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Florian Diehlmann

FACILITY LOCATION PLANNING IN RELIEF LOGISTICS

DECISION SUPPORT FOR GERMAN AUTHORITIES

Scientific Publishing

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Karlsruher Institut für Technologie (KIT)
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Band 38

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by
Florian Diehlmann

KIT Scientific Publishing

Karlsruher Institut für Technologie
Institut für Industriebetriebslehre und industrielle Produktion
u. Deutsch-Französisches Institut für Umweltforschung

Facility Location Planning in Relief Logistics:
Decision Support for German Authorities

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Karlsruhe, May 2021

Florian Diehlmann

Abstract

Disasters have devastating impacts on societies, affecting millions of people and businesses each year. The delivery of essential goods to beneficiaries in the aftermath of a disaster is one of the main objectives of relief logistics. In this context, selecting suitable locations for three different types of essential facilities is central: warehouses, distribution centers, and points of distribution. The present dissertation aims to improve relief logistics by advancing the location selection process and its core components.

Five studies published as companion articles address substantial aspects of relief logistics. Despite the case studies' geographical focus on Germany, valuable insights for relief logistics are derived that could also be applied to other countries. Study A addresses the importance of public-private collaboration in disasters and highlights the significance of considering differences in resources, capabilities, and strategies when using logistical models. Moreover, power differences, information sharing, and partner selection also play an important role. Study B elaborates on the challenges to identify candidate locations for warehouses, which are jointly used by public and private actors, and suggests a methodology to approach the collaborative warehouse selection process. Study C investigates the distribution center selection process and highlights that including decision-makers' preferences in the objective function of location selection models helps to raise awareness of the implications of location decisions and increases transparency for decision-makers and the general population. Study D analyzes the urban water supply in disasters using a combination of emergency wells and mobile water treatment systems. Selected locations of mobile systems change significantly if vulnerable parts of the population are prioritized. Study E highlights the importance of accurate information in disasters and introduces a framework that allows determining the value of accurate information and the planning error due to inaccurate information.

In addition to the detailed results of the case studies, four general recommendations for authorities are derived: First, it is essential to collect information before the start of the disaster. Second, training exercises or role-playing simulations with companies will help to ensure that planned collaboration processes can be implemented in practice. Third, targeted adjustments to the German disaster management system can strengthen the country's resilience. Fourth, initiating public debates on strategies to prioritize parts of the population might increase the acceptance of the related decision and the stockpiling of goods for the people who know in advance that they will likely not receive support.

The present dissertation provides valuable insights into disaster relief. Therefore, it offers the potential to significantly improve the distribution of goods in the aftermath of future disasters and increase disaster resilience.

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Part I.

Framework, Foundations and Implications

1. Introduction and Motivation

The first wave of the COVID-19 pandemic highlighted the vulnerability of supply chains during disasters in an unprecedented way. All over the world, shortages for a large variety of products were reported in the media, from toilet-paper (The Washington Post 2020) and disinfection liquids (abcNEWS 2020) to clinical ventilators (The New York Times 2020).

As a response to these shortages, German authorities stepped up, collaborated closely with organizations and companies from the private sector, and implemented measures to ensure the population's supply. For example, authorities supported farmers flying in desperately needed seasonal workers (DW 2020b), purchased medical goods such as masks (The Local 2020) or ventilators (Reuters 2020), or distributed goods to vulnerable parts of the population with the help of the Bundeswehr (DW 2020f). Moreover, the installation of different types of facilities was a critical component of their relief intervention. At the beginning of the pandemic, these facilities were, for instance, mobile test facilities to conduct tests for Sars-Cov-2 (DW 2020e), warehouses to store a large number of masks (Merkur 2020), or temporary hospitals to offer additional space for critical care patients (DW 2020a). Later, issues such as the location of vaccination centers became relevant (DW 2020d).

