. Thereby, this paper proves that good solutions can be achieved within a reasonable runtime.

In our baseline scenario, we estimate that around 900 cooling vans are required to serve the medically vulnerable group of Berlin inhabitants over 64 years of age with food. With a sensitivity analysis, we investigate different operational measures of the delivery concept during pandemics and show how a fleet size of less than 200 vehicles could be reached. Among other things, this requires collaboration between food and parcel delivery services and a division into fresh and dry food. Our findings reveal that the available cooling vehicles could be sufficient to implement the home delivery concept in Berlin, albeit with restricted service quality. The analysis also demonstrates that lowering the service time per household or the delivery frequency has a similarly high resource-saving impact.

The success of this distribution concept for the vulnerable population depends on the coordination of the collaboration. To achieve a better response time, we suggest already elaborating a comprehensive concept in a pre-disaster context (preparedness phase) with all involved public and private actors and stakeholders.

Besides the presented fleet size optimization, alternative scenarios that require different optimization objectives, for example, a shortage of drivers, are conceivable during pandemics. As stated by Huff et al. (2015), diseases or quarantines are likely to cause worker absenteeism in the food and logistics sector due to interpersonal contacts and potential infection chains within and across companies. For a home delivery concept that requires a large number of delivery staff, this scenario could shift the focus to staff as the most critical resource.

Additionally, we suggest research taking into account multiple hub locations to include the decision about which hubs to use in order to serve all vulnerable groups and to decrease the travel times of the last-mile delivery. Enhancing the model with a heterogeneous fleet formulation and considering larger trucks, especially for delivering demand points with high demand, could facilitate a more efficient last-mile delivery.

Applying the CVRP for all other Berlin districts besides Lichtenberg would lead to more accurate results and supersede the extrapolation step. A data base with non-aggregated households could avoid the high variance per demand point and make the results even more reliable. Lastly, this model should be further applied to other geographical regions, other products (e.g. medical supply) or differently defined vulnerable groups, such as persons with preexisting conditions or those in quarantine. Other actors like the fire brigade, army or nongovernmental disaster relief organizations could improve the concept with their vehicle support.

Another opportunity to generate higher cooling vehicle savings would be a last-mile distribution system with a higher number of decentralized micro hubs and a delivery of passively cooled food with unspecific vehicles. Proving this concept needs further investigation.

To comprehensively view this problem, we seek advice from other fields of research, especially regarding legal restrictions, the epidemiological effects of home delivery strategies and their acceptance among vulnerable populations.

We conclude that the benefits of our research are valuable to retailers and logistics companies operating a home delivery service for vulnerable populations during pandemics. Moreover, our research serves policymakers who are devising plans to improve infection prevention while ensuring the population's supply security.

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D.7 Appendix

Scenario ID	Scenario	Delivery vehicles	Tours	Average utilization [%]	People [in thousands]*	Persons per tour	Travel time per tour [min]	Service time per tour [min]	Total time per tour [min]	Stops per tour
A1	A_2_3_8_65	901.0	8,325	83.7	505.0	121.4	37.2	257.1	309.7	3.1
	A_2_3_8_70	814.0	7,247	85.5	451.0	124.2	39.8	264.3	319.1	4.1
A2	A_2_3_10_65	711.0	8,325	85.1	505.0	121.4	37.2	257.1	309.7	3.1
	A_2_3_10_70	642.0	7,247	87.6	451.0	124.2	39.8	264.3	319.1	4.1
A3	A_2_1.5_8_65	520.0	8,097	86.0	505.0	124.9	38.5	129.1	182.6	3.3
	A_2_1.5_8_70	461.0	6,725	92.6	451.0	134.4	38.0	141.8	195.9	4.6
A4	A_1_3_8_65	508.0	8,185	85.1	505.0	61.8	33.8	130.7	179.8	2.1
	A_1_3_8_70	461.0	7,293	85.4	451.0	61.9	35.5	131.1	181.7	2.5
A5	A_2_1.5_10_65	409.0	8,097	87.3	505.0	124.9	38.5	129.1	182.6	3.3
	A_2_1.5_10_70	364.0	6,725	92.8	451.0	134.4	38.0	141.8	195.9	4.6
A6	A_1_3_10_65	405.0	8,185	86.9	505.0	61.8	33.8	130.7	179.8	2.1
	A_1_3_10_70	366.0	7,293	87.4	451.0	61.9	35.5	131.1	181.7	2.5
A7	A_1_1.5_8_65	317.0	7,817	89.1	505.0	64.7	32.1	68.1	115.4	2.2
	A_1_1.5_8_70	292.0	6,940	89.7	451.0	65.1	33.5	68.9	117.8	2.7
A8	A_1_1.5_10_65	250.0	7,817	89.9	505.0	64.7	32.1	68.1	115.4	2.2
	A_1_1.5_10_70	226.0	6,940	90.4	451.0	65.1	33.5	68.9	117.8	2.7
B1	B_1_3_8_65_Total	927.0	9,505	78.4	505.0	106,3	37.9	213.2	268.9	2.8
	B_1_3_8_65_Fresh	457.0	3,820	49.8		132.3	45.5	280.8	351.7	3.2
	B_1_3_8_65_Dry	470.0	5,685	89.1		88.9	35.0	187.8	237.8	2.6
	B_1_3_8_70_Total	845.0	8,920	73.5	451.0	101.3	39.3	203.2	259.7	3.3
	B_1_3_8_70_Fresh	415.0	3,439	49.4		131.4	46.0	279.5	347.3	4.1
	B_1_3_8_70_Dry	430.0	5,481	82.6		82.4	36.8	174.6	226.8	3
B2	B_1_1.5_10_65_Total	418.0	7,893	88.3	505.0	128.1	36.4	133.7	185.4	3.4
	B_1_1.5_10_65_Fresh	190.0	2,195	86.6		230.3	41.6	243.0	300.2	5.3
	B_1_1.5_10_65_Dry	228.0	5,698	88.9		88.7	34.5	92.6	142.3	2.7
	B_1_1.5_10_70_Total	384.0	7,078	88.0	451.0	127.7	38.3	133.8	187.3	4.3
	B_1_1.5_10_70_Fresh	169.0	1,950	87.2		231.7	44.1	245.5	305	6.9
	B_1_1.5_10_70_Dry	215.0	5,128	88.3		88.1	36.1	91.8	143.1	3.3

Note(s): *The number of people to serve corresponds with the respective vulnerable group definition in D.4.1.1 of all seniors per age definition, who are living in pure senior household (70% of the total senior population in Berlin).

Table D.2: Results for delivery mode A and B (the scenario labels follow the logic *"delivery mode_deliveries per week_service time_working hours_age"*)

E Improving emergency preparedness through public-private collaboration – dual-use warehouses for food supply

Abstract

Public preparedness measures for essential goods in countries are often outdated and under-utilized, while private companies efficiently organize everyday supply. In this study of a public-private partnership, we conceptualize and evaluate dual-use warehouses for food supply in a developed country.

In a practice-based research project with authorities and companies in Germany, we evaluate the use of dual-use warehouses, regarding feasibility and its barriers for implementation. We also discuss trade-offs between public and private actors' objectives. We relate the concept to preparedness measures, disaster management, and business practices in different countries. Additionally, we conduct a case study that combines utility analysis for locations with location-allocation models. Although public and private actors independently choose different locations, collaborating with several partners yields good results for emergency response, especially when those partners strategically develop the network.

The study contributes to the literature on of public-private partnerships, especially for emergency preparedness. It presents a practically applicable concept to accommodate the conditions in developed countries and supports practitioners' decision-making to ensure emergency supply.

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E.1 Introduction

Disasters and ensuing emergencies are regular occurrences around the world. Among these disasters have been hurricanes and tornadoes in the US, the devastating earthquakes in Turkey in 2020, and the floods in Australia and Germany in 2021 (Stewart et al., 2009; Direct Relief, 2020; Guardian, 2021; CNN, 2021; BBC, 2021). Storms, floods, and earthquakes are increasing in number and severity (David Swanson and Smith, 2013). For legal reasons, developed countries have adopted emergency preparedness measures for food supply and other parts of their infrastructure (German Federal Office for Civil Protection and Disaster Assistance, 2019a).

Countries' needs determine the emergency care infrastructure, reserves, and stored goods, but these resources are often inadequate and infrastructure is unused, untested, and under-utilized. In Switzerland, stored goods have only slowly adapted to today's requirements. Germany has more than 150 emergency warehouses with unused reserves and which are disconnected from food supply chains. The US has a redundant infrastructure parallel to the commercial food supply (Jaberg, 2020; BMEL, 2020b; Palin, 2017). There is a stark contrast between the lack of public preparedness and the private sector, where large retailers maintain large-scale networks of warehouses, distribution centers, and stores. They operate their own fleets and use third-party transport companies, orchestrated through up-to-date IT systems and optimized processes. Collaboration and clustering are good examples of established industry structures that yield significant efficiencies in private sector operations. Consequently, as an example, one study has found that the US food system is resilient enough not to need stockpiles other than those of companies to ensure a food supply during crises (Palin, 2017).

Meanwhile, means of cross-sector collaboration between public and private actors have long existed, from contracting for services to dedicated private-public partnerships, for instance, for infrastructure projects (van Ham and Koppenjan, 2001) and the private sector regularly supports humanitarian missions (Nurmala et al., 2018). We therefore propose a Public-Private Emergency Collaboration (PPEC) for an emergency food supply. The PPEC would consist of dual-use warehouses that serve commercial and emergency purposes and where partners establish standard processes for emergency response. Public actors could better plan actual emergency responses by leveraging private infrastructure, reducing redundancy and costs. Enhancing the private sector's continuity planning, companies could profit both from direct remunerations and improved resilience (Tatham and Pettit, 2010; Ojha et al., 2013). This study stems from a practice-based research project (Gallien et al., 2015), encouraged by and conducted in cooperation with practitioners from German federal and local authorities and the private sector.

We conducted a case study to assess the feasibility of the PPEC concept and its value to public and private actors. We also discuss the trade-offs between the objectives of the two actors, their willingness to collaborate, and barriers to implementation. We propose an integrated actor-specific planning and development of a dedicated collaboration structure particularly to avoid past shortcomings of applying standard (commercial) practices in disasters (Day, 2014). In addition to analysis of secondary data on potential locations and model results to identify networks, we draw from our exchange with practitioners. We conclude from the case study that public and private actors would choose different locations separately, but leveraging infrastructure from several private partners yields good results for public emergency preparedness, closing separate warehouses altogether. Strategically developing the warehouse network with additional dual-use locations could improve these outcomes.

The remainder of the study is structured as follows: We present the organizational details and context of our PPEC. We then describe the background of emergency food supply in developed countries, the literature, and the theoretical and practical involvement of private actors in emergency food supply and preparedness. We then present our methodology, followed by the case study and its results. The study closes with a discussion of the PPEC and its potential implementation.

E.2 Public-private emergency collaboration on food supply

From discussions with representatives from authorities and companies in food supply chains, we present a PPEC on food supply and investigate its fit for emergency preparedness and logistical efficiency. In the concept, private partners use *dual-use warehouses* for regular food supply and collaborate with a public partner when an emergency food supply is needed. The commercial company operates the warehouses and stores emergency supplies. The company receives compensation for storage and warehousing processes. Actors establish collaboration procedures ahead of emergencies, and public authorities can monitor stock at their discretion. Authorities coordinate the response through established channels and infrastructure in an emergency. Collaboration mechanisms include the basic supply chain design, technological and information sharing practices, and joint practices, all of which are beneficial for response and recovery after disaster and disruption (Duong and Chong, 2020; Dash and Dixit, 2022).

Today, warehouses play a central role in the food supply. The large number of warehouses operated by private retailers, the breadth of food products, and the number of stores downstream underline this fact. Warehouses bridge supply and demand, pool and bundle products before regional distribution, and store nonperishable food. The warehouse location is an important long-term decision in designing a distribution network. Hence, warehouses in suitable locations are the foundation for any collaboration between public and private actors. In contrast to infrastructure held and provided by the public sector, the private actors play a crucial role in deciding upon a location and building the facilities. Apart from the physical dual-use warehouse, the PPEC on emergency food supply considers cooperation in transportation and warehouse staff and equipment, establishing processes for crisis response, and using IT and communication systems. The PPEC thus becomes an integral part of a comprehensive emergency preparedness plan that includes aspects beyond physical pre-positioning (Jahre et al., 2016; Kunz et al., 2014).

A PPEC requires collaboration well in advance of a disaster by bringing together authorities and their partners in the private sector. Partners would, ideally, decide on locations and their design to satisfy their individual needs (*greenfield planning*). However, private companies have already built efficient networks of warehouses and infrastructure in developed countries (Zentes et al., 2017). Therefore, building an entirely new infrastructure is extremely expensive and potentially unnecessary, making it more efficient for the public to leverage private infrastructure. Hence, we evaluate the use of existing warehouses for emergency food supply, known as *brownfield planning*.

Public and private actors, or emergency and regular food supply, have their own goals, constraints, and requirements. Operating in different environments, they pursue distinct objectives for locations and strategies, such as inventory turnover (Holguín-Veras et al., 2012; Day, 2014; Duong and Chong, 2020). We integrate both perspectives through ongoing exchange with actors from both sectors and adaptable evaluation techniques.

Our evaluation focuses on Germany, following our direct partners from public authorities and private companies. However, PPEC should be generalizable since similar discussions on emergency food supply concepts are relevant for other developed countries. We, therefore, discuss the emergency food supply in other countries, the generalizability of PPECs, and our results throughout the study.

E.3 Background

Emergency supplies and preparedness concerning food and other vital items are essential public responsibilities in many developed countries, as shown by an overview of preparedness goals and measures from five OECD countries. While countries differ in strategies for preparedness, a collaboration of public actors with food retailers using their warehouses for emergency stocks (dual-use) is widely applicable.

We summarize the literature on the emergency food supply and our proposed PPEC in Table E.2. To the best of our knowledge, our study is the first to propose a PPEC on food warehousing and evaluate the concept. It supports the decision-making process for both public and private actors by integrating actor-specific costs and location criteria. Lastly, we evaluate the involvement of private actors in emergency supply.

E.3.1 Emergency food supply in developed countries

Countries face many risks, ranging from natural disasters or man-made crises to disruptions in (international) supply chains. If such risks materialize and crises unfold, a critical sector in the population's well-being is food supply. The emergency plans of many countries reflect its importance. Table E.1 gives an overview of five different countries and their measures. We draw on information from two recent studies (German Federal Office for Civil Protection and Disaster Assistance, 2019a, 2019b), if not indicated otherwise.

OECD - Organisation for Economic Co-operation and Development.