The selected facility locations strongly affect the outcome of the intervention. For instance, a remotely located temporary hospital will most likely not fill with patients. Moreover, it will be difficult to supply it with essential goods. Similarly, a warehouse without access to the road network would not be an efficient selection. Therefore, scientific studies optimizing location decisions in disasters provide the opportunity to improve relief logistics. For example, Moline, Goentzel, and Gralla (2019) show that applying a dedicated decision support tool for opening and operating temporary disaster recovery centers can reduce average costs by 75%. However, integrating knowledge from scientific studies supporting such location decisions is exceptionally challenging. According to Kovács and Moshtari (2019), this may be due to a vast majority of available studies being too abstract and assumption-based. Moreover, the combination of the unique disaster situation, high time pressure, and the time it takes to adjust existing models further increase complexity (Kovács and Moshtari 2019). Consequently, optimization models that support location decisions are more likely to prevail in the practical world if they are developed specifically for an anticipated decision. Additionally, they need to include the local specificities, dynamics, and available resources (Kovács and Moshtari 2019).

In this context, the project "NOLAN"[1] was initiated, aiming to improve the German population's supply with critical goods during disasters. It is funded by the German Federal Ministry of Education and Research (BMBF) and coordinated by the Institute for Industrial Production at the Karlsruhe Institute of Technology (IIP 2020). One key component of the project is to support German authorities in their logistical decision making. The present dissertation, together with the companion articles, has been developed in the context of this project and was inspired by numerous discussions and workshops with experts from German authorities and the private sector.

The dissertation aspires to support decision-makers before and during disasters. Moreover, disaster resilience is increased with the help of five studies addressing German disaster management authorities' location decisions. These five studies assess the selection of different facilities along the relief chain[2] – from warehouses via distribution centers to distribution points. The studies provide several approaches for decision-makers faced with these concrete decisions. Furthermore, indirect implications can be generalized into four cross-study topics, which lead to managerial recommendations for disaster management authorities. Consequently, the dissertation provides essential insights for researchers and practitioners and can, thereby, improve resilience against future disasters.

The dissertation is structured as follows: Chapter 2 includes an overview of related terms and literature. Chapter 3 outlines the research objectives of the dissertation. The results of the individual studies are highlighted in chapter 4, before the managerial implications of the studies are discussed in chapter

1 "Scalable Emergency Logistics for Urban Areas as Public-Private Emergency Collaboration," in German: "Skalierbare **No**tfall-**L**ogistik für urb**an**e Räume als Public-Private Emergency Collaboration."

2 An overview of the theoretical background of relief chains follows in chapter 2.4

5. Finally, the dissertation is summarized and critically examined in chapter 6. The companion articles are attached at the end of the dissertation.

2. Theoretical Foundation

2.1. Classification of Disasters

The term "disaster" can be derived from Latin, being translated as "away from the stars" (Coppola 2007, p. 25). From a superstitious perspective, an unlucky constellation of the stars leads to drastic consequences (Eshghi and Larson 2008). According to the International Federation of Red Cross and Red Crescent, "a disaster is a sudden, calamitous event that seriously disrupts the functioning of a community or society and causes human, material, and economic or environmental losses that exceed the community's or society's ability to cope using its own resources. Though often caused by nature, disasters can have human origins" (IFRC 2020).

The classification characteristics of disasters include the root of the disaster and the time it takes for the disaster to unfold (Coppola 2007). In this context, disasters can either be triggered by technological malfunctions or occur naturally (EM-Dat 2020). Examples of technological disasters are explosions in chemical plants or nuclear reactors. Natural disasters include, inter alia, landslides or hurricanes. Considering the time it takes for a disaster to unfold, sudden- and slow-onset disasters are distinguished (Gupta et al. 2016). Sudden-onset disasters include earthquakes and flash-floods, while slow-onset disasters include droughts and famine. Depending on the disaster context, a variety of actors can become active and play an essential role.

2.2. Active Organizations in Disasters

The activity of different actors strongly depends on the local characteristics of the disaster area. While a less developed country like Mozambique required much international support in the aftermath of Cyclone Idai (UNOCHA 2020), the economically more mature United States coped with recent hurricanes primarily on their own – especially due to a strong public and private sector (NASEM 2020). Consequently, disaster research always has to consider the local context and available resources, making the transfer of knowledge challenging.

Considering Germany, which is rarely affected by large-scale natural disasters, public disaster management is based on the principle of *subsidiarity* and lies in the remit of the federal states (BMI 2015). For example, in the federal state of Baden-Württemberg, either the direct local administration (e.g., mayors' offices or the offices of the district administration), the *"Regierungspräsidium"* (the regional council), or the Ministry of the Interior Baden-Württemberg (MIDMBW 2020) are responsible. The responsible organization is mainly determined by the disaster's geographic concentration (MIDMBW 2020). If more than one district is affected, responsibility shifts towards the Regierungspräsidium. If more than one Regierungspräsidium is affected, the Ministry of the Interior is in charge. Moreover, the escalation stage of the local administration is bypassed in case of an incident in the vicinity of nuclear facilities (MIDMBW 2020).