Country	Emergency supply goal	Emergency food supply measures	Involved actors				Explanation/ Details	References
			Governmental actors	Companies	NPOs	Households		
United States	Ensure basic nutrition of the population	National warehouses and distribution centers (using Web Emergency Operation Center)	Federal government and agencies (DHS[1], FEMA[2], USDA[3]), State governments (OEM[4]), Local governments	Warehousing companies, Partner institutions	Aid organizations, Food banks, Hospitals		Legal Requirement (Stafford Act), National Response Framework (incl.	German Federal Office for Civil Protection and Disaster Assistance (2019a), p. 117-119, 195-220
		Pre-Positioned Disaster Supplies Program (PPDS)	FEMA, OEM				National Preparedness	
		Disaster Supplemental Nutrition Assistance Program (D-SNAP)	FEMA, OEM, Food and Nutrition Service (USDA)				Systems), FEMA Preparedness Framework, Food	
		Local preparedness, e.g. NYC: Local warehouses (+emergency exercises)	NYC Emergency Management, Food Access Lead Team	Food companies, Restaurants, Caterers	Aid organizations, Food banks		Access Plan	
		Recommendation of personal provision	DHS(FEMA), USDA[3]		Aid organizations	All households		
Germany	Ensure basic nutrition of the population	Emergency Reserves: Federal Grain Reserve, Civil Food Reserve	Federal Government, State governments, Local governments, BMEL[5] , Federal government agency BLE	Warehousing companies	Aid organizations		Legal Requirement (Food Security and Prevention Act, ESVG)	German Federal Office for Civil Protection and Disaster Assistance (2019a), p. 54-56, German Federal Office for Civil Protection and Disaster Assistance (2019b), p. 155-157
		IS-ENV[6]	x					
		Emergency exercises	x	Companies, Trade unions				
		Collaboration guidelines	x	x				
		Recommendation of personal provision	BBK[7]			All households		
Switzerland	Ensure supply of essential	Compulsory stockpiling with duty to deliver	Federal council, EAER[8], FONES[9]	Private sector experts, Essential goods companies			Legal Requirement (Constitution, Art. 102)	German Federal Office for Civil Protection and Disaster Assistance (2019a), p. 101;
	goods	Recommendation of personal provision	x			All households		German Federal Office for Civil Protection and Disaster Assistance (2019b), p. 172f.
United Kingdom	Ensure food security	Strong cooperation between public/private sector e.g. National Resilience Capabilities Programme and BC plans (+emergency exercises)	BAGCP[10], DEFRA[11], FCELG[12], DCLG-RED[13], BERG[14], CCS[15], VSCPF[16], Resilience teams (local)	Food industry/ trade, Trade unions, Restaurants, Caterers	Aid organizations		Legal Requirements (Civil Contingencies Act 2004, Contingency Regulations 2005)	German Federal Office for Civil Protection and Disaster Assistance (2019a), p. 120, 133-135, 139; German Federal Office for Civil Protection and Disaster Assistance (2019b) p. 174-177
		Recommendation of personal provision	x		Aid organizations	All households		
		Studies and research	DEFRA	x			Planning	
France	Ensure supply of	General prevention and supply measures	National Government, Prefectures, CIAV[17]		Aid organizations			German Federal Office for Civil Protection and Disaster Assistance (2019a), p. 63,
	essential goods	Emergency preparedness program DEMETER (+emergency exercises)	x + "mission officers"	Food production and trade				German Federal Office for Civil Protection and Disaster Assistance (2019a), p. 173
		Recommendation of personal provision	National Government			All households		

"x": as in the cell above

[1]Department of Homeland Security, [2]Federal Emergency Management Agency, [3]US Department of Agriculture, [4] Offices of Emergency Management

[5]Federal Ministry of Food and Agriculture, [6]Information system for emergency food supply, [7]Federal Office for Civil Protection and Disaster Assistance

[8]Federal Department of Economic Affairs, Education and Research, [9]Federal Office for National Economic Supply, [10] Business Advisory Group on Civil Protection

[11]Department of Environment Food and Rural Affairs, [12]Food Chain Emergency Liaison Group, [13]Department for Communities and Local Government, Resilience and Emergencies Division, [14]Business Emergency Resilience Group, [15]Civil Contingencies Secretariat, [16]Voluntary Sector Civil Protection Forum, [17]Cross-Government Victim Support Unit

Table E.1: Emergency food supply strategies and measures in the US, Germany, Switzerland, the UK, and France.

We focus on developed countries that share specific characteristics. For instance, the private sector is responsible for the food supply. Companies manage a cost-efficient food supply with short storage times and high inventory turnover through a network of warehouses and distribution centers (Zentes et al., 2017; Lidl, 2020). Countries often have a few large retailers that command the majority of the market share, like Walmart in the US or a handful of retail chains in Germany (Statista, 2018; LZ, 2018). The infrastructure maintained by these retailers is substantial. Walmart operates 210 distribution centers and over 5,000 retail stores in the US (Walmart, 2021b, 2021). In Germany, Lidl owns around 40 regional warehouses and 3,200 retail stores in Germany (Lidl, 2020). In the UK, Tesco has about 30 warehouses and 3,500 retail stores (Zentes et al., 2017). In addition to private infrastructure, developed countries can take advantage of an advanced public transport infrastructure that enables efficient transport and distribution.

However, governments and public authorities assume responsibility in times of crisis. Legal provisions lay the basis for such responsibility and following measures, such as the US Stafford Act of 1988, the UK Civil Contingencies Act of 2004, or the German Food Security and Prevention Act (ESVG) of 2017. Based on these provisions, authorities regularly implement the strategies, infrastructure, and measures to ensure a food supply during an emergency or crisis.

In all five developed countries shown in Table E.1, households are recommended to maintain a supply of emergency provisions. In addition, the United States, Germany, and Switzerland have dedicated stockpiles for emergencies. While Germany relies solely on public stocks and Switzerland leaves stockpiling entirely to sellers of specified products, the US uses both stocks directly managed by the Federal Emergency Management Ageny (FEMA) and pre-contracted supplies available from private partners. Moreover, authorities place containers with essential relief items close to vulnerable locations through the Pre-Positioned Disaster Supplies Program (PPDS). States or cities in the US can have additional programs as part of their preparedness measures. In contrast, France and the UK do not maintain public stockpiles.

FEMA maintains a Logistics and Supply Chain Management System to manage warehouses for transparency and processing in crises, directly linked to large commercial retailers and their stock levels, such as Target. Germany uses an information system (IS-ENV) to coordinate federal, state, and local authorities. France has implemented the system DEMETER, which lists information about food producers and retailers. Furthermore, DEMETER acts as a decision-support tool in planning for different scenarios.

The United Kingdom cooperates with the private sector and has established several consortia to bring actors together. Unlike most other countries, the UK abandoned public stockpiling in 1995 in an effort to update its preparedness system. Priority is instead given to business continuity planning, for instance, enabling food retailers to continue their role in the food supply during crises. Single agreements between retailers, authorities, and owners of critical infrastructures add to preparedness in the UK.

Stockpiles, information exchange, and recommendations for personal provisions play central roles in most developed countries. Degrees and forms to involve private actors in the emergency food chain vary among countries. The PPEC adds to existing stockpiles and information exchange, and it could help improve efficiency. Benefits are obvious where countries or providers today maintain dedicated warehouses and stocks solely for emergencies. Under current legal requirements in many countries, emergency storage is often required and cannot be abandoned as in the UK. We provide detailed examples of collaboration from three countries later in this section.

Topic	Details or definition	References
Disaster management concepts		
Inventory pre-positioning	Focus in the humanitarian sector; Storing of relief supplies, especially in disaster-prone areas; Wide range of potential products, e.g.: food, non-food, medical, or equipment for emergency response	Clay Whybark (2007); Campbell and Jones (2011); Duran et al. (2011); Kunz et al. (2014); Jahre et al. (2016); Ali Torabi et al. (2018); Pan et al. (2020); Sabbaghtorkan et al. (2020)
Preparedness	One of four phases in disaster management, before a disaster happens; includes five key elements: human resources, knowledge management, process management, financial resources, and community efforts (van Wassenhove, 2006)	van Wassenhove (2006); Kapucu (2008); Kunz et al. (2014); Ali Torabi et al. (2018)
Facility location planning		
Location-allocation problems	Central outputs of the models: facility locations, assignment of demand to facilities, and number of facilities needed; cost- and coverage-focused formulations depending on the context	Cooper (1963); Haghani (1996); Balcik and Beamon (2008); Loree and Aros-Vera (2018)
Location criteria integration	Additional criteria apart from cost or coverage objectives; integration through holistic processes, multi-objective models, or comparative identification and weighting of criteria	van Thai and Grewal (2005); Badri (1996); Tzeng et al. (2007); Jahre et al. (2016); Liu et al. (2021); Chuang (2002); Roh et al. (2013, 2015)
Cross-sector partnerships		
Public-private partnerships	"Cooperation of some sort of durability between public and private actors in which they jointly develop products and services and share risks, costs, and resources which are connected with these products" (van Ham and Koppenjan, 2001)	van Ham and Koppenjan (2001); Wettenhall (2003); Hodge and Greve (2007); Stewart et al. (2009); David Swanson and Smith (2013)
Public-private emergency collaboration	"A special form of public–private partnership (PPP) which is deliberately designed for the purpose of improved crisis management by joint coordination and cooperation between private and public representatives" (Wiens et al., 2018)	Qiao et al. (2010); X. Wang et al. (2016); Wiens et al. (2018); Diehlmann et al. (2021)

Table E.2: Overview of concepts and literature related to the proposed PPEC.

E.3.2 Concepts of disaster management

Pre-positioning is a commonly used strategy in preparing for emergencies. It is included here as the physical component in our PPEC concept. It is applied to store relief supplies close to disaster-prone areas (Kunz et al., 2014). International humanitarian organizations such as the United Nations High Commissioner for Refugees (UNHRCR) and CARE International have facilities to store essential relief items in preparation for emergencies and disasters (Jahre et al., 2016; Duran et al., 2011). Pre-positioned products include food items (e.g., ready-to-eat meals), non-food items (e.g., tents or blankets), medical products, and any equipment needed in emergency response (Balcik and Beamon, 2008). Pre-positioning comes with high costs for the facilities and goods stored as well as with problems of product expiry due to low inventory turnover (Kunz et al., 2014; Clay Whybark, 2007).

More comprehensively, emergency *preparedness* addresses not only physical assets such as stocks and warehouses but also what Kunz et al. (2014) term "disaster management capabilities." Those include activities in human resources (e.g., training staff), knowledge management (best practices, scenario planning), process management (preparation of response plans), resources (quickly available financial resources), and community efforts (local disaster planning, public awareness) as outlined by van Wassenhove (2006). Due to the unpredictable nature of disasters and emergencies, these demands are largely unknown. Potential benefits of investing in broader disaster management capabilities, therefore, include the effective allocation of resources in disaster response, general applicability of such capabilities, and lower costs than for large-scale pre-positioning (Kunz et al., 2014). The proposed collaborative concept focuses on broader preparedness efforts.

E.3.3 Facility location planning

For both preparedness and pre-positioning in the field of food supply, *facility location planning* entails long-term decisions. Typically, location-allocation problems, introduced by Cooper (1963), must be solved. Thereby, facilities are placed (location), and demand is assigned to be fulfilled through these locations (allocation). These problems are decisive for both public and private actors for two reasons: their direct impacts on the system's operating cost and on the timeliness of the response (Haghani, 1996). Although the importance of the factors may vary among types of actors, both are considered in many cases. For commercial applications, cost-focused models are customarily applied, while coverage problems are often used in emergency and other response-oriented settings (Balcik and Beamon, 2008).

Apart from cost and coverage objectives, specific other criteria are decisive in (pre-) selecting facility locations. In this regard, researchers have found various ways to incorporate factors such as the transportation infrastructure or workforce in proximity. Integration takes place in stages (van Thai and Grewal, 2005), in multi-objective models (Badri, 1996; Tzeng et al., 2007), or by identifying and comparatively weighting criteria (Chuang, 2002; Roh et al., 2013, 2015). We integrate specific objectives and location criteria in our evaluation of the PPEC for a federal state in Germany.

E.3.4 Cross-sector partnerships

Collaboration between public and private actors extends across sectors and can be subsumed under the auspices of *public-private partnerships (PPP)*. Institutionally, PPP is defined as a "cooperation of some sort of durability between public and private actors in which they jointly develop products and services and share risks, costs, and resources which are connected with these products" (van Ham and Koppenjan, 2001). Other scholars have taken up the debate about wide-ranging definitions, such as discussing the term being used, but also as a new word for concepts like "privatization" that have lost broad public support (Hodge and Greve, 2007). Nonetheless, the concept is still discussed in disaster and emergency studies. For the US, Stewart et al. (2009) examine public-private relationships and their central role for community resilience, identifying the numerous positive influences of stronger relationships. Another study evaluates private (logistics) firms' motivation to engage in disaster response and through which operations they could create value in such responses

(David Swanson and Smith, 2013). Broader application of private sector involvement in disaster management is known in humanitarian aid, however (Nurmala et al., 2018).

Public-private emergency collaboration (PPEC) is a form of PPP that uses joint coordination and cooperation between public and private actors for improved crisis management (Wiens et al., 2018). The collaboration comprises both regular and relief supply chains. For that reason, the collaboration needs to be set up well before a disaster. At the same time, dedicated crisis management procedures do not come into play until disaster strikes (Wiens et al., 2018). X. Wang et al. (2016) proposed a framework to evaluate Walmart's involvement in the relief supply chain after Hurricane Katrina 2005, arguing for private sector involvement (proactive outsourcing) especially for the supply of perishable goods during crises. Apart from this discussion in the literature, only a few instances of collaborations are known (Diehlmann et al., 2021).

Overall, the cross-sector partnership is the managerial centerpiece of our PPEC concept. As with the discussed potentials of, shortcomings of, and barriers to PPP (Hodge and Greve, 2007), our emergency-focused concept requires validation regarding all involved actors. We therefore integrate both actors' perspectives and objectives and discuss their objections and recommendations in our evaluation of the concept.

E.3.5 Private actors in emergency food supply and preparedness

The PPEC should improve preparedness by bringing public and private actors together. In delimitation to our concept, we provide examples of private company involvement in emergency (food) supply and preparedness. We contrast the goals of public and private actors and point out the potential value of a PPEC for both partners.

E.3.5.1 Examples of private actor involvement

In Table E.3, we evaluate three examples of private actors' involvement in emergency food supply and preparedness. The examples showcase different approaches to and extents of emergency supply and preparedness.

Walmart's engagement is entirely voluntary and without any formal public control or agreements (German Federal Office for Civil Protection and Disaster Assistance, 2019a), which is insufficient for the government's obligation to ensure a reliable and controllable emergency supply. Similarly, FCELG and other consortia in the UK are informal. However, companies regularly assist in crises, and business continuity is a critical way of returning to normal after a disaster (Gabler et al., 2017). Swiss compulsory stocks are more binding, being publicly controlled but fully managed by private actors. It is, therefore, well suited to emergency purposes. However, it again creates a parallel infrastructure with questionable utilization, and stored goods are highly inflexible due to, for instance, the need for a dedicated infrastructure. Nonetheless, the Swiss system resembles our PPEC, which relies entirely on the existing infrastructure.

	Walmart, United States	Food Chain Emergency Liaison Group (FCELG), United Kingdom	Compulsory stocks, Switzerland
Private actor(s)	Walmart Inc.	Companies in food industry, retail associations	Sellers of compulsory stocked items, stockholding organizations
Public actor(s)	State and local authorities (e.g., Florida)	Department of Environment, Food and Rural Affairs, lower-level authorities	Federal Office for National Economic Supply
Agreement	None	Informal	Contracts
Details	Emergency Operation Center for monitoring and coordination in crises, six disaster distribution centers; regular donations; increased engagement since Hurricane Katrina (2005)	Focus on business continuity management; regular meetings for information exchange; regular donations	Organized through stockholding organizations for each product group, sellers hold compulsory stocks of pre-defined goods (e.g., cereals, rice, sugar); compensation through surcharge for consumers
Authorities' role	Sharing disaster information (at most)	Facilitator; sharing public planning and research insights in normal times; sharing disaster information during crises	Contract partner; monitoring stocks and adjusting requirements; may release reserves in crises
References	German Federal Office for Civil Protection and Disaster Assistance (2019a); Walmart (2021); NBC Universal (2006)	German Federal Office for Civil Protection and Disaster Assistance (2019a)	réservesuisse (2021); German Federal Office for Civil Protection and Disaster Assistance (2019a, 2019b)

Table E.3: Examples of private sector involvement in emergency food supply and preparedness from the US, UK, and Switzerland.

E.3.5.2 Goals of private and public actors

In normal times, private companies in the food supply aim for cost-efficient warehousing through short storage times and high inventory turnover (Zentes et al., 2017). Public actors, however, merely monitor emergency stocks and facilitate exchange (see Tables E.1 and E.3).

Roles and goals change significantly in times of crisis: Public actors ensure security for the population, set up points of distribution for essential goods, or repair damaged infrastructure. At the same time, companies seek to sustain or re-start business, generate revenue, and protect employees (Gabler et al., 2017). Even for less disastrous crises, such as the COVID-19 pandemic, commercial food supply came to a test and both continuity planning and stronger supply chain collaboration bear potentials to improve resilience, all of which are parts of the proposed PPEC (Burgos and Ivanov, 2021). Nonetheless, long-lasting collaborations in warehousing are feasible only if chosen locations are valuable and attractive for both actors to fulfill their objectives. Different strategies between public and private actors potentially complicate the selection of joint locations.