Due to the different resources and shifts of responsibilities during an escalating disaster, the collaboration between different agencies and bureaus is necessary to account for departments' different resources and expertise. This process of mutual support for each other is organized with *"Amtshilfe"* applications, formalizing responsibilities and costs of the collaboration (see, for instance, BMI (2015) for an overview of the process for inter-state disaster assistance). Moreover, the German government installed the *Federal Office of Civil Protection and Disaster Assistance* (BBK) as a federal agency subordinate to the Federal Ministry of the Interior. The BBK is in charge of "matters related to civil protection and disaster assistance" (BMI 2020). For example, they support preparedness measures (BBK 2020) or provide information and coordination during disasters with their Joint Information and Situation Centre (GMLZ; BMI (2020)).

The scientific literature underlies the BBK's significant role by stressing the importance of coordination and collaboration of all involved actors, even though each actor of an emergency may play a crucial role for a successful intervention (Balcik, Beamon, et al. 2010). For example, Holguín-Veras, Jaller, et al. (2012) argue that even though donors have good intentions, their donations often do not address the population's actual needs. Delivering these goods to disaster areas leads to congestion of transportation infrastructure and, consequently, inhibits the supply of essential goods. At the same time, humanitarian organizations cannot offend donors by turning down offered goods (Holguín-Veras, Jaller, et al. 2012). Another example is the different legal power. While authorities can respond to a disaster by adjusting rules and regulations, logistics service providers need to follow these specifications. Even though they can try to achieve legal adjustments through lobbying, coordination is essential to avoid disruptions in supply chains.

The collaboration of authorities and private actors during emergencies is essential since both actors play a central role in supplying the population (Nurmala, Leeuw, and Dullaert 2017; Nurmala, Vries, and Leeuw 2018). In ordinary times, private actors supply goods to the population. Following Diehlmann, Lüttenberg, et al. (2020, p. 8), private actors include all "firms involved in the supply of essentials like food or medicine (e.g., producers, retailers, or logistics service providers)." On the other hand, authorities become responsible during disasters. Thereby, the term "authorities" refers to all public actors, defined as "institutions and organizations under the control of public authorities on a federal and/or provincial level" (Diehlmann, Lüttenberg, et al. 2020, p. 7).

Collaboration between public and private actors falls under the umbrella-term of *Public-private Emergency Collaboration* (PPEC; Wiens et al. (2018)). PPECs are necessary since, in many cases, public or private actors cannot cope with a disaster by themselves. This is, inter alia, caused by the different periods each actor becomes active. For example, the locations of supermarkets are selected to provide goods to the population in ordinary times. On the other hand, a disaster might come with limited mobility of the population, demanding shorter distances between people and points of distribution. Therefore, different suggestions for maximum walking distances in disasters exist in the literature (EPA 2011; Fischer and Wienand 2013). For example, the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety defines the maximum walking distance as 1 km (BMUB 2014). However, the average distance between a person and a supermarket in Germany is above 3 km (Neumeier 2014), indicating that the private sector's distribution infrastructure will not be sufficient and collaboration necessary.

Due to the significant impact of disasters on society, combined with the variety of disaster types, practitioners and researchers need to prepare for potential disasters, manage the response towards disasters efficiently, and learn from past disasters. These processes are classified in the so-called

Disaster Management Cycle (DMC), which is a core component of disaster management literature (H. Khan, Vasilescu, and A. Khan 2008).

2.3. The Disaster Management Cycle

The following four repeating phases define the DMC (Coppola 2007):[1] *Response*, *Recovery*, *Mitigation*, and *Preparedness* (see Figure 2.1).

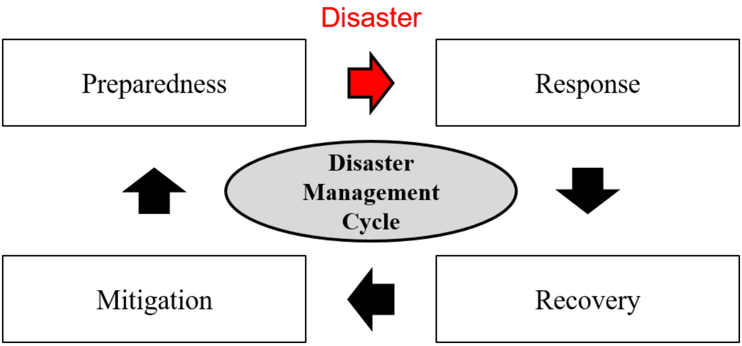


Figure 2.1: Overview of the Disaster Management Cycle.

The Response-Phase starts right after the impact of a disaster, focusing on providing relief to the affected area. After the immediate consequences of the disaster are survived, the Recovery-Phase becomes paramount, aiming to "returning victims' lives back to a normal state" (Coppola 2007, p. 8), or even to "build back better" (Mannakkara, Wilkinson, and Francis 2014, p. 1). While it might take months or years to go through the Recovery-Phase (Coppola 2007), the following Mitigation-Phase addresses the impact of potentially upcoming disasters, mitigating the effect of future incidents. Finally, the Preparedness-Phase's objective is to reduce the impact of a specific upcoming disaster (Coppola 2007).

1 Note that the phases fluently go into each other and may overlap. Furthermore, a variety of disciplines (for example, sociology or psychology) affected the DMC, leading to unclear origins of the concept (Coetzee and van Niekerk 2012), as well as some variations within the naming of the DMC's components (for example, some scholars prefer the name *Prevention-Phase* instead of the more frequently used term *Mitigation-Phase* (Baldini et al. 2011; BMIAT 2020)).

Around 80% of the costs of the immediate disaster response is caused by logistics (van Wassenhove 2006), indicating the importance of efficient logistics management. According to Christopher (2016, p. 2), logistics can be defined as "the process of strategically managing the procurement, movement and storage of materials, parts and finished inventory (and the related information flows) through the organisation and its marketing channels in such a way that current and future profitability are maximised through the cost-effective fulfilment of orders."

The stream of research focusing on logistics in the context of disasters falls under the umbrella term of *Humanitarian Logistics*. Like traditional business logistics, the management of the flow of goods, information, and finances is central in this stream (Kovács and Spens 2007). However, humanitarian logistical models need to address the particular characteristics of disasters. These characteristics are, for instance, the pursuit of (partially) non-financial objectives, the lack of information, or the often "once-in-a-lifetime"-periodicity of decisions (in contrast to repetitive decisions in business logistics; Holguín-Veras, Jaller, et al. (2012, p. 499)).

Humanitarian Logistics is central to two different types of disaster operations: continuous aid and disaster relief (Kovács and Spens 2007). Continuous aid refers to continuous support during long-lasting crises like providing supplies to a refugee camp. In contrast, disaster relief refers to the response in the aftermath of a disaster. Thus, relief logistics includes all logistical aspects of providing goods during disaster relief. The present dissertation aspires to support decision-makers during their relief logistics decisions. Consequently, the next subsection's focus is on the related key components.

2.4. Relief Logistics

According to Suzuki (2012), relief logistics consists of three major streams: *network flow problems*, *inventory management*, and *facility location problems*. While "network flow problems consist of supply and demand points, together with several routes that connect these points and are used to transfer the supply to the demand" (Bertsekas 1998, p. 2), inventory management refers to "planning and controlling inventory from the raw material stage to the customer" (Arnold, Chapman, and Clive 2008, p. 254). Moreover, facility location problems focus on "determining the 'best' location for one or several facilities or equipments in order to serve a set of demand points" (Laporte, Nickel, and Saldanha da Gama 2019, p. 1).

Depending on the relief network's considered layout, a plethora of facility types and decisions can be analyzed. In general, a relief network consists of *Central Warehouses*, which represent the origin of the goods in the network, and the *Points of Distribution* (PoDs), where beneficiaries receive goods. Moreover, *Distribution Centers* can serve as auxiliary infrastructure, e.g. as pre-positioning locations in anticipation of a disaster (Cotes and Cantillo 2019) or as cross-docks for transportation (see also Figure 2.2). Multiple variations of this basic setting exist in the literature – for instance, including a relief chain without additional distribution centers (Balcik and Beamon 2008), or taking warehouses out of the scope when addressing last-mile optimizations (Noyan, Balcik, and Atakan (2016); see also Anaya-Arenas, Renaud, and Ruiz (2014) for a systematic review).