Commercial and humanitarian or emergency supply chains are often separately investigated. However, scholars have identified partnering and cross-learning opportunities between the two applications: Gabler et al. (2017) emphasize that despite their different goals, both actors can provide the population with the best possible supply and benefit from resilient supply chains themselves. For example, it is a crucial goal of humanitarian logistics to supply the population with essential goods as quickly as possible to alleviate suffering (Kovács and Spens, 2007). At the same time, the re-entry of private actors into the market and recovery of their business processes is crucial. Kovács and Spens (2007) highlight the linkage of business and humanitarian logistics and discuss similarities such as risk management and continuity planning.

Following these potential synergies, several studies suggest dedicated public-private collaborations (van Wassenhove, 2006; Cozzolino, 2012; Wiens et al., 2018).

E.3.5.3 Value for public and private actors from collaboration

A PPEC can help both actors increase their efficiency. Public actors profit from the resources of private actors, giving better coverage to warehouse networks for emergency supply. Moreover, countries like the US and Germany that maintain public emergency stocks could reduce the number of warehouses and the amount of unused goods, thereby saving taxpayers' money. Moreover, practical experts expect efficiency gains in warehousing. In terms of distribution, a large number of commercial warehouse locations would allow public actors to decentralize their network of warehouses, thereby shortening response times in emergencies. According to another practitioner from a large German retailer, public authorities might use their extensive commercial store networks for distribution in emergencies.

Furthermore, private actors can improve the resilience of their businesses and receive financial compensation for storage and warehouse handling activities. Companies profit from established continuity plans for their operations, improving disaster immunity and, hence, financial performance (Ojha et al., 2013; Tatham and Pettit, 2010). Moreover, they could make a profit by storing public emergency goods while benefiting from the collaboration through access to up-to-date demand and supply information in a crisis (Wiens et al., 2018; Burgos and Ivanov, 2021) and established communication and operation channels (Diehlmann et al., 2021). Engagement of retailers in the UK and Walmart's collaboration with state authorities demonstrate such potential (Table E.3). Companies that are affected by a crisis through physical assets, supply disruptions, or absent customers tend to be eager to cooperate with public actors to strengthen their supply chain (Stewart et al., 2009). Private actors can also benefit from subsidies, training possibilities for staff, and advertising options (Carland et al., 2018). Lastly, corporate social responsibility (CSR) has become increasingly important. This is not for altruistic reasons, but also because of positive relationship between CSR-related engagement (like participation in a PPEC) and corporate financial performance (Madsen and Rodgers, 2015; Cho et al., 2019). Companies appearing in emergency supply and as important actors for people's well-being, because they receive increased media coverage and achieve reputational gains (Wiens et al., 2018).

E.4 Methodology

Although public-private collaboration exists in some domains and potential benefits have been discussed, specific applications must be rigorously evaluated. Our proposed PPEC for emergency food supply is no exception. Evaluation serves to support practitioners' decision-making and to test the concept in an application. We therefore present our three-part evaluation. It begins with the involvement of project partners and experts (Gallien et al., 2015). We then evaluate regions in the geographical area regarding their suitability for joint warehouse locations using utility analysis and actor-specific location criteria. Finally, we develop location-allocation models that determine optimal networks of collaboratively used warehouse locations to assess the proposed PPEC.

E.4.1 Involvement of practitioners

German public authorities aim for more substantial private sector involvement in emergency preparedness, motivating the general problem set. We then validated our PPEC for joint warehousing with practitioners from the public sector and supply chain professionals from a logistics service provider and a food retailer. A more comprehensive range of commercial and emergency logistics experts evaluated location criteria in utility analysis to assess geographical regions. Finally, we discussed the modeling results with practitioners regarding the applicability, steps to implementation, and obstacles or conflicts that need practical resolve.

E.4.2 Evaluation of regions with actor-specific location criteria

We assess the attractiveness of a region with the help of utility analysis (Zangemeister, 2014). Within the analysis, we determine criteria in a literature review, weigh these criteria with the help of experts, and obtain a final score by summing up the products of criteria weights with the region's performance regarding the criteria.

We identify actor-specific criteria by using the literature, publicly available reports, and inputs from discussions with decision-makers. The Supplementary Material details criteria for weighting and data processing. Final attractiveness results offer insights into location selection strategies. Furthermore, results serve as one input for the following optimization models.

E.4.3 Determination of optimal networks

Regardless of the objectives, the location models aim to establish warehouses at analyzed locations and enable deliveries to all demand points. Thus, the solution contains locations where warehouses are opened (i) and the allocation of demand points to warehouses (ii). Cooper (1963) introduced these location-allocation problems. Optimization seeks a cost-effective solution in most commercial applications. Apart from the basic case with one warehouse location, optimization balances transportation and fixed costs for the solution. While more warehouses lead to shorter average transport distances and, thus, lower transportation costs, establishing and maintaining more locations creates fixed costs for each warehouse. Hence, a third result from the model is the optimal number of warehouses to be established (iii).

E.4.3.1 Single-objective optimization

Different model adaptations are needed to take specific objectives into account: First, we distinguish commercial or private actors, like food retailers, that deliver from their warehouses to stores, and public authorities, such as federal ministries for civil protection, that need to ensure the emergency food supply. Models reflect the differences in the location criteria and the costs.

E.4.3.1.1 Commercial scenario *Logistics costs* (LC) usually consist of direct transportation costs, costs for warehousing, commissioning, and related services. Planning, administrative, and order processing costs as well as investment costs, interest, and depreciation are considered additionally (DSLV, 2015). We focus here on location-dependent costs.

$$min \quad TC + FC \tag{E.1}$$

The first part of the objective function (E.1) describes the transportation costs (TC) incurred depending on the allocation of demands to warehouse locations. It assumes direct deliveries. The second term regards fixed costs (FC) from opening warehouses. Taken together, this means that $LC = TC + FC$. We point out details of the cost factors in the case study.

E.4.3.1.2 Emergency scenario In the cost optimization for the emergency scenario, *deprivation costs* (DC) borne by people (or beneficiaries) are added to LC, resulting in *Social Costs* $SC = LC + DC$ (Holguín-Veras et al., 2012). DC occurs if people lack food, medical treatment, or shelter. The application of DC is widely discussed in literature (Holguín-Veras et al., 2013; Loree and Aros-Vera, 2018; Cotes and Cantillo, 2019; X. Wang et al., 2017). We describe the used deprivation cost function in the case study.

We normalize the two added components with *Ideal* and *Nadir Points*, frequently used in multi-objective optimization. On the one hand, the Ideal Point contains the optimal objective values for each criterion. On the other hand, the Nadir Point contains the worst possible value for each criterion. Optimizations for each criterion lead to both points. As such, the points represent upper and lower bounds for the set of efficient solutions (Ehrgott and Tenfelde-Podehl, 2003).

Normalization of LC and DC through Ideal and Nadir points is applied in the objective function (E.2). It combines normalized LC (LC^{std}) and DC (DC^{std}) objectives. Due to normalization and summation, the objective value is between 0 and 2 ($SC^{opt} \in [0; 2]$).

$$min \quad LC^{std} + DC^{std} \tag{E.2}$$

E.4.3.1.3 Attractiveness optimization Optimal attractiveness in both commercial and emergency scenarios is defined as maximum average attractiveness of all chosen locations (AT).

$$\mathbf{max} \quad AT \tag{E.3}$$

The pure attractiveness optimization does not account for spatial layouts. Thus, it is only a reference value for the highest possible attractiveness value when placing an adequate number of sites. Considered regional attractiveness scores differ among actors and are considered in the optimizations for the commercial and emergency scenarios. Average attractiveness AT is between 0 and 1 ($AT \in [0;1]$).

E.4.3.2 Multi-objective optimization

In addition to common cost objectives (e.g., transportation and fixed costs), we consider the local attractiveness scores. They serve as distinct qualitative input to the model, incorporating predefined criteria that actors consider important in placing warehouses for their purpose. Cost and attractiveness goals may compete, requiring the use of multi-objective optimization to combine them (Kallrath, 2013). The single-objective models already balance transportation and fixed costs (i.e., logistics costs) as well as deprivation costs for the emergency scenario, comparable to the location of points of distribution after disasters in Loree and Aros-Vera (2018). In addition, however, the multi-objective models integrate actor-specific location criteria.

We use goal programming to combine optimization goals. In contrast to pre-emptive or lexicographic goal programming, in which goals are ordered by importance, we apply non-preemptive goal programming to balance cost factors and attractiveness. Costs and (numerical) attractiveness inputs are not ranked in the first place, but both are considered equally crucial for the decision. The optimization then minimizes deviations between the optimal value for each objective and the value determined within the multi-objective optimization (Kallrath, 2013). The following paragraphs show the specific objective functions and new variables. We refer to the Supplementary Material for the optimization for attractiveness and detailed constraints.

E.4.3.2.1 Logistics costs and attractiveness The objective function (E.4) captures deviations in LC and attractiveness compared to their optimal values for the multi-objective optimization in the commercial scenario. It weights costs and attractiveness equally. We discuss sensitivity to changes in weights with the results in the case study.

$$min \quad d_{LC}^{-} + d_{AT}^{+} \tag{E.4}$$

Further constraints set LC in relation to (lower) optimal LC^{opt} through slack variable d_{LC}^{-} and attractiveness in relation to (higher) optimal AT^{opt} and (lower) AT^{min} through d_{AT}^{+}. Slack variables must be positive and become part of the base in the solution (Kallrath, 2013).

E.4.3.2.2 Social costs and attractiveness Objective function (E.5) similarly captures deviations in SC and attractiveness in the emergency scenario. As for the commercial case, we discuss sensitivity to different weights in the case study.

$$min \quad d_{SC}^{-} + d_{AT}^{+} \tag{E.5}$$

Again, further constraints connect SC and attractiveness to the reference (optimal) values for each goal. Slack variables d^{-}_{SC} and d^{+}_{AT} are positive.

E.4.3.3 Secondary conditions

Aside from individual objectives, the models share most secondary conditions, which are fundamental to location-allocation problems. First, the entire demand of every location must be satisfied through one or more warehouses. The allocation variable, showing how much demand of a demand point is satisfied from a specific warehouse, must be positive. Second, the total capacity of all opened warehouses must be greater than or equal to total demand, meaning that enough warehouses must be opened to satisfy the demand. Variables indicating if a location is used for a warehouse are binary. Third, we limit the number of warehouses to be opened by requiring a minimum average warehouse utilization U_{WH}. With this, the capacity of all opened warehouses is tied to actual demand. This is especially important when only optimizing for attractiveness, as costs have no influence here. Again, we explain all models and optimization in the Supplementary Material.

E.5 Case study

We evaluate the proposed PPEC with a case study in Germany. As a detail to Table E.1, German authorities maintain approximately 150 emergency warehouses with stocks of grains and legumes (BMEL, 2020b). Around €20 million are spent per year on this system, which is rarely if ever needed and thus has extremely low inventory turnover (Rexroth, 2010). In public disaster management plans, authorities do not own transport equipment. Still, they require help from the private sector to deliver stored items from undisclosed warehouse locations to beneficiaries. Therefore, stored goods are not readily available in an emergency. Moreover, some products need further processing before distribution (e.g., grains), which complicates the crisis response.

Realizing these deficiencies, the partners in the research project that led to our study aspired to develop better solutions for emergency food supply through public-private collaboration. Authorities see dual-use warehouses as one opportunity to achieve their strategic goal of involving the private sector in public crisis management.

E.5.1 Feasibility of the concept

Decision-makers agree on the technical feasibility of shared warehousing and potential efficiency gains by merging the two infrastructures.

We discussed the requirements and objectives of public and private actors with experts from both fields and learned that private partners are willing to help under the following conditions. Responsibility must be taken by the state, which fits the PPEC with leading involvement of public actors, in contrast to purely voluntary engagement. Moreover, payment or monetary compensation must be adequate, and processes must be simple enough to fit into private partners' daily business. Experts confirm that focusing on warehouses as the last instance before reaching customers or the population in stores is reasonable. Moreover, the high density of both warehouses and stores should make the use of existing infrastructure even more appealing for emergency preparedness. However, several practical concerns must be resolved for implementation, including limited space in existing locations, distinct labeling of emergency stocks, and guidelines for their handling. Walmart's voluntary engagement in the US has the particular advantage of using specific disaster distribution centers and clearly separating regular commercial from emergency operations (Walmart, 2021). However, the proposed PPEC is more reliable for planning from the public side, and it can gradually integrate dual-use warehouses into existing systems. As another example, partners consider stock monitoring decisive. Various systems used, such as those in the US or France, would also be feasible in the studied context, potentially based on Germany's existing systems used for information exchange among authorities.

Authority representatives, on the other side, depend on cooperative companies but regard the following points as particularly critical: permanent monitoring by public authorities to ensure contractual fulfillment, reasonable compensation for companies, and responsibly managing existing market power of the large food retailers, which the state could potentially reinforce through a PPEC. Finally, antitrust and procurement law issues are foreseeable with PPEC agreements. While we have discussed monitoring, the integration of several retailers could resolve the latter two points. More partners are especially advantageous, as model results show.

E.5.2 Federal state of Baden-Württemberg

While a federal authority maintains the network of emergency warehouses in Germany, all public experts confirm that primary responsibility in case of disasters is on the state level. Consequently, the federal authority plans its reserves for the different states and according to their respective population densities. Thus, focusing on one state as a single public decision entity is reasonable. In this case, commercial actors agreeing to participate in a PPEC could extend or partially substitute for the existing network of warehouses.

In our case study, we look at the German federal state of Baden-Württemberg (BW). With approximately 1,100 municipalities and 11 million residents, BW can be considered representative of Germany. A public authority and private firms jointly decide locations for dual-use warehouses. Hence, the network should balance efficient everyday commercial operations with suitability for emergency supply. Locations in our case study are municipalities, LAU2 regions as defined by the European Union (EU, 2020). The Supplementary Material contains all details about the underlying criteria, metrics, and scores as well as a discussion of the scores' validity based on the actual locations of a food retailer.

Figure E.1 depicts in black the regions that are most appealing to both actors. Furthermore, dotted and crosshatched areas are highly attractive for only one of the two actors, according to their location criteria. Consequently, several regions in the northwest of BW are attractive for

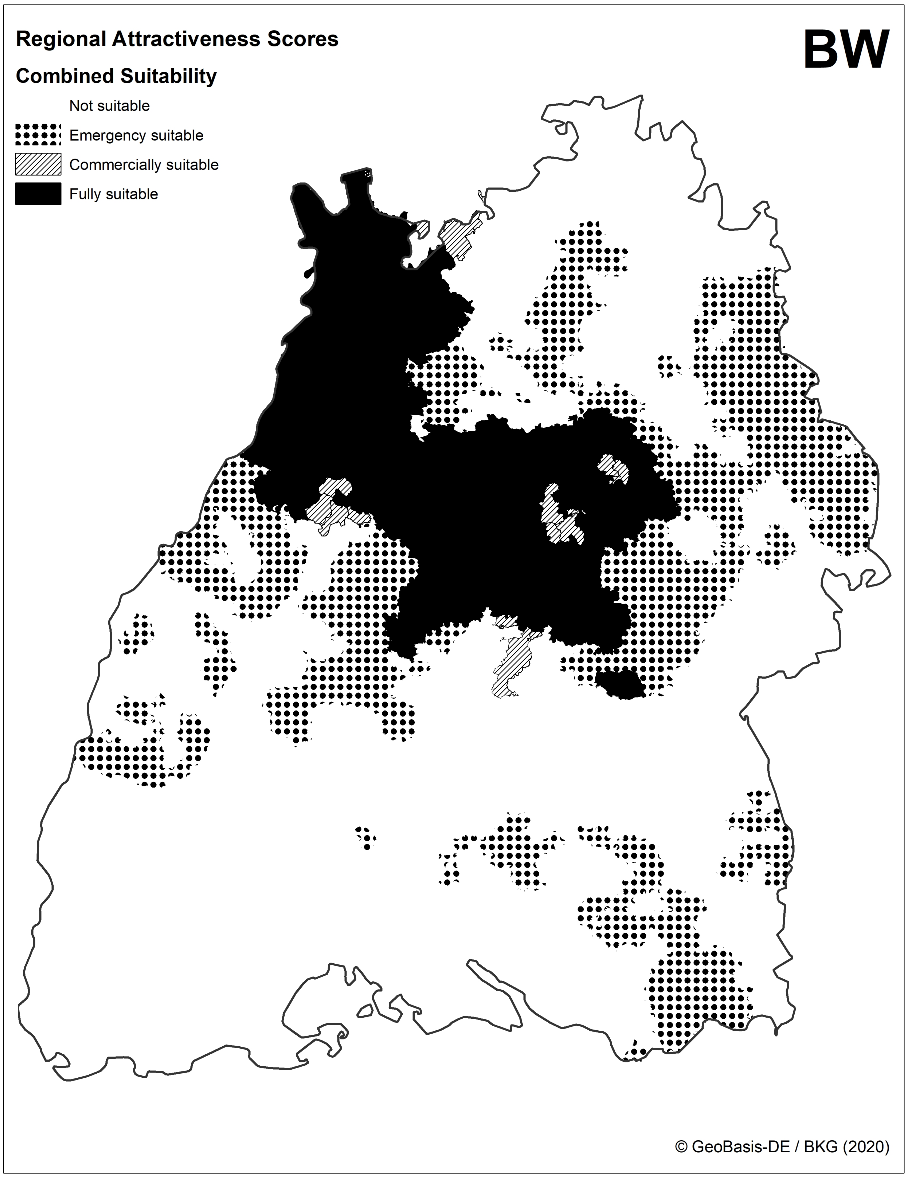

Figure E.1: Final attractiveness scores for Baden-Württemberg per LAU2 unit - suitability for both actors.

both actors, while regions in the southwest score comparably low. Even though this does not account for the specifications of a logistical network, decision-makers could use this to identify regions for which attractiveness should be improved (e.g., through investments in infrastructure). Moreover, companies could include this information in their location decision process. In our location optimization, we use the underlying regional attractiveness scores as an input factor for the optimization models.