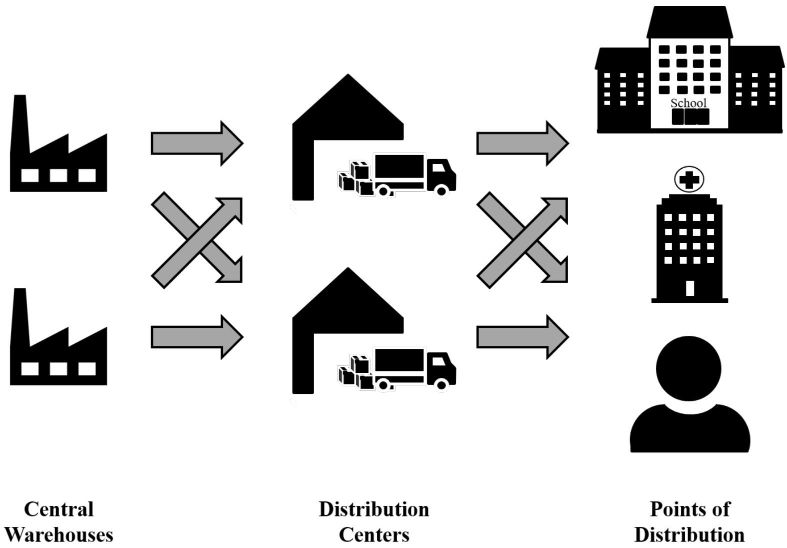


Figure 2.2: Overview of a generic relief chain.

The selection of appropriate facility locations along the relief chain is challenging. However, there is already a variety of studies addressing different decisions. For example, Charles et al. (2016) analyze optimal locations for global warehouses of an international organization, while Khayal et al. (2015) present a tool to select locations for temporary distribution centers. Moreover, Moreno et al. (2018) introduce an approach to select PoDs under consideration of uncertainties.

Nevertheless, multiple research areas have not been studied thoroughly yet. Therefore, additional studies can improve relief logistics further. An overview of the research objectives that are pursued within the present dissertation, together with related relief decisions, follows in the next chapter. A detailed presentation of the studies' results follows in chapter 4.

3. Research Objectives

The present dissertation aims to contribute to the body of literature and improve the outcome of future relief interventions with the help of five scientific studies. The following section provides a brief overview of the addressed research objectives. Afterward, section 3.2 locates the studies within the relief chain.

3.1. Opportunities to Improve Relief Logistics

3.1.1. Increase Knowledge About Public-Private Collaborations

As described in section 2.2, various actors become active during disaster relief. These actors contribute to the disaster response depending on their individual motivation, objectives, and resources. In this context, the role and importance of the different groups of actors have been studied intensively (see, e.g., Kovács and Spens (2007) and Balcik, Beamon, et al. (2010)). The efficient collaboration of all actors involved is key to relief logistics (Balcik, Beamon, et al. 2010). This becomes especially important considering PPECs (Nurmala, Leeuw, and Dullaert (2017), Nurmala, Vries, and Leeuw (2018), and Wiens et al. (2018); see also section 2.2). However, there are no frameworks or general studies that address possible logistical components that should be included in quantitative PPEC models. Moreover, the identification of these components can be a catalyst for future PPEC research. This research objective is pursued in Study A.

3.1.2. Support Decision-Makers Selecting Locations for Warehouses

The locations of warehouses strongly affect the impact of relief logistics. In this context, *location factors* play a central role. Location factors represent the factors that affect the decision for a new facility (Schmenner, Huber, and Cook 1987). Many studies already elaborated on different factors in the commercial context, e.g., focusing on different industry sectors (Saracoglu 2020) or countries (Ramírez-Alesón and Fleta-Asín 2016). Moreover, several studies analyzed location factors in the humanitarian context (see, for example, Dekle et al. (2005) and Roh, Jang, and Han (2013)). However, there is no study contrasting location factors from both perspectives, comparing different regions' attractiveness. This is remarkable since these results are of high value for disaster authorities and private actors that want to collaborate. Moreover, there is no methodology available to identify potential locations for jointly used (warehouse) facilities. Study B approaches this research objective.