E.5.3 Resulting networks of warehouse locations

Private and public actors differ considerably in their objectives and scope. We first apply the presented optimizations on each actor and scenario separately. The resulting networks, costs, and attractiveness provide a baseline for any collaboration. Departing from these *greenfield* results, we present approaches utilizing existing warehouses (i.e., *brownfield*) for the strategic development of a network of locations suitable for effective and efficient emergency food supply. We point out inputs and assumptions for the models before moving to the model results.

E.5.3.1 Potential locations and demand

Private actors only consider their stores as demand points to be supplied through regional warehouses. Moreover, food retailers exclude municipalities that are below a certain threshold of inhabitants as possible store locations. We use a value of 5,000 people for our case study, which several German food retailers use (e.g., Rewe (2019) and Lidl (2019)). Applying this restriction, 502 of 1,102 municipalities remain demand locations. Furthermore, private actors only provide supplies for their market share (e.g., 10% of the population that one retailer needs to supply).

In contrast, public actors must consider different demand locations and not exclude smaller municipalities for economic reasons. In this case, schools or other public buildings may be used in addition to supermarkets for food distribution in an emergency. Consequently, public planners must ensure deliveries to all 11 million potentially affected people.

Food demand per person and day is only slightly different between commercial and emergency planning. Including food and beverages: 3.64kg commercial demand and 3.20kg demand in emergencies, based on per capita consumption of food in Germany and ministry recommendation for personal provisioning (Henrich, 2017; BMEL, 2020a).

E.5.3.2 Transportation costs

Transportation distances were calculated with the help of an extensive digital topographical model of Germany, including BW (BKG, 2018). We obtained the freight cost rate (c_{truck}) of €0.0583 per ton and km for a 24t full truckload with 100% utilization from a German logistics service provider.

E.5.3.3 Warehouse costs and utilization

Fixed warehouse costs include factors that include the acquisition of land, investment in local infrastructure, building construction cost, and equipment. We base our cost and capacity estimation on recent projects by German food retailers (e.g., Flemming (2017); NWZ Online (2016)) and have it validated by logistics experts from the field. We consider two types of warehouses: 1) a standard warehouse offers sufficient capacity to satisfy the demand of 300,000 people at an investment of €40 million; and 2) a large warehouse can supply up to 1,800,000 people, requiring an investment of €100 million.

Since food items only reflect around 76% of the goods in a typical food retailer's assortment (EHI Retail Institute, 2017), mentioned costs are adjusted accordingly. We assume a depreciation period of 20 years and an interest rate of 7% p.a. We restrict the number of warehouses by setting a minimum average warehouse utilization (U_{WH}) of 80%.

E.5.3.4 Deprivation costs

Deprivation costs can be determined in various ways (see, e.g., Shao et al. (2020) for a recent overview). Deprivation cost functions (DCFs) should be determined for the present scenario and country (Shao et al., 2020). However, we integrate deprivation costs as a penalty, penalizing large distances from warehouses to demand locations. We, therefore, use the DCF of Cotes and Cantillo (2019), which was determined based on the waiting time $t_{i,j}$ and the willingness-to-pay for a food pack. While the country context is different, emergencies and goods in question are similar. Function values are normalized whenever combined with local (Euro) cost units.

$$dc(t_{i,j})\ [€] = 0.0063 \cdot t_{i,j}^3 - 0.2555 \cdot t_{i,j}^2 + 5.8403 \cdot t_{i,j}$$

Under the assumption of unrestricted transport equipment and personnel, waiting time is calculated through distance and truck speed before the optimization. The assumption is justified due to public rights to seize such capacity under certain circumstances. In addition to the distances described in this section, we assume an average speed of 45 km/h. The resulting transportation times in the federal state are all less than eight hours, resulting in maximum deprivation costs (i.e., willingness-to-pay) of €32 per person and day. Deprivation costs are considerably low in a small and well-developed area with dense transportation networks, as in our case study. Nevertheless, they count into social costs and penalize longer distances, allowing a balanced solution regarding different costs.

E.5.3.5 Results of the optimization models

The optimization models are implemented in GAMS and solved with CPLEX. We present the results of the warehouse location optimizations in the federal state of BW. Results shown are only for multi-objective models, combining cost and attractiveness objectives. We leave the discussion of single-objective results to the Supplementary Material, briefly discuss the weighting of different objectives: We weigh costs and attractiveness equally in all multi-objective models, as in the model before. There is no evidence to change these weights, but actors could decide on weights individually. From model runs with varying weights, we conclude that equal weights are reasonable, and results are fairly insensitive to minor changes to weights. However, competing objectives must be transparent and clear for decision-makers.

Table E.4 shows results for both actors and greenfield vs. brownfield planning. We first discuss greenfield optimizations. They are the reference for both actors and approximate the public warehouse network, which is confidential for security reasons. Next, we evaluate the utilization of

Converted with an exchange rate of COP 3,706 per EUR (Finanzen.net, 2020).

BW	Commercial (Private)		Emergency (Public)						
	All-new locations (*Greenfield*)			Existing locations (*Brownfield*)					
				Locations of...			One new + locations of...		
	10% market share	100% market share	Public authority	One retailer	Two retailers	Six retailers	One retailer	Two retailers	Six retailers
Locations									
Number of warehouses	4	7	26	6	8	10	7	12	19
Thereof large	0	6	3	6	7	7	7	6	4
Thereof small	4	1	23	0	1	3	0	6	15
Costs [per day, in 1,000 €]									
Logistics costs (LC)	43	232	283	218	217	227	217	209	232
Transportation costs	11	105	42	99	71	65	79	43	34
Opening costs	32	127	241	119	146	162	138	166	198
Deprivation costs (DC)			28,059	64,464	46,876	43,333	52,003	28,904	23,335
Average attractiveness	0.6485	0.6487	0.6124	0.5383	0.5606	0.5739	0.5579	0.5019	0.5222

Table E.4: Multi-objective model solutions for private and public actors in greenfield (left) and brownfield (center to right) planning.

existing (retailer) warehouse locations (brownfield), allowing integration of one or multiple private partners, and, lastly, strategically adding an all-new warehouse. Analyses show that integration of more partners, while presumably more complex, outperforms single or few partners. Adding one new warehouse freely again improves results for the emergency response and even reaches those from the greenfield planning.

Greenfield optimizations let actors create all-new locations according to their preferences. The most evident difference between public and private actors appears in the number of sites, regardless of the assumed market share of the private actor. The larger number of warehouses that emergency actors place is attributable to deprivation costs, which favor shorter distances and, thus, require more warehouses. As a result, chosen locations differ considerably for the two single actors (Figure E.2).

For the two private actors, an accumulation of locations is in the center of the federal state, around its capital city Stuttgart. This is consistent with measures of population density, showing the highest values in the center and on the western border of BW. Emergency optimization, in contrast, leads to 26 locations spread widely across BW (encircled 'X'), again particularly dense in the center of the state. The significant gap in the number and placement of optimal locations makes optimal all-new locations impossible, let alone the discussion of existing networks.

Based on the emergency model for public authorities, we now only consider existing commercial warehouse locations as candidates for collaborative warehouse sites. We use existing sites of up to the six largest food retailers, which account for approximately 55% market share (LZ, 2018). Besides using existing warehouses, collaboration needs coordination and specific capabilities. Such coordination is more complex with more partners. However, more partners means more potential locations, resulting in shorter distances for distribution. To evaluate this, we start by using only the sites of one retailer, moving on to two, and then all six of the largest retailers and their locations. Figure E.4 shows logistics and deprivation costs for a different number of retailers, relative to the greenfield planning before. In the case of *one retailer*, logistics costs are 23% lower than greenfield, while deprivation costs more than double (+130%). Including more partners consistently decreases deprivation costs, and all combinations lead to lower logistics costs than the baseline with all-new

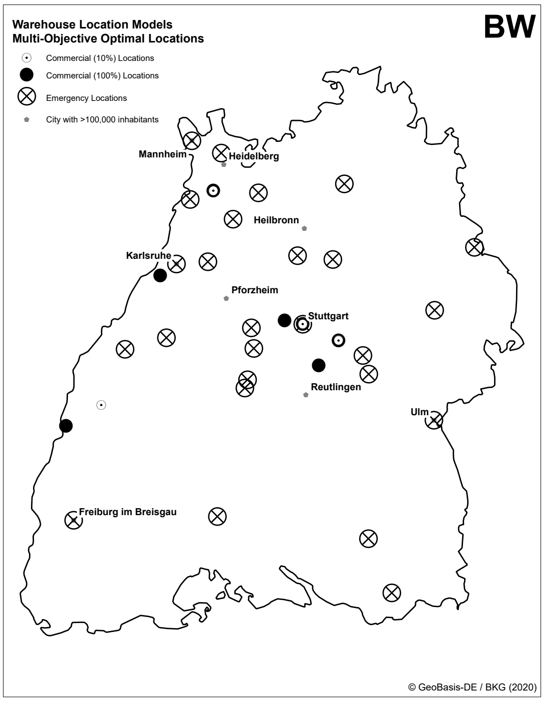

Figure E.2: Multi-objective optimal locations for public (emergency) and private (commercial) actors with all-new locations (greenfield planning).

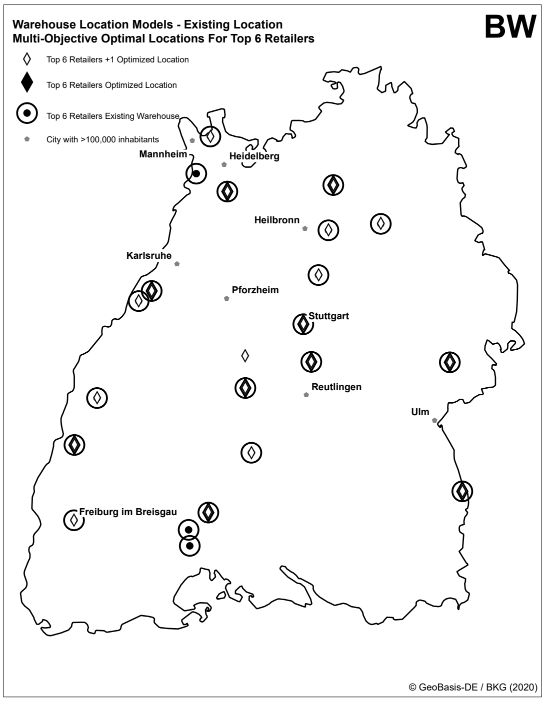

Figure E.3: Multi-objective optimal public (emergency) locations based on existing warehouse locations of largest six food retailers (brownfield planning).

locations; see Table E.4. Logistics costs, however, do not seem to fall indefinitely with an increasing number of partners.

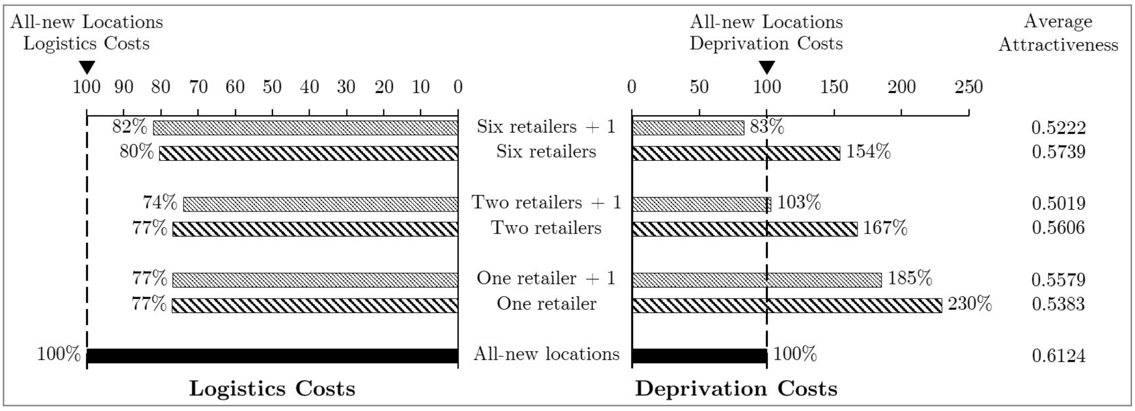

Figure E.4: Logistics costs, deprivation costs, and average attractiveness for different numbers of retailers and locations being included in public (emergency) brownfield planning, relative to all-new locations (bottom, greenfield).

Regardless of the number of retailers, the average attractiveness of the locations is significantly lower than for all-new locations. The smaller number of available locations clearly limits overall attractiveness, and existing sites were not chosen according to emergency but instead for commercial attractiveness.

Deprivation costs are consistently higher for all combinations of retailers. Since all-new locations had the lowest cost here, we propose a network of existing sites, strategically extended with single new and collaboratively planned sites. We expect deprivation costs to decrease in this option. We again evaluate the option starting with one retailer's locations, two, and, finally, all six. In addition to existing locations, it is now possible to select one location freely from all municipalities. Figure E.4 shows logistics and deprivation costs for the adaptation, both in comparison to all-new locations in greenfield planning and the exclusive use of existing locations. For *one retailer + 1*, logistics costs remain the same, while deprivation costs are clearly reduced. For *two retailers + 1* and *six retailers + 1*, results are even more promising: Logistics costs stay well below those of the greenfield solution, while deprivation costs significantly improve. Logistics costs, among all solutions, are the lowest when two retailers are involved. Details can be found in Table E.4. We note that deprivation costs are lower for one brownfield case than for all-new locations. Even though this may not be intuitively expected, attractiveness is again considerably lower than for the greenfield solution, showing the trade-off between cost and attractiveness.

Regarding the numbers, types, and exact locations of warehouses: The number increases with the involvement of more retailers, generally favoring smaller warehouses, thus increasing decentralization (Table E.4). In all cases, locations chosen in the former adaptation remain part of the solution when freely adding one location. Figure E.3 shows locations for the six largest retailers (+1).

The adaptation leads to three conclusions: 1) adding one location consistently improves outcomes, especially for deprivation costs; 2) the overall number of sites increases, particularly adding small (emergency) warehouses to the network, which increases decentralization; and 3) formerly chosen locations remain part of the solution.

E.5.4 Evaluation of results and barriers by practitioners

After conceptualizing and evaluating the PPEC for the federal state, we discussed the results again with project partners. While we present the results for our case study, we have evaluated the attractiveness scores for all of Germany. The experts unanimously confirm that results are valid nationwide. However, one primary concern arose around the suitability of regions, as shown in Figure E.1. Less attractive areas could easily be regarded as less critical, while the state is obliged to strive for equal living conditions and, thus, must not discriminate among regions. Model results show no such discrimination, and attractiveness results hint at potentials to increase regions' attractiveness.

Another concern of public partners is the market power of retailers that collaboration could reinforce and antitrust and procurement regulations. However, model results provide a nuanced perspective on this: Solutions consistently improved with integrating more partners and their locations. This is advantageous for several reasons: Starting with the critique of the public partners, authorities should stay neutral in working with commercial companies, especially considering antitrust and public procurement issues. The inclusion of more partners certainly reduces the need to choose single ones, avoiding being locked-in on the part of public actors. In addition, the integration of more partners allows the public actor to choose from more potential locations. Moreover, retailers may strategically re-locate their warehouses or change strategies in the future. Having a variety of partners would again avoid lock-in. Lastly, results on all-new locations in the former section show a significant gap in the optimal locations for both actors. Again, choosing from a more extensive set of sites generally leads to better solutions. As one downside, having more partners increases coordination efforts and interfaces. However, no practitioner regarded this as a potential problem.

Considering private partners' concerns about potentially limited space in existing locations, the integration of several partners and long-term development of dual-use warehouses appear to provide a sufficient basis for finding solutions in this regard.

The concept needs to be concretized on various practical aspects needed for implementation, including IT systems for monitoring, contracting between public and private actors, and running the system under emergency conditions. Such disaster management capabilities are essential for preparedness (Kunz et al., 2014). Despite barriers to implementation that need resolution, practitioners from both sides are positive about the proposed PPEC, acknowledging the potential for both effectiveness and efficiency of the emergency food supply.

E.6 Discussion

We propose a PPEC, a special instance of public-private partnership, for food warehousing through the development of dual-use warehouses. While owned by private companies, warehouses are connected to and used by authorities to organize emergency food supply in times of crisis. Consequently, joint planning and implementation are needed.

Our study evaluates the feasibility of the concept and its value for both actors. It therefore also discusses trade-offs among objectives, actors' willingness to collaborate, and barriers to implementation. We use a case study of a federal state in Germany to evaluate the concept through secondary data analysis and specific optimization models. We continuously exchange on and validate the concept with project partners from practice. We first find that both actors choose mostly different locations and overall networks independently. Generally, authorities prefer more decentralized stocks evenly spread across the state. On the other side, retailers maintain fewer locations close to densely populated areas. Those differences are grounded in distinct goals and location criteria that both actors have. While private actors choose locations for warehouses relative to their stores and suppliers, authorities are obliged to ensure supply for the whole population. High inventory turnover and availability and labor costs are decisive for private actors, while authorities especially require reliable transport infrastructure, equipment, and low social costs in case of an emergency. Therefore, location and cost criteria lead to different solutions for both actors.

The study shows that integrating several food retailers and their warehouses in such collaboration yields good results for emergency preparedness. Generally, integrating more partners improves outcomes from a cost perspective but complicates collaboration. However, practitioners unanimously view this as manageable. At the same time, integration of more partners yields significant advantages, especially for authorities: It avoids lock-in effects with single partners, ensures far-reaching neutrality toward market actors, and generally allows choosing from a broader set of options. More potential locations enable the public actors to have a more extensive set of evenly distributed locations, aligned with their objectives and obligations. Additionally, private actors see potential limitations in available warehousing space in existing sites and, thus, could more easily join such collaboration with smaller stocks per site.

Using existing warehouses should decrease required investment in locations, especially for public authorities. Moreover, since the facilities are already established and productive, all required infrastructure, personnel, and processes are in place. Operationally, the required adjustments for specific emergency processes and training are small. The use of existing locations reduces the changes necessary for comprehensive preparedness (Kunz et al., 2014).

We propose jointly chosen additional single facilities as a strategic option. Results in this option are again improved and provide a valuable opportunity for authorities to develop their emergency stocks network in the future. Moreover, the evaluation of regions for both actors can help increase attractiveness for private companies in locations deemed valuable for public preparedness. We limit our analysis to adding one location as it is unlikely that public actors will abandon their warehouses at once but rather gradually increase private sector involvement, first through existing sites. Only then would jointly planned dual-use warehouses follow.

We note that theoretically optimal solutions are not overly sensitive to changes in single locations regarding the models' results. For example, one might choose a neighboring municipality for practical reasons without drastically changing overall costs. Deprivation costs drive the number of locations in the emergency case, as the comparison of single- versus multi-objective optimization in the Supplementary Material shows. Overall, multi-objective models are insensitive to small changes in objectives' weights. The results for changing numbers of retailers in collaboration remain unaffected since (in)sensitivity was consistent for changes in either direction.

We discuss emergency food supply in developed countries and provide an overview. While the countries share a competitive private food sector, public authorities differ in their intensity to leverage it for required emergency preparedness. The proposed PPEC focuses on using existing infrastructure, minimizing the need for separate locations and entire parallel structures. The concept is most directly applicable to change today's setup of emergency stocks in the US and Germany, where private actors are involved voluntarily or ad-hoc and authorities maintain dedicated warehouses that are redundant and costly (Palin, 2017; Rexroth, 2010). Arguably, voluntary engagement like Walmart in the US is highly helpful in crises. However, it does not fulfill the legal requirements for public authorities regarding preparedness. Therefore, it can only serve as an additional resource but not replace publicly controlled preparedness measures.

The Swiss model is closer to our concept, integrating all sellers of essential goods but using dedicated infrastructure only for emergency stocks. It is expensive, compared to German emergency stocks, but also serves to balance the food market in the small country with less of a self-sufficient food supply (Rexroth, 2010; German Federal Office for Civil Protection and Disaster Assistance, 2019b). The government in the UK is not required to keep physical stock but relies on informal collaboration with the private sector and business continuity preparations. French preparedness measures include no emergency stocks either but rely on information exchange and decision-support. For both countries, the proposed PPEC could improve monitoring of stocks and add specific goods for emergencies to privately-held stocks.

The concept appears to be a valuable option for emergency preparedness in different countries while being more directly applicable in some than in others. However, information exchange, stock monitoring, and privately held emergency stocks in warehouses are helpful for all included countries. Lastly, potential advantages become accessible for public authorities through the cross-sector collaboration and use of infrastructure, equipment, personnel, IT systems, and processes. Efficient transportation and handling through existing (horizontal) collaborations in the private sector, labor pooling in clusters, and general resource sharing support operational efficiency. Private partners agree and stress the need for processes compatible with their daily operations. Including efforts in regards of continuity planning and a remuneration, companies can profit from the collaboration themselves (Ojha et al., 2013; Burgos and Ivanov, 2021). Although partners' goals differ, effective collaboration in case of emergencies profits both public and private sectors (Gabler et al., 2017; Kovács and Spens, 2007).

The study has some limitations that affect the transfer of the concept into practice. To start with, we argue emergency preparedness. However, our study only evaluates locations for dual-use warehouses, not going into more detailed planning. Experts correctly point at issues needing detailing for implementation, such as specific items and stock levels and their integration at existing locations with limited space. Aspects that directly influence pre-positioning locations, such as vulnerability to natural risks, are included in our analysis. Stocking details are, however, not included but are decisive parameters in planning and cost modeling (Campbell and Jones, 2011; D. Wang et al., 2023). The same holds true for the actual implementation of an information exchange system, enabling efficient coordination (Dash and Dixit, 2022). Other crisis dynamics are likely to influence the networks, for instance, damage to the infrastructure, uncertainty regarding data, or a shift in inventory or demand (Pan et al., 2020). While we include some criteria geared at resilience, our approach does not cover dynamics. Consequently, future studies investigating these uncertainties and dynamics in warehouse location planning might deepen the understanding of efficient collaboration.

E.7 Conclusion

We present a public-private emergency collaboration on food warehousing through dual-use warehouses. The warehouses are used by private partners in normal times for food supply while enabling a public emergency response in times of crisis.

The study of a large federal state in Germany provides encouraging results to pursue a PPEC on food warehousing, using existing locations of several commercial food retailers and strategically adding single new facilities over time. Closely involved practitioners from public and private sectors unanimously evaluate the concept and results as plausible, understandable, and worthy of further investigation. At the same time, project partners raised important issues that need to be assessed and resolved.

Positive results warrant attention to open questions that must be addressed for specific implementations of the concept. Starting from the particular spatial scope and the objectives of the authorities, an evaluation of the food market structure is needed to determine potential commercial partners. Practitioners correctly point out that bringing all potential actors together requires a great effort. As one of them put it, the coordinating authority must "get everyone on board" and "whoever gets to organize this will face a great effort." Therefore, concrete collaboration conditions and schemes must be developed and evaluated together. The strategic option to add jointly planned locations can significantly improve emergency preparedness. For public authorities, this means they need to analyze gaps in the network of existing sites and then determine potential additional locations. Since collaboration is particularly desirable for public authorities, they should aim for collaboration, also in potentially new locations, and only consider single dedicated public warehouses to pre-position emergency supplies if no collaboration is possible.

Incorporating the private sector's warehouses into authorities' emergency preparedness plans offers potential benefits for both sides and society at large. At the same time, implementing the concept is a demanding process that requires a profound understanding of the requirements of both actors and their objectives. Our study proposes a PPEC for food warehousing in dual-use facilities, providing results that underline the potential value of such collaboration and laying out future steps for practitioners and research opportunities for academia.

Declaration of interest

This research was supported by the German Federal Ministry of Education and Research (BMBF) in the NOLAN project (grant numbers 13N14457 and 13N14459).

E.8 Supplementary material

E.8.1 Metrics for attractiveness score

As described in the companion article, the selection of appropriate metrics is crucial for the attractiveness score. Table E.5 highlights our selection for the German-wide attractiveness score. Due to comparably low consistency ratios, we had to disregard the evaluation results of one expert (see also Saaty (1977); Saaty and Ozdemir (2003) for further insights on the components of AHP).

Note that, due to our case study's focus on BW, the German-wide analysis regards additional criteria. These criteria are indirectly included in the optimization models for BW and, therefore, not considered in the BW-wide analysis. Considering the commercial score, these criteria are *Market in Proximity* and *Land Availability and Price Level*. Considering the emergency score, *Proximity to Beneficiaries* is additionally included in the German-wide analysis.

In most cases, a criterion is evaluated using multiple metrics. If possible, the values of these metrics were weighted under consideration of their relative importance. For instance, criterion C.4 ("Availability of different transport modes") consists of three metrics representing the distance to a port, a train station, or an airport. To account for their varying importance for transportation, we weighted them according to their relative share of transportation volume (Hütter, 2016).

Furthermore, we need to normalize criteria values. In this context, it is crucial to investigate minimum and maximum values as well as the mean of the data (Fleming and Wallace, 1986). Upper and lower bounds represent minimum and maximum values within the data in most cases. Further adjustments can be necessary due to outliers that are identified using standard tools such as a boxplot (Williamson et al., 1989).

We set the boundaries for outliers based on the interquartile range (IQR), the distance between the 25% and 75% quartiles. All values above the 75% quantile plus 1.5 times the IQR are considered outliers and regarded with the value of 1. Values below the 25% quantile minus 1.5 times the IQR are regarded with the value of 0. Consequently, we norm each value dependent on its position within the outlier-adjusted interval (see for instance Voogd (1982)).

Lastly, we distinguish benefit and cost metrics and invert cost metrics to measure them on the same scale as benefit metrics. Benefit metrics refer to an interpretation of higher values as favorable outcomes (e.g., market size measured by customers in proximity). On the other hand, lower values are preferred for cost metrics (e.g., tax rates; Voogd (1982)). Consequently, scores for cost metrics are transformed by subtracting the standardized score from 1.

Code	Criterion	Metrics	Description	Cost/ Benefit	Weight	Source
C.1	Market in Proximity	Population within 50km	Overall population in all NUTS3 units within 50km distance	b	1	Eurostat (2019e)
C.2	Producer Proximity	Regional food producer density	Food and drink producers and companies per NUTS2 unit relative to its area	b	1	Eurostat (2019f, 2019a)
C.3	Transport Infrastructure Quality and Reliability	Travel time to highway	Travel time to next highway by car per LAU2 unit [<=15min, 15-30min, 30-45min, 45-60min, >=60min]	c	0.25	BBSR (2012)
		Street network density	Street network length per NUTS3 unit relative to its area	b	0.25	BKG (2019); Eurostat (2019a)
		Bridge conditions	Share of bridges graded "not sufficient" or worse per NUTS3 unit	c	0.25	BAST (2018b)
		Street conditions	Share of streets with conditions rating for intensive inspection per NUTS1 unit	c	0.25	BMVI (2018)
C.4	Availability of Different Transport Modes	Distance to port	^{a}Street network distance to next port per LAU2 unit	c	0,65^{a}	BKG (2019)
		Distance to station	^{a}Street network distance to next cargo train station per LAU2 unit	c	0,34^{a}	BKG (2019)
		Distance to airport	^{a}Street network distance to next airport per LAU2 unit	c	0,01^{a}	BKG (2019)
C.5	IT and Telecommunications Infrastructure	Broadband availability	Share of households with broadband access per NUTS1 unit	b	0.33	Eurostat (2019b)

		Internet speed	Average internet speed per NUTS1 unit, rural and urban areas distinguished according to no. of inhabitants	b	0.33	Verivox GmbH (2016)
		4G availability	Share of households with 4G access per NUTS1 unit	b	0.33	BMVI (2019a)
C.6	Availability and Skills of Labor Force	Job vacancy times	Average job vacancy times in logistics per NUTS1 unit	c	0.33	BA (2019)
		Population	Population between age 15 and 64 per NUTS3 unit	b	0.33	Eurostat (2019e)
		Formal education	Share of population between age 15 and 64 with education above ISCED level 3 (at least secondary education) per NUTS2 unit	b	0.33	Eurostat (2019d)
C.7	General Labor Costs	Net labor costs	Net labor costs in transportation and logistics per hour per NUTS1 unit	c	1	Destatis (2016)
C.8	Land Availability and Price Level	Availability of new industry property	Share of newly sold industry property relative to existing industry area between 2014 and 2017 per NUTS1 unit	b	0.5	Destatis (2020b); Eurostat (2019a)
		Price for new industry property	Average price for industry property between 2014 and 2017 per NUTS1 unit	c	0.5	Destatis (2020b)
C.9	Local Taxes	Business tax	[b]Business tax ("Gewerbesteuer") collection rate per LAU2 unit	c	0,79[b]	Destatis (2018)
		Property tax	[b]Property tax ("Grundsteuer B") collection rate per LAU2 unit	c	0,21[b]	Destatis (2018)
E.1	Proximity to Beneficiaries	Reachable population	Population reachable within 60min by truck per LAU2 unit	b	1	ORS (2020)
E.2	Road Connections	Travel time to highway	Travel time to next highway by car per LAU2 unit [<=15min, 15-30min, 30-45min, 45-60min, >=60min]	c	0.5	BBSR (2012)
		Street network density	Street network length per NUTS3 unit relative to its area	b	0.5	BKG (2019); Eurostat (2019a)
E.3	Airport proximity	Distance to airport	Street network distance to next airport per LAU2 unit	c	1	BKG (2019)
E.4	Transport Infrastructure Resilience and Quality	Street network density	Street network length per NUTS3 unit relative to its area	b	0.25	BKG (2019); Eurostat (2019a)
		Highway accesses	Number of highway junctions within 20km radius	b	0.25	BKG (2019)
		Bridge conditions	Share of bridges graded "not sufficient" or worse per NUTS3 unit	c	0.25	BAST (2018b)
		Street conditions	Share of streets with conditions rating for intensive inspection per NUTS1 unit	c	0.25	BMVI (2018)
E.5	IT and Telecommunications Infrastructure	Broadband availability	Share of households with broadband access per NUTS1 unit	b	0.33	Eurostat (2019b)
		Internet speed	Average internet speed per NUTS1 unit, rural and urban areas distinguished according to no. of inhabitants	b	0.33	Verivox GmbH (2016)
		4G availability	Share of households with 4G access per NUTS1 unit	b	0.33	BMVI (2019a)
E.6	Availability of Transport Equipment	Origin freight traffic	Domestic annual road freight traffic in tons per originating NUTS3 unit	b	0.25	Eurostat (2019c)

		Destination freight traffic	Domestic annual road freight traffic in tons per destination NUTS3 unit	b	0.25	Eurostat (2019c)
		Transit freight traffic	Average freight traffic density in vehicles per hour per NUTS2 unit	b	0.25	BAST (2018a)
		Logistics firm density	Warehousing and logistics firms per NUTS2 unit relative to its area	b	0.25	Eurostat (2019f, 2019a)
E.7	Minimum Distance to Critical Facilities	Nuclear power plants	Euclidean distance to next nuclear power plant per LAU2 unit	b	0.33	GLOBAL 2000 (2019); BKG (2019)
		Refineries and chemical sites	Euclidean distance to next refinery or other chemical industry site per LAU2 unit	b	0.33	VCI (2019); BKG (2019)
		Airport	Euclidean distance to next (major) airport	b	0.33	ADV (2020); BKG (2019)
E.8	Vulnerability to Natural Risks	Storm hazard	Hazard for winter storm (50 year event) per LAU2 unit	c	0.33	CEDIM (2019)
		Earthquake hazard	Hazard for earthquake (475 year event) per LAU2 unit	c	0.33	CEDIM (2019)
		Water proximity	Euclidean distance to sea or next river per LAU2 unit	b	0.33	BKG (2019)
E.9	Minimum Distance to Large Cities	Type of region	Type of region per LAU2 unit according to RegioStaR 7 typology	b	1	BMVI (2019b)

[a] Weight depends on relative share of the volume of goods that are transported on the transport mode (65%/34%/1%; Hütter (2016))
[b] Weight depends on relative share of the tax type (80%/20%; Destatis (2020a))

Table E.5: Overview of selected criteria and metrics.