3.1.3. Include Preferences in Objective Functions

Appropriate objective functions are highly debated in the field of humanitarian logistics. While the first humanitarian logistics studies applied commercial objectives towards humanitarian contexts, novel approaches allow researchers to account for the special characteristics of a disaster response (Holguín-Veras, Jaller, et al. 2012; Holguín-Veras, Pérez, et al. 2013). One of these novel approaches is considering the concept of *social costs*, which was introduced to the humanitarian sector by Holguín-Veras, Jaller, et al. (2012). The main difference to the commercially used approaches is the combination of a proxy for human suffering, so-called *deprivation costs*, with logistics costs. However, several limitations inhibit applying the model in studies (see, for example, Shao et al. (2020) for a recent discussion of the advantages and disadvantages of deprivation costs). Consequently, extending the concept of social costs can facilitate the application of the approach and, therefore, allow researchers and decision-makers to better account for humanitarian specificities in their models. While there are multiple opportunities to extend the concept, an option with high relevance for practitioners is to include decision-makers' preferences with the help of a weighted-sum approach. This research gap is approached in Study C.

3.1.4. Take Advantage of Synergies Utilizing All Available Resources

Researchers developed various approaches to define humanitarian supply chains (see, for example, Charles et al. (2016) and Balcik and Beamon (2008)). In particular, humanitarian water supply chains received much attention. For example, Clasen and Boisson (2006) investigate the application of household-based ceramic water filters, Dorea, Bertrand, and Clarke (2006) the application of clarifiers on the community level, or Garsadi et al. (2009) the application of mobile water treatment systems. However, there is no study that focused on the combination of mobile treatment systems and the already installed local emergency infrastructure. An example of local infrastructure is the German emergency well system, consisting of grid-independent wells distributed all over Germany. In Berlin, more than 900 wells can provide water during emergencies (Fischer and Wienand 2013).

Combining the available resources is challenging since it emphasizes the problem of prioritization. A supply chain based on non-mobile wells offers little flexibility. Even though the well network has been extended in the last decades, the well system was initially designed during the cold war. Consequently, the fit with the local demographics is highly questionable. On the other hand, a large amount of water can be distributed via wells.

In contrast, mobile systems offer high flexibility, while the total amount of water that can be distributed through them is comparably low. The combination of both technologies offers the chance to supply a large amount of water to the general population while prioritizing vulnerable groups. However, the consequences for the general population that arise from the prioritization of vulnerable people need to be well-understood to make such an important decision. Study D contributes to this stream of research.

3.1.5. Collect More Accurate Information

Accurate information is crucial for successful disaster interventions (Altay and Labonte 2014; Celik and Corbacioglu 2010; Day, Junglas, and Silva 2009). When it comes to the demand for critical goods, much knowledge lies within the hands of private actors, who interact with their customers regularly. On the other hand, authorities need to obtain access to accurate information – for example, by confiscating or purchasing information (as done by the US FEMA (Federaltimes 2019)). Even though research agrees that uncertainty plays an important role in relief logistics (Ahmadi, Seifi, and Tootooni 2015; Charles et al. 2016; Vahdani et al. 2018), the effects of different information accuracy levels remain unclear. Simultaneously, there is no approach for quantifying the effects of different intervention strategies on the private sector if the decision is based on accurate or inaccurate information. Understanding these effects is the objective of Study E.

3.2. Addressed Decisions Within the Relief Chain

The studies address different decisions along the relief chain (see also Figure 2.2). Study A provides a general framework and insights relevant to decisions on each relief chain stage. Moreover, Study B supports the warehouse location decision, and Study C aims to identify locations of distribution centers. Furthermore, Studies D and E suggest locations where critical goods can be distributed during disaster relief.

Moreover, efficient facility location decisions in relief logistics are always accompanied by a multitude of preconditions and consequential implications. Even though these aspects are often not directly considered in logistics problems, they strongly affect the success of facility location decisions. The study-based design allows deriving managerial recommendations regarding four of such general cross-study topics: *Information Management*, *Company Involvement*, *German Specifities*, and *Trade-offs*.