E.8.2 Germany-wide attractiveness score

E.8.2.1 Weights for criteria

The resulting weights for each criterion are shown in Table E.6.

E.8.2.2 German attractiveness score

Figure E.5 presents the final commercial (left) and emergency (middle) attractiveness scores. The maps show all German municipalities with their respective score from light blue (lowest attractiveness) to dark blue (highest). Commercially, the city and region of Berlin and a large area in the federal state of Northrhine-Westphalia in the western part of Germany (including, e.g., Cologne, Düsseldorf, and Dortmund) are most attractive. Other metropolitan regions, e.g., Hamburg, Stuttgart, or Munich, are also rather attractive. The Northern part of Hesse in the middle of Germany and some border regions are least attractive.

Commercial attributes and weights		Emergency attributes and weights	
Market in proximity	0.19	Proximity to beneficiaries	0.09
Producer proximity	0.07	Road connections	0.11
Transport infrastructure access and reliability	0.12	Airport proximity	0.05
Availability of different transport modes	0.05	Transport infrastructure resilience and quality	0.16
IT and telecommunications infrastructure	0.06	IT and telecommunications infrastructure	0.13
Availability and skills of labor force	0.19	Transport equipment availability	0.18
General labor costs	0.16	Minimum distance to critical facilities	0.08
Land availability and price level	0.13	Minimum distance to large cities	0.08
Local taxes	0.04	Vulnerability to natural risks	0.12

Table E.6: Selected location criteria and resulting weights for private (commercial) and public (emergency) actors and scenarios.

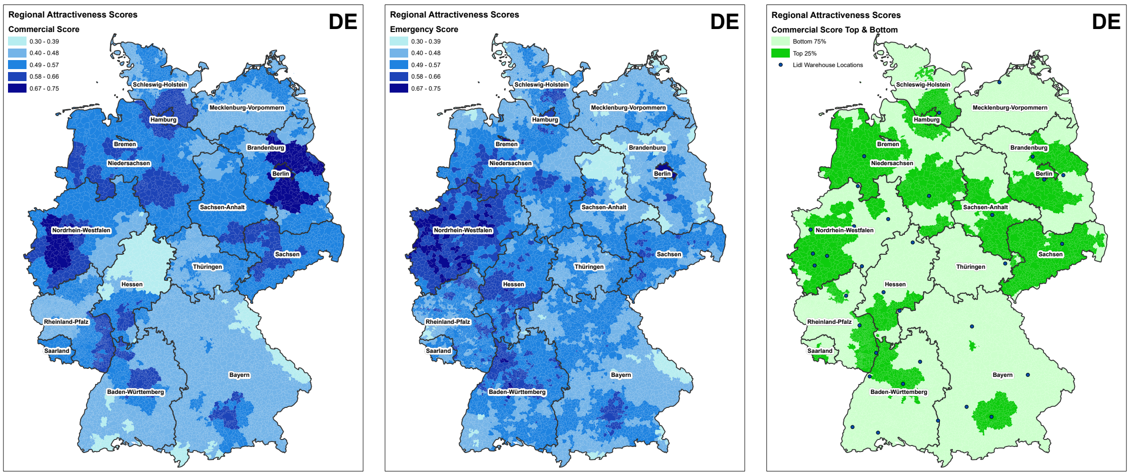

Figure E.5: Final attractiveness scores for Germany (DE) per LAU2 unit; left: Commercial attractiveness; middle: Emergency attractiveness; right: 25% commercially most attractive regions and publicly available Lidl warehouse locations.

Considering emergency attractiveness, the city of Berlin is also most attractive, together with the city of Bremen in the north and various municipalities in Northrhine-Westphalia. The least attractive regions are in Northern Saxony-Anhalt, areas of Brandenburg, and Eastern Bavaria. Overall, large cities are rather attractive for both scenarios. All but one of the largest 20 cities in Germany are among the most attractive 25% in both scores.

We illustrate the transparency gains through both scores with the help of one municipality, whose attractiveness largely differs between both scenarios. While in the commercial score, a large region north and south of Berlin (northeast of Germany) is highly attractive (i.e., dark blue), some municipalities north of Berlin are among the least attractive (i.e., light blue) for the emergency scenario. One of these municipalities is Stechlin, north of Berlin and close to the border between the federal states of Brandenburg and Mecklenburg-Vorpommern further north. The village is commercially especially attractive due to low labor costs and proximity to Berlin, implying a large market. For emergencies, however, its overall transport and IT infrastructure and the population in close reach are far below average, resulting in a low overall score. The combination of different scores allows to draw far-reaching conclusions on a very detailed level.

Furthermore, the score aims to provide practical guidance in finding a macro-location for new warehouses. To validate our results, we cross-check it with real commercial warehouse locations of supermarket chain Lidl (Figure E.5, right). Therefore, we highlighted Lidl's, publicly available (Lidl, 2020) 39 warehouse locations on a map that points out regions which score within the *Top 25%* commercial attractiveness regions (dark green) and the *Bottom 75%* (light green). If the score were not relevant at all, around 25% of all Lidl locations would have been supposedly located in the dark green areas. However, we identified 19 out of 39 locations (approx. 49%) in attractive regions, with several warehouses close to dark green areas.

Moreover, the network grew over a long time and factors such as the availability of a suitable property at the time of construction play a crucial role. Combined with the fact that we regard the German borders as system boundaries, neglecting attractive markets in the neighboring regions, the results suggest that the score is helpful to identify attractive locations.

E.8.3 Warehouse location models

Table E.7 contains all variables used in this section and the models. Table E.8 presents our modeling and optimization approach. We use this structure since it allows us to understand the individual components more clearly and points out trade-offs more clearly than a pure multi-objective optimization. Therefore, we developed three models for both types of actors and their respective scenarios: cost minimization, attractiveness maximization, and multi-objective optimization. Cost minimization in the emergency scenario and multi-objective optimization for both scenarios require various objective values as inputs for standardization.

We use adaptations of the underlying models to optimize specifically for standardization (steps 1.5, 1.6, 2.1, 2.2, and 2.6). The following sections introduce and discuss the optimization models. Adaptations are mentioned accordingly.

E.8.3.1 Cost optimization

E.8.3.1.1 Minimization of logistics costs

Note that, due to public authorities' confidentiality, we cannot validate the emergency score similarly.

$$min \quad \sum_{i=1}^{m}\sum_{j=1}^{n} x_{i,j} \cdot tp_{i,j}^{s} + \sum_{i=1}^{m} \left(y_i^b \cdot F^b + y_i^l \cdot F^l \right) \tag{E.6}$$

s.t.

$$\sum_{i=1}^{m} x_{i,j} = 1 \quad \forall j \in J \tag{E.7}$$

$$y_i^l \leq y_i^b \quad \forall i \in I \tag{E.8}$$

$$\sum_{j=1}^{n} x_{i,j} \cdot P_j^s \leq y_i^b \cdot C^b + y_i^l \cdot C^l \quad \forall i \in I \tag{E.9}$$

$$\sum_{i=1}^{m} y_i^b \cdot C^b + y_i^l \cdot C^l \leq \sum_{j=1}^{n} P_j^s \cdot \frac{1}{U_{WH}} \tag{E.10}$$

$$x_{i,j} \geq 0 \quad \forall (i,j), i \in I, j \in J \tag{E.11}$$

$$y_i^b, y_i^l \in \{0; 1\} \quad \forall i \in I \tag{E.12}$$

The first term of the objective function (E.6) describes transportation costs (TC) that occur depending on the allocation of demands to warehouse locations. It assumes direct deliveries to the demand points. The second term regards fixed costs (FC) from opening small (y_i^b) and large (y_i^l) warehouses. Overall, it holds that $LC = TC + FC$ as given in the manuscript.

Equations (E.7) ensure that the whole demand is fulfilled. For modeling reasons, we introduce Equations (E.8) which restrict opening a large warehouse to locations where a small warehouse is already located. However, this does not affect the strategy's practical implementation since we technically add up their capacities. Any location will always have either no or exactly one (small or large) warehouse. We show this in the model solutions for the case study. Following, (E.9) allow allocation only until a warehouse's capacity is reached. In turn, if no warehouse exists at a certain location ($y_i^b = y_i^l = 0$), allocation is not possible.

Equation (E.10) constrains the overall number of warehouses relative to the population to be supplied in certain scenarios. The left side of the equation describes the overall capacity of all opened warehouses. It is set to be less or equal to the sum of the population divided by the minimum average warehouse utilization U_{WH}. With U_{WH} being smaller or equal to 1, overall warehouse capacity is equal or free to be slightly larger than the actual demand. Moreover, allocation can only be positive (E.11), and warehouses of both sizes are either opened or not, which is reflected by binary variables y_i^b and y_i^l in (E.12).

The optimization determines both optimal LC and the number and location of warehouses.

E.8.3.1.2 Minimization of social costs

In the cost optimization for the emergency scenario, *deprivation costs* (DC) beared by people (or beneficiaries) are added to LC, resulting in so-called *Social Costs* (Holguín-Veras et al., 2012): $SC = LC + DC$.

We standardize components with *Ideal* and *Nadir Points*, which are widely used in multi-objective optimization. The Ideal Point contains the optimal objective values for each criterion. On the other hand, the Nadir Point contains the worst possible value for each criterion. Both points are obtained through optimizations for each single criterion (steps 2.1 and 2.2 in Table E.8). As such, the points represent upper and lower bounds for the set of efficient solutions (Ehrgott and Tenfelde-Podehl, 2003).

The standardization of LC and DC through Ideal and Nadir points is applied in objective function (E.13). It combines LC (Eq. (E.6)) and DC objectives. Due to the standardization, the objective value is between 0 and 2 ($SC^{opt} \in [0;2]$). The function changes into $LC^{std} + DC^{std}$ as given in the manuscript.

$$min \quad \frac{\left[\sum_{i=1}^{m}\sum_{j=1}^{n} x_{i,j}\cdot tp_{i,j}^{s_e} + \sum_{i=1}^{m}\left(y_i^b\cdot F^b + y_i^l\cdot F^l\right)\right] - LC^{opt,s_e}}{LC^{nad,s_e} - LC^{opt,s_e}} + \frac{\left[\sum_{i=1}^{m}\sum_{j=1}^{n} x_{i,j}\cdot dp_{i,j}\right] - DC^{opt}}{DC^{nad} - DC^{opt}} \tag{E.13}$$

s.t.

Eq. (E.7), Eq. (E.8), Eq. (E.9), Eq. (E.10), Eq. (E.11), Eq. (E.12)

E.8.3.2 Attractiveness optimization

Even though attractiveness scores are primarily considered in the multi-objective optimizations together with costs, the determined scores allow to optimize solely for attractiveness, too. Spatial distribution of the locations may be far from optimal when neglecting transportation volumes and costs. Nevertheless, it provides important information and a baseline for attractiveness in multi-objective optimization. Hence, we discuss and evaluate attractiveness separately. The following model maximizes the average attractiveness of opened warehouses.

$$max \quad \sum_{i=1}^{m} y_i^b \cdot A_i^s \tag{E.14}$$

s.t.

$$\sum_{i=1}^{m} y_i^b = \hat{y}^{s,b} \tag{E.15}$$

Eq. (E.7), Eq. (E.8), Eq. (E.9), Eq. (E.10), Eq. (E.11), Eq. (E.12)

While optimizing the average attractiveness of all warehouse locations, explicit cost considerations are disregarded. Consequently, the objective function (E.14) only considers locations of opened warehouses and their respective attractiveness values for scenario s ($s \in S$). Average attractiveness is computed afterward.

Equations (E.7) to (E.12) are unchanged from the former models. To ensure obtaining the optimal solution, we iterate the model over all possible numbers of warehouses as $\hat{y}^{s,b}$, fixed in Equation (E.15). Average attractiveness AT^{s} is computed from the sum of all locations divided by the number of warehouses opened. We use its optimum value $AT^{opt,s}$ as input for the multi-objective optimization.

E.8.3.3 Multi-objective optimization

Besides different goals between actors as described in the introduction, we also consider multiple goals one decision maker aims to satisfy. In addition to common cost objectives, e.g., transportation and fixed costs, we take the aforementioned local attractiveness scores into account. They serve as distinct and more qualitative input to the model, using pre-defined criteria that actors consider important in placing warehouses for their purpose. Cost and attractiveness goals may compete, necessitating the use of multi-objective optimization to combine them (Kallrath, 2013).

We use goal programming to combine various optimization goals. In contrast to pre-emptive or lexicographic goal programming, in which goals can be clearly ordered by importance, we apply non-preemptive goal programming to balance cost factors and attractiveness. Costs as quantitative and attractiveness as mainly qualitative input are not ranked in the first place. Both are instead considered equally crucial for modeling. The optimization then minimizes deviations between the optimal value for each objective and the value determined within the multi-objective optimization (Kallrath, 2013).

E.8.3.3.1 Commercial scenario: logistics costs and attractiveness

The following optimization model generates the optimal locations and allocations in the commercial scenario.

The objective function (E.16) captures deviations in LC and attractiveness compared to their optimal values. Equation (E.17) sets standardized LC in relation to optimal $LC^{opt,c}$ through slack variable d^{-}_{LC}. $LC^{opt,c}$ standardized is 0, since: $\frac{LC^{opt,s_c} - LC^{opt,s_c}}{LC^{max,s_c} - LC^{opt,s_c}} = 0$. Equation (E.18) standardizes attractiveness similarly. Again, the optimal reference value on the right side must be standardized. Following, the right side is: $\frac{AT^{opt,s_c} - AT^{min,s_c}}{AT^{opt,s_c} - AT^{min,s_c}} = 1$. Slack variables must be positive (Equations (E.19)). Therefore, at most one in each pair of slack variables becomes part of the base in the solution (Kallrath, 2013).

In line with the attractiveness optimization, the model is iterated over all possible numbers of warehouses.

$$min \quad d_{LC}^{-} + d_{AT}^{+} \tag{E.16}$$

s.t.

$$\frac{\left[\sum_{i=1}^{m}\sum_{j=1}^{n} x_{i,j} \cdot tp_{i,j}^{s_c} + \sum_{i=1}^{m}\left(y_i^b \cdot F^b + y_i^l \cdot F^l\right)\right] - LC^{opt,s_c}}{LC^{max,s_c} - LC^{opt,s_c}} - d_{LC}^{-} = 0 \tag{E.17}$$

$$\frac{\sum_{i=1}^{m}\left(y_i^b \cdot A_i^{s_c}\right)/\hat{y}^{s_c,b} - AT^{min,s_c}}{AT^{opt,s_c} - AT^{min,s_c}} + d_{AT}^{+} = 1 \tag{E.18}$$

$$d_{LC}^{-}, d_{AT}^{+} \geq 0 \tag{E.19}$$

Eq. (E.7), Eq. (E.8), Eq. (E.9), Eq. (E.10), Eq. (E.11), Eq. (E.12), Eq. (E.15)

E.8.3.3.2 Emergency scenario: social costs and attractiveness

The following optimization model generates the optimal locations and allocations in the emergency scenario.

$$min \quad d_{SC}^{-} + d_{AT}^{+} \tag{E.20}$$

s.t.

$$\left[\frac{\left(\sum_{i=1}^{m}\sum_{j=1}^{n} x_{i,j} \cdot tp_{i,j}^{s_e} + \sum_{i=1}^{m}\left(y_i^b \cdot F^b + y_i^l \cdot F^l\right)\right) - LC^{opt,s_e}}{LC^{nad,s_e} - LC^{opt,s_e}} + \frac{\left(\sum_{i=1}^{m}\sum_{j=1}^{n} x_{i,j} \cdot dp_{i,j}\right) - DC^{opt}}{DC^{nad} - DC^{opt}}\right] \cdot \frac{1}{2} - d_{SC}^{-} = \frac{SC^{opt}}{2} \tag{E.21}$$

$$\frac{\sum_{i=1}^{m}\left(y_i^b \cdot A_i^{s_e}\right)/\hat{y}^{s_e,b} - AT^{min,s_e}}{AT^{opt,s_e} - AT^{min,s_e}} + d_{AT}^{+} = 1 \tag{E.22}$$

$$d_{SC}^{-}, d_{AT}^{+} \geq 0 \tag{E.23}$$

Eq. (E.7), Eq. (E.8), Eq. (E.9), Eq. (E.10), Eq. (E.11), Eq. (E.12), Eq. (E.15)

The objective function (E.20) includes the deviation of social costs and attractiveness from their optimal values. Equation (E.21) connects LC and DC through slack variable d_{SC}^{-} to the optimal value for social costs (SC^{opt}). As mentioned above, standardized SC is between 0 and 2 due to its two components. Both terms on the left and right sides of the equation are, therefore, divided by 2. Otherwise, slack variables were larger than for attractiveness, giving an unintended overweight to SC in the objective function.

Equation (E.22), similar to equation (E.18) in the commercial scenario, sets attractiveness in relation to its optimum value. The right side simplifies to 1 since $\frac{AT^{opt,s_e} - AT^{min,s_e}}{AT^{opt,s_e} - AT^{min,s_e}} = 1$. Again, we iteratively run the model for all possible numbers of warehouses to ensure the determination of an optimal solution.

E.8.4 Optimization results

E.8.4.1 Greenfield - details

Distinct optimizations for each actor and with new locations reveal consistent results for the different objectives. In every case, i.e., the emergency actor, the (hypothetical) commercial actor for 100% of the market, and the 10% commercial actor, costs are always lowest in the dedicated optimization and attractiveness highest in its specific optimization. Multi-objective models provide solutions to trade-offs of the objectives. In the case of the commercial actor for 10% market share, for example, LC are 3.3% higher compared to the solution when only optimizing for LC (see Table E.9). Similarly, attractiveness is 1.2% lower in the multi-objective than in the dedicated optimization. Compared, LC are 24% higher than optimal when optimizing attractiveness and attractiveness 8.5% lower vice versa.

The overall number of warehouses is the same for different objectives for each commercial actor, four and seven, respectively. Stuttgart, the state's largest city and capital, is included in all solutions. For the two commercial actors only, three out of four locations in the 10% case match locations from the 100% case. An accumulation of locations is in the center of the federal state, around its capital city Stuttgart. This is consistent with measures of population density, showing the highest values in the center and on the western border of BW.

Emergency optimization, in contrast, leads to 26 locations spread widely across BW, again especially dense in the center of the state. The number of locations is the same for the SC and multi-objective optimizations but greatly differs from the attractiveness one (seven). This difference is clearly induced by the cubic deprivation cost function, which we included for this scenario. Additional variable costs tied to every transport lead to an increased number of locations to be optimal. The significant gap in the number of optimal locations makes optimal all-new locations largely impossible and warrants further attention for existing locations in the following sections.

E.8.4.2 Sensitivity analyses

We weigh costs and attractiveness equally in all multi-objective models, as shown in the model described before. There is no particular evidence to change these weights, but actors could decide on weights individually. To account for possible adjustments, we ran the models for varying weights to understand the results' sensitivity to them. We varied weights for costs (attractiveness) from 1 (0), which is the single-objective case, to 0.75 (0.25) to 0.6 (0.4) to 0.5 (0.5), the case described above, and vice versa (0/1, 0.25/0.75, 0.4/0.6). For both commercial optimizations, variation in logistics costs is up to 11% in either direction except for the single-objective cases. Attractiveness changes around 1% maximum. Clearly, the single-objective cases lead to significant changes in the disregarded objective. The numbers of locations are unchanged throughout all variations and changed weights evenly drive sensitivity.

However, sensitivity is more significant for the emergency case. Nonlinear deprivation costs vary most (up to 28%), followed by logistics costs with up to 16% in variation. Moreover, the number of locations changes. Attractiveness is again largely insensitive. Logistics and deprivation costs are distinct and competing cost objectives. Discussion of deprivation costs shows that more locations are always beneficial since distances decrease and, hence, transport times. Logistics costs, on the other side, balance fixed location and variable transport costs. When splitting logistics into transportation and opening costs, the competition is even more transparent. Transportation costs follow deprivation costs and, therefore, fall when more locations are added. On the other side, opening costs fall with a larger weight put to attractiveness, which results in fewer locations. For the small changes in weights (0.6/0.4 and 0.4/0.6), changes are less significant.

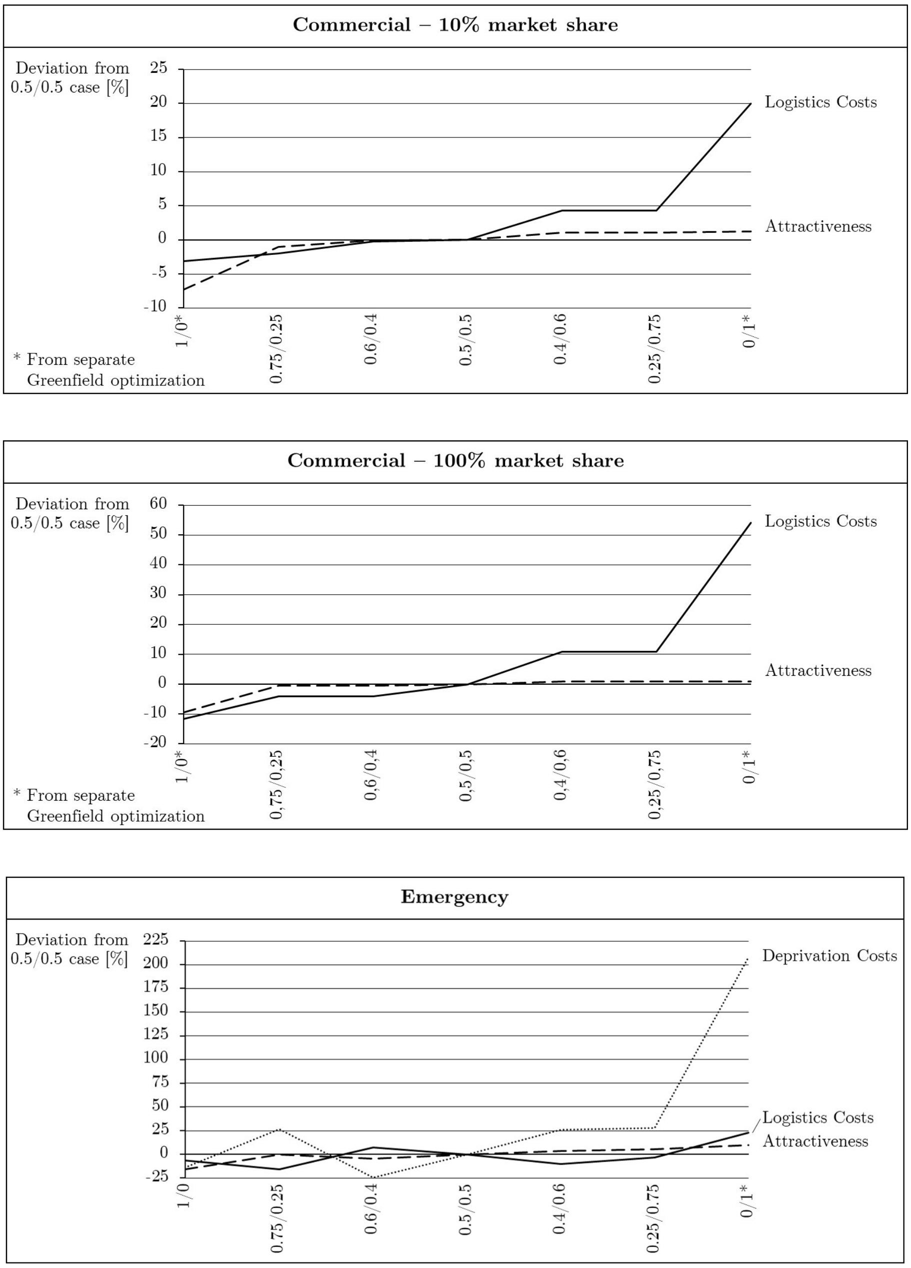

Figure E.6: Results from sensitivity analysis (Greenfield, all-new locations)

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Symbol	Explanation	Remark/ Details
Sets		
L	Set of locations	subsets I ($\|I\| = m$) and J ($\|J\| = n$)
S	Set of scenarios	$S = \{s_c, s_e\}$ (c: commercial, e: emergency)
T	Set of warehouse types	$T = \{b, l\}$ (b: standard, l: large)
Inputs		
P_j^s	Population at location j being supplied in scenario s	$s \in S, j \in J$
$D_{i,j}$	Distance from location i to j	[km]; $i \in I, j \in J$
$H_{i,j}$	Deprivation costs per person determined by travel time from location i to location j	$H_{i,j} = dc(t_{i,j})$ [€]; $i \in I$, $j \in J$
W^s	Daily demand in scenario s	[kg per person]; $s \in S$
c_{truck}	Cost per ton and kilometer in truck	
C^t	Capacity of warehouse type t	[people to be supplied], $t \in T$
U_{WH}	Warehouse utilization (used capacity as share of C^t)	$U_{WH} \in [0; 1]$
F^t	Fixed costs for warehouse type t	[€per day]; $t \in T$
$tp_{i,j}^s$	Transport costs between i and j in scenario s	$tp_{i,j}^s = D_{i,j} \cdot \frac{c_{truck}}{1000} \cdot P_j^s \cdot W^s$ [€per day]; $s \in S$, $i \in I$, $j \in J$
$dp_{i,j}$	Deprivation costs when location j is supplied from location i	$dp_{i,j} = P_j^{s_e} \cdot H_{i,j}$ [€]; $i \in I$, $j \in J$
A_i^s	Attractiveness of location i in scenario s	$s \in S, i \in I$
$\hat{y}^{s,b}$	Fixed number of warehouse locations in scenario s (to iterate)	$s \in S, b \in T$
Decision Variables		
$x_{i,j}$	Share of j's demand that is supplied from location i	$x_{i,j} \in [0; 1], i \in I, j \in J$
y_i^t	Warehouse of type t is opened at location i	$y_i^t \in \{0, 1\}, t \in T, i \in I$
d_{LC}^-	Slack variable for logistics costs	
d_{SC}^-	Slack variable for social costs	
d_{AT}^+	Slack variable for average attractiveness	
Output Metrics		
$LC^{opt,s}, LC^{max,s}$, $LC^{nad,s}$	Optimal/ Maximum/ Nadir logistics costs in scenario s	$s \in S$
AT^s	Average attractiveness for scenario s	$s \in S$
$AT^{opt,s}, AT^{min,s}$	Optimal/ Minimal average attractiveness in scenario s	$s \in S$
DC^{opt}, DC^{nad}	Optimal/ Nadir deprivation costs in emergency scenario	
SC^{opt}	Optimal social costs in emergency scenario	
$MO^{opt,s}$	Optimal multi-objective value for scenario s	$s \in S$

Table E.7: Variables and sets used in the optimization models.

Scenario	Commercial			Emergency		
Optimization	Step	Objective	Output	Step	Objective	Output
Cost	1.1	Minimize LC	LC^{opt,s_c}	2.1	Minimize LC*	LC^{opt,s_e}, DC^{nad}
				2.2	Minimize DC*	LC^{nad,s_e}, DC^{opt}
				2.3	Minimize SC	SC^{opt}
Attractiveness	1.4	Maximize AT	AT^{opt,s_c}	2.4	Maximize AT	AT^{opt,s_e}
Multi-Objective	1.5	Maximize LC*	LC^{max,s_c}			
	1.6	Minimize AT*	AT^{min,s_c}	2.6	Minimize AT*	AT^{min,s_e}
	1.7	Minimize LC, Maximize AT	MO^{opt,s_c}	2.7	Minimize SC, Maximize AT	MO^{opt,s_e}

Table E.8: Optimization sequences for commercial and emergency scenario. LC: Logistics costs; DC: Deprivation costs; SC: Social costs (sum of logistics and deprivation costs); AT: Attractiveness; MO: Multi-objective. Variable names as in the formal location model. *Adapted optimization for standardization.

BW	Commercial						Emergency		
	10% market share			100% market share					
	Costs	Multi-objective	Attrac-tiveness	Costs	Multi-objective	Attrac-tiveness	Costs	Multi-objective	Attrac-tiveness
Locations									
Number of warehouses	4	4	4	7	7	7	26	26	7
Thereof large	0	0	0	6	6	7	3	3	7
Thereof small	4	4	4	1	1	0	23	23	0
Costs [per day, in 1,000 €]									
Logistics costs	42	43	52	205	232	357	273	283	314
Transportation costs	10	11	20	78	105	219	32	42	175
Opening costs	32	32	32	127	127	138	241	241	139
Deprivation costs							21,573	28,059	109,614
Average attractiveness	0.6009	0.6485	0.6565	0.5870	0.6487	0.6540	0.5268	0.6124	0.6682

Table E.9: Model solutions for commercial (left and center) and emergency (right) greenfield planning optimized for costs, attractiveness, and combined in multi-objective optimization.

F Impact analysis of extended payment terms in food supply chains during a demand shortfall

Abstract

The current pandemic has disrupted many supply chains, among them food supply chains, and their physical and financial flows. Therefore, companies with high bargaining power may extend their payment terms to downstream suppliers as a reaction to decreased financial cash flow. We model a stylized three-stage food supply chain and use simulation to analyze the effects of a demand shortfall. We then investigate the effects of payment term extensions by different companies. We find that although extending payment terms can be beneficial for a single company in the short run, it will harm the supply chain in the long-run and conclude that incentives should be put into place to motivate companies accordingly.

F.1 Introduction

The COVID-19 pandemic has caused many different disruptions and challenges for single businesses, but also for whole supply chains. Companies fell short on paying their liabilities as less goods were sold, or they struggled receiving the supplies as producers were closing their productions (Barman et al., 2021).

In response to disruptions during the pandemic, companies with high market power extended their own payment terms to increase their liquidity in the short-term (Di Marcantonio et al., 2022). However, this can harm long-term supply chain performance (Esenduran et al., 2022). This can

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This chapter includes the article:
Zienau, A., Alazzeh, M., Hansen, O., Imdahl, C., Wiens, M. and Schultmann, F. (2023). Impact analysis of extended payment terms in food supply chains during a demand shortfall. In O. Grothe, S. Nickel, S. Rebennack, O. Stein (Eds.), *Operations Research Proceedings 2022: Selected Papers of the Annual International Conference of the German Operations Research Society (GOR), Karlsruhe, Germany, September 6-9, 2022 (in press)*. Springer Nature.

be especially impactful in food supply chains, where profit margins are low and few companies control a large share of the market downstream (i.e. retail and wholesale companies).

In this work, we study the relation between the physical flow of goods and the financial flow. Although there is a direct relationship between extended payment terms and increased delivery risks, the consequences of extending payment terms in a supply chain are so far scarcely researched. To our knowledge, Esenduran et al. (2022) is one of the few studies which looks into the extension of payments in supply chains and the related effects. Esenduran et al. (2022) analyze the impact of extended payment terms in combination with supply chain risk management measures such as quick response and backup suppliers and show how extended payment terms can harm the buyer's operations. In another study, Tsai (2008) model cash flow risk in supply chains and show how decreasing a firm's cash conversion cycle (CCC) increases cash flow risks.