Information Management refers to the importance of information in disasters, while Company Involvement aims to increase the understanding, how authorities can better involve companies in their relief interventions. Moreover, German Specificities include implications targeted towards the German infrastructure that follow from the case studies' geographical focus. Finally, all insights that aim to improve the understanding of conflicting objectives are collected in the domain of Trade-offs.

	Study A	Study B	Study C	Study D	Study E
Information Management	X	X		X	X
Company Involvement	X	X	X		X
German Specificities		X		X	X
Trade-offs	X	X	X	X	

Table 3.1: Overview on the contributions of each study to the cross-study topics.

Table 3.1 links the studies to the cross-study topics. A description of the studies and their results follows in the next chapter. The managerial implications derived from the cross-study topics are discussed in chapter 5.

4. Summary of Studies and Results

4.1. Study A: A Framework for Public-Private Emergency Collaborations

The following section refers to the content of the article "Public-Private Collaborations in Emergency Logistics: A Framework based on Logistical and Game-Theoretical Concepts." This article was written in collaboration with Markus Lüttenberg, Lotte Verdonck, Marcus Wiens, Alexander Zienau, and Frank Schultmann, and was published in the KIT-IIP *Working Paper Series in Production and Energy* as Diehlmann, Lüttenberg, et al. (2020).

Study context and contributions

The study's objective is to provide an overview of PPECs in theory and practice, introduce a framework for the logistical and game-theoretical modeling of PPEC components, and discuss a basic game-theoretical model depicting a simplified PPEC.

As crises of the past have shown, authorities cannot cope with large-scale disasters by themselves (see, for example, the response to Hurricane Katrina in the United States (Department for Homeland Security and Counterterrorism 2006)). While researchers have identified various organizations involved in disaster relief (see section 2.2), Nurmala, Leeuw, and Dullaert (2017) and Nurmala, Vries, and Leeuw (2018) highlight the central role of private actors in disasters. Moreover, Wiens et al. (2018) stress the potential of PPECs. However, no study provides an overview of the state-of-the-art of PPECs, their key components, and essential aspects to consider in quantitative PPEC studies. This gap is addressed in Study A. A presentation of the main results and points of discussion of the study follows.

Results and Discussion

Even though the literature clearly indicates that PPECs are promising components of effective disaster responses, only a minimal number of PPECs are formally defined in reality. While there is no apparent reason for their scarcity, examples from the COVID-19 pandemic highlighted that, nevertheless, PPECs can be introduced spontaneously. An example is the support of private actors during the purchasing process of face masks. After authorities struggled to find enough suppliers of face masks, they asked private actors to take over negotiations and use their contacts to acquire masks for them (Tagesschau.de 2020). Moreover, private actors got actively involved and started producing critical goods themselves (Focus 2020).

The already established PPECs, on the other hand, tend to target broader preparedness-topics. For example, the German UP-KRITIS, a working group consisting of experts from the public and private sector, aims to increase critical infrastructure resilience and general knowledge exchange (UPKRITIS 2019). A reason for this could be that private companies want to keep their independence and flexibility, as indicated by Walmart after they rejected the role of "emergency merchandise supplier" (Chen et al. 2013, p. 136). Therefore, authorities should aim for a collaboration on a voluntary basis without legal commitment if they wanted to set-up a formalized PPEC with an operational focus. In this context, the (intermediate) results of the research project "NOLAN," in which researchers from the Karlsruhe Institute of Technology, the TU Dresden, and the 4flow AG systematically investigate PPECs (IIP 2020), seem to be very promising. The research partners plan to establish the so-called "AK NOLOG," a permanent working group where public and private actors can collaboratively increase the understanding of the operational relief distribution processes, share best practices, get to know each other better, and organize disaster exercises.

In addition to the insights and implications from the discussion of the state-of-the-art of PPECs, the logistical modeling framework provides valuable guidance for researchers and practitioners who want to analyze PPECs quantitatively (Figure 4.1).