For a stylized multi-echelon food supply chain consisting of a supplier, a producer and a wholesaler, we develop a model in which we design physical flows to meet the downstream service level with a (s,S) order policy. Inspired by lock-downs during the COVID-19 pandemic, we analyze how a shortfall of demand in gastronomy and payment extensions of upstream companies impact supply chain performance using simulation. In this regard, we also evaluate the results of adjusted financial flows using each stage's CCC.

We find that while extending payment terms can increase the CCC of a company in the short run, it can greatly harm the supply chain, and thus the company which increased its payment terms, in the long-run. Our study enables researchers and practitioners to analyze the interplay between physical and financial flows in crises and to evaluate corporate decisions on an extension of payment. Thereby, it can also serve as decision support for public actors' crisis management that affects commercial supply chains.

F.2 Model

We set up a stylized model of a three-echelon food supply chain, consisting of a supplier (*Stage 3*), a producer (*Stage 2*), and a wholesaler (*Stage 1*), where the latter serves external aggregated demand from the gastronomy sector (*Stage 0*), see Figure F.1. This will allow us to analyze how adjusting extended payment terms at the wholesaler or producer can affect performance and balance of the whole supply chain. Decisions within the supply chain can be made each day t. Aggregated demand from the gastronomy received by the wholesaler is assumed to be uniformly distributed: $D_{1,t} \sim \mathcal{U}(900, 1100)$.

The wholesaler however, will only accept this demand (partially or fully) conditionally. To avoid accumulating too much backlog, the amount of demand from the gastronomy, which the wholesaler can accept per day, is capped at the sum of the current inventory position and a maximum backlog $B_1^{\max}$. Hence, the net (accepted) demand at the wholesaler is defined as:

$$\tilde{D}_{1,t} = \min(B_{1,t-1} + D_{1,t}, I_{1,t} + B_1^{\max}) \tag{F.1}$$

The physical flow from the producer to the wholesaler is denoted as $S_{1,t}$ and the flow from the wholesaler to the gastronomy as $S_{0,t} = \min(\tilde{D}_{1,t}, I_{1,t})$ accordingly. Therefore, the wholesaler's on-hand inventory at the end of any day can be described as:

$$I_{1,t} = I_{1,t-1} + S_{1,t} - S_{0,t}. \tag{F.2}$$

Backlog is calculated at the end of a day as $B_{1,t} = (\tilde{D}_{1,t} - S_{0,t})^{-}$. The wholesaler places an order $O_{1,t}$ at the producer following a (*s,S*)-order policy. Hence, we introduce the target inventory level S_1, the reorder level s_1 and the producer's delivery time L_2 and define orders that have been placed at the producer but not yet delivered: $O^o_{1,t} = \sum_{i=1}^{t-1} O_{1,i} - \sum_{i=1}^{t-1} S_{1,i}$.

$$O_{1,t} = \begin{cases} S_1 - (I_{1,t} + O^o_{1,t}) + L_2 \cdot \mathbb{E}(D_{1,t}) + B_{1,t} & \text{if } I_{1,t} + O^o_{1,t} \leq s_1 \\ 0 & \text{if } I_{1,t} + O^o_{1,t} > s_1 \end{cases} \tag{F.3}$$

We denote the available monetary funds at the wholesaler before production at day t as $M_{1,t}$, and the planned time until payment from the gastronomy to the wholesaler as r_1 days. Given that p_1 is per unit price the gastronomy pays to the wholesaler, the payment received by the wholesaler at the beginning of a day is then $M^-_{0,t} = S_{0,t-r_1} \cdot p_1$. Daily operations at the wholesaler also generate fixed cost C_1^{fix} and the wholesaler has to cover inventory-dependent storage costs $C^h_{1,t} = I_{1,t-1} \cdot c^h_1$.

Each day, the wholesaler pays the producer an amount $P_{2,t}$, which includes planned payments and delayed payments. These payments are subject to the per unit price p_2 the wholesaler agreed upon with the producer. It follows that $P_{2,t} = S_{1,t} \cdot p_2$ is the planned part of the payment of the wholesaler to the producer. Additionally, we define the payment extension of a liability as $\Delta_{2,t} = r_2 + k$. Here, we denote u as the interest rate for late payment and k as the earliest delay at which the wholesaler can pay his liabilities plus interest $P_{2,t} \cdot (1 + k \cdot u) \leq M_{1,t+\Delta_{2,t}}$.

In conclusion, all payments by the wholesaler for a given day are defined as

$$M^-_{1,t} = \sum_{n:\{n+\Delta_{2,n}=t\}} P_{2,n}. \tag{F.4}$$

Hence, the available monetary funds at the wholesaler before production starts are

$$M_{1,t} = M_{1,t-1} - C_1^{fix} + M^-_{0,t} - M^-_{1,t} - C^h_{1,t}. \tag{F.5}$$

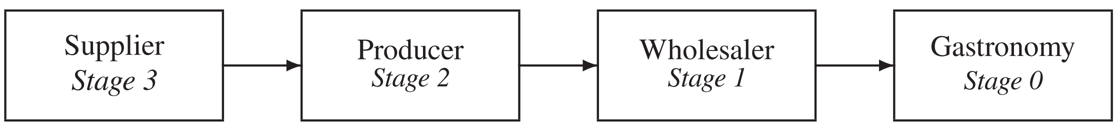

Figure F.1: Serial system

Similar processes apply to the producer. The producer receives payments $M^-_{1,t}$ from the wholesaler each day, and has to pay his liabilities, fixed costs, inventory holding costs and production costs. The payables are $P_{3,t} = S_{2,t} \cdot p_3$ and in t the producer pays $M^-_{2,t} = \sum_{n:\{n+\Delta_{3,n}=t\}} P_{3,n}$. Inventory holding costs are assessed for raw material and finished good, such that $C^h_{2,t} = I^{raw}_{2,t-1} \cdot c^h_{2,raw} + I_{2,t-1} \cdot c^h_2$. The production costs $C^p_{2,t}$ are dependent on the financial ability to fund production and the available money for production is thus

$$M_{2,t} = M_{2,t-1} - M^-_{2,t} - C^{fix}_2 + M^-_{1,t} - C^h_{2,t} - C^p_{2,t-1}. \tag{F.6}$$

Based on the available monetary funds the production quantity $Q_{2,t}$ is determined. The producer aims to produce a standard quantity q equivalent to his mean demand until he reached his target inventory s_2, which is set to ensure downstream availability. The producer has limited flexibility to increase or decrease his production dependent on demand realization as follows:

$$Q^{plan}_t = \begin{cases} 0.9q & \text{if } I_{2,t-1} \geq s_2 \\ q & \text{if } 0 \leq I_{2,t-1} < s_2 \\ 1.1q & \text{if } B_{2,t-1} > 0 \end{cases} \tag{F.7}$$

The realized production quantity is determined by the amount of available raw material and the available monetary funds $M_{2,t}$ because production generates costs:

$$Q_{2,t} = \min(Q^{plan}_t, M_{2,t}/c^p_2, I^{raw}_{2,t-1}) \tag{F.8}$$

Consequently, production costs of $C^p_{2,t} = Q_{2,t} \cdot c^p_2$ emerge each day.

Following production, the producer ships the number of goods ordered by the wholesaler: $S_{1,t+L_2} = \min(O_{1,t}, I_{2,t-1} + Q_{2,t})$

Hence, by the end of the day, the inventory level of raw and finished goods can be calculated as follows:

$$I^{raw}_{2,t} = I^{raw}_{2,t-1} - Q_{2,t} + S_{2,t} \qquad \text{and} \qquad I_{2,t} = I_{2,t-1} + Q_{2,t} - S_{1,t} \tag{F.9}$$

The producer orders new raw material from the supplier according to a (s,S) policy. Utilizing the outstanding orders $O^o_{2,t} = \sum^{t-1}_{i=1} O_{2,i} - \sum^{t-1}_{i=1} S_{2,i}$ this is

$$O_{2,t} = \begin{cases} S^{raw}_2 - I^{raw}_{2,t} + O^o_{2,t} + q \cdot L_3 + B_{1,t} & if I^{raw}_{2,t} + O^o_{2,t} < s^{raw}_2 \\ 0 & if I^{raw}_{2,t} + O^o_{2,t} \geq s^{raw}_2 \end{cases} \tag{F.10}$$

where s^{raw}_2 is set to cover a 90% service level and S^{raw}_2 to cover average lead time demand.

The supplier receives the incoming payments from the producer $M^-_{2,t}$ and pays its fixed costs C^{fix}_3 and the production costs from the previous day $C^p_{3,t-1}$.

$$M_{3,t} = M_{3,t-1} + M^-_{2,t} - C^{fix}_i - C^p_{3,t-1} \tag{F.11}$$

After that, the supplier aims to supply the number of units ordered by the producer. If the supplier's money is not sufficient for production, as many units of raw material are purchased as the the supplier can financially afford. c_3^p is a price per unit.

$$Q_{3,t} = \min(O_{2,t}, M_{3,t}/c_3^p) \tag{F.12}$$

Consequently, production costs of $C_{3,t}^p = Q_{3,t} \cdot c_3^p$ emerge each day. After his delivery time, the supplier delivers the goods to the producer, i.e. $S_{2,t+L_2} = \min(O_{2,t}, I_{3,t-1} + Q_{3,t})$.

F.3 Results

During normal times, the physical and financial flows in supply chain is balanced around the mean demand per day - cost and prices are in a relation that generates a margin for each stage. The price at which the supplier sells the unprocessed good is set at $p_3 = 10$. He encounters fixed costs per day of $C_3^{fix} = 5000$ and production costs of $c_3^p = 4$ per unit. This leaves him with a margin of 10%. After processing, the producer sells the good for a price of $p_2 = 20$ per unit. With this revenue, he covers fixed costs of $C_2^{fix} = 6000$, production costs of $c_2^p = 2$ per unit and inventory costs (Weighted Average Cost of Capital) for both his stock of raw and finished goods at the end of each day, at a rate of $c^h = 0.05$ times the unit price (p_3 for raw, p_2 for finished goods), per year. This equals a margin of slightly less than 10%, depending on the daily inventory costs that apply. The margins used are in line with prevalent values in the food processing industry.

The wholesaler uses his large network to sell the finished good to the gastronomy, at a price of $p_1 = 30$. He pays fixed costs of $C_1^{fix} = 8000$ and is subject to the inventory holding cost rate c^h. He is left with a margin of over 6%, which is less than in the food processing industry, but a commonly low value for food trade and retail in general, as it is a very competitive market.

The maximum backlog the wholesaler will allow is half of average daily demand at $B_{1,t} = 500$. Each payment outside a crisis is due after 30 days, for all stages, based on average values from practice. The interest rate for late payments is set at $u = 8.12\%$ per year, in line with the number currently issued by the German Central Bank. The starting capital for the supplier amounts to over one month of fixed production cost, the values for the producer and wholesaler are set to cover four months, in line with their higher market power. Delivery times between stages are set at $L_2 = L_3 = 5$ days. As a reaction to the fluctuation in demand, the reorder points and the target inventory levels are set to $s_1 = s_2^{raw} = 5400$ and $S_1 = S_2^{raw} = 10400$ accordingly. This ensures meeting the downstream service level of 90% at the wholesaler stage.

To analyze the consequences of a negative shock in demand, as it was caused by the current pandemic during the first lockdown(s), we assume that the base value of demand (the average) is reduced to 40% of its former value. Hence, in case of a lockdown $D_{1,t}^{shock} \sim \mathcal{U}(360, 440), \forall t \subseteq T^{shock}$ applies in the model and production capacities, reorder points and target inventory levels are adjusted accordingly. The demand shock lasts from day 40 (warm-up period) to 100 in the simulation.

We evaluate the effects of this disruption on the supply chain in Table 1 using different indicators. The *Service level* describes the delivery reliability downstream, where the wholesaler satisfies the demand of the gastronomy. A *Disruption* at the supplier stage is captured by the total days the supplier has insufficient monetary funds to produce any raw material. Each day the producer does not have any raw material, production is disrupted at this stage. Lastly, any day the wholesaler has to turn down demand from the gastronomy because it exceeds his maximum backlog level, is also counted as a disruption. The column *Breakdown* indicates whether a supply chain member went bankrupt and at which day of the simulation this occurred. We also evaluate the financial performance of each supply chain stage using the CCC. It measures how many days it takes to convert expenses into income from customers by taking into account *Days Inventory Held*, *Days Sales Outstanding* and *Days Payables Outstanding*. The lower the CCC, the better the financial performance of a company. A negative CCC is possible for companies with high bargaining power who receive money from their customers before they pay their suppliers (Stewart, 1995). All results displayed in Table F.1 are the average over 10 simulation runs.

		Disruption				CCC		
Scenario	Service level	Sup	Prod	Wh	Breakdown	Sup	Prod	Wh
Normal	90.61	0.00	0.10	0.00	no	31.99	6.87	6.55
Crisis	84.70	0.00	0.60	1.70	no	32.20	7.88	7.46
$\Delta r_1 = 15$	85.01	0.00	0.30	1.80	no	32.20	22.78	-3.44
$\Delta r_1 = 30$	85.04	0.00	0.60	1.30	no	32.23	40.48	-13.57
$\Delta r_2 = 15$	42.01	180.60	121.90	113.80	311.90	41.85	-10.41	1.75
$\Delta r_2 = 30$	34.75	233.30	207.30	199.90	200.40	49.82	-19.46	3.75
$\Delta r_1 \& \Delta r_2 = 15$	42.95	177.40	117.90	118.20	321.10	42.12	3.08	-11.58
$\Delta r_1 \& \Delta r_2 = 30$	34.22	233.10	207.90	201.30	200.20	49.69	0.58	-22.67

Table F.1: Scenarios and results

When comparing the first two scenarios, *Normal* and *Crisis*, we find that the crisis causes minor disruptions at downstream stages and also negatively affects the downstream service level and the CCC of each stage. The decreased financial performance can lead companies with high bargaining power to extend their payment terms in order to bring their CCC down. Hence, we investigate what happens within the supply chain when the wholesaler or the producer, or both, extend their payment terms to 45 or 60 days. Δr_1 (wholesaler) and Δr_2 (producer) describe scenarios with extended payment terms of either 15 or 30 days. Note that a value of 60 days is currently the legally allowed maximum, set by Directive 2019/633/EU.

It improves the wholesaler's CCC compared to the crisis scenario, when he is the only supply chain partner that extends his payment terms (15 or 30 days). It comes at a disproportionate cost for the producer in terms of CCC though. Furthermore, the downstream service level does not improve significantly. If only the producer extends his payment terms, it also decreases the producer's CCC. However, this time the cost for the supply chain is even greater. While this intervention also lowers the CCC of the wholesaler, it greatly increases the CCC of the supplier, to the degree where disruptions occur frequently at all stages. This culminates in the supplier going bankrupt on average at day 312 or 200, depending on the degree of the payment term increase. If both the wholesaler and the producer extend their payment terms at the same time, the effects are similar to those of an extension by only the producer.

F.4 Conclusion

Although the crisis has negative effects on all stages of the supply chain, in our scenarios it is actually best if no company in the supply chain extends its payment terms and the whole supply chain bears the consequences of the crisis. This underlines the complicated situation a company might find itself in. While extending payment terms can be an attractive option in the short-run, it is harmful for the whole supply chain in the long run, and thus also for the company that extends the payment terms itself. Yet, there is evidence from practice that this was often the case (Di Marcantonio et al., 2022).

An implication for managers is thus that they should consider carefully whether extending payment terms to achieve a small financial advantage is worth the potential aftermath, such as liquidity risks, along the supply chain. Typically, companies are not linked to a single upstream and a single downstream partner. Consequently, a company's liquidity risk that results from the downstream partner's payment term extension increases with a greater sales share with the downstream partner. Moreover, future research could investigate price changes as a response to extended payment terms. We also conclude that, while the Directive 2019/633/EU already limits the possible magnitude of payment term extensions, additional incentives to avoid extensions or affordable (free) loans for companies in need can be worthwhile options.

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