From a logistical perspective, differences in resources, capabilities, and strategies are essential. For example, tensions may arise from competing long-term strategies: While private actors usually follow financial objectives to satisfy

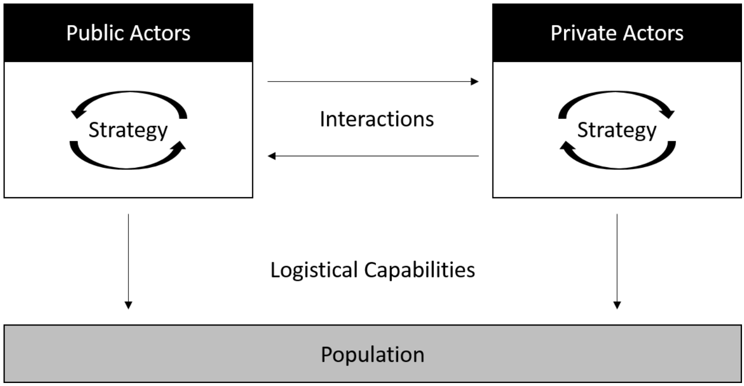


Figure 4.1: Interdependencies in Public-Private Emergency Logistics (see also Figure A.3).

shareholders or ensure their long-term liquidity, public actors can focus on reducing the population's suffering. Moreover, power differences, information sharing, and partner selection are important aspects to consider. Legal aspects can be examples of power differences since public actors have the power to adjust the legal context of the intervention (as, for instance, happened all over the world during various partial or full lockdowns as part of the COVID-19 pandemic response). Additionally, the game-theoretical model and example developed in Study A indicate the powerful implications drawn from such quantitative PPEC analyses.

4.2. Study B: Selecting Locations for Warehouses in PPECs

The following section refers to the content of the article "Identifying Joint Warehouse Locations in Public-Private Emergency Collaborations." This article was written in collaboration with Maximilian Löffel, Alexander Zienau, Markus Lüttenberg, Marcus Wiens, Stephan Wagner, and Frank Schultmann, and has been submitted to a scientific journal.

Study context and contributions

The study's objective is to compare the suitability of different regions as a warehouse location from authorities' and companies' perspectives and to develop a methodology to select locations for shared warehouses. These warehouses can be used to supply goods to the general population during ordinary times and to beneficiaries during disasters.

Private actors supply goods to the population with the help of supply chains that continuously aim to increase their efficiency. While authorities observe the market in ordinary times, they need to intervene when the supply drops in times of a disaster. For example, German authorities stepped up during the COVID-19 pandemic and, among other things, loosened driving restrictions for logistics providers (BMVI 2020) or supported farmers during the harvest workers' immigration process (BReg 2020). Furthermore, in case of more severe disturbances, authorities can activate goods from the so-called "Zivile Notfallreserve" (eng: "Civil emergency reserve"), in which large amounts of rice or legumes are stored (BLE 2020). Furthermore, the "Bundesreserve Getreide" (eng: "Federal grain reserve") offers large amounts of wheat and other grains (BLE 2020). Even though these goods could provide helpful relief to beneficiaries, various operational and legal factors inhibited the activation of these resources (Rexroth 2010). Consequently, authorities spend much money maintaining goods they barely need (Rexroth 2010).

One approach for increasing the relief chain's flexibility and efficiency includes involving private actors more directly in disaster preparedness. For instance, this incorporates using their infrastructure and goods in disasters instead of setting up new supply chains. While this requires many operational agreements (for example, an increase of safety stock or the prioritization of deliveries on behalf of authorities), authorities can save money compared to the current, non-cooperative setup by defunding the barely used infrastructure. Hence, part of this money could be spent setting incentives for private actors and, thus, lead to solutions from which both actors profit.

The selection of a location both actors benefit from is a challenging task. In the context of this study, it is approached in two ways. With the help of a structured approach, it is possible to determine a region's general attractiveness as a quantitative score using expert interviews, AHP, and selected metrics. Furthermore, this score can be utilized as one of the objectives of a series of mixed-integer linear models with goal-programming objectives.

These models suggest the structures of different logistics networks using actor-specific combinations of objectives. Following, mapping the different networks leads to solutions that are of interest to both actors. These locations can, therefore, be the starting point for discussions on candidate PPEC locations.

Overall, the study contributes to the body of literature in two different ways. First, the attractiveness score represents a very flexible approach to evaluating and comparing different regions' suitability. It can support PPEC-practitioners to understand the required characteristics of the partner better. Second, the introduced models effectively combine multiple objectives and offer a unique perspective of collaborative location selection for disaster preparedness. A presentation of the main results and points of discussion of the study follows.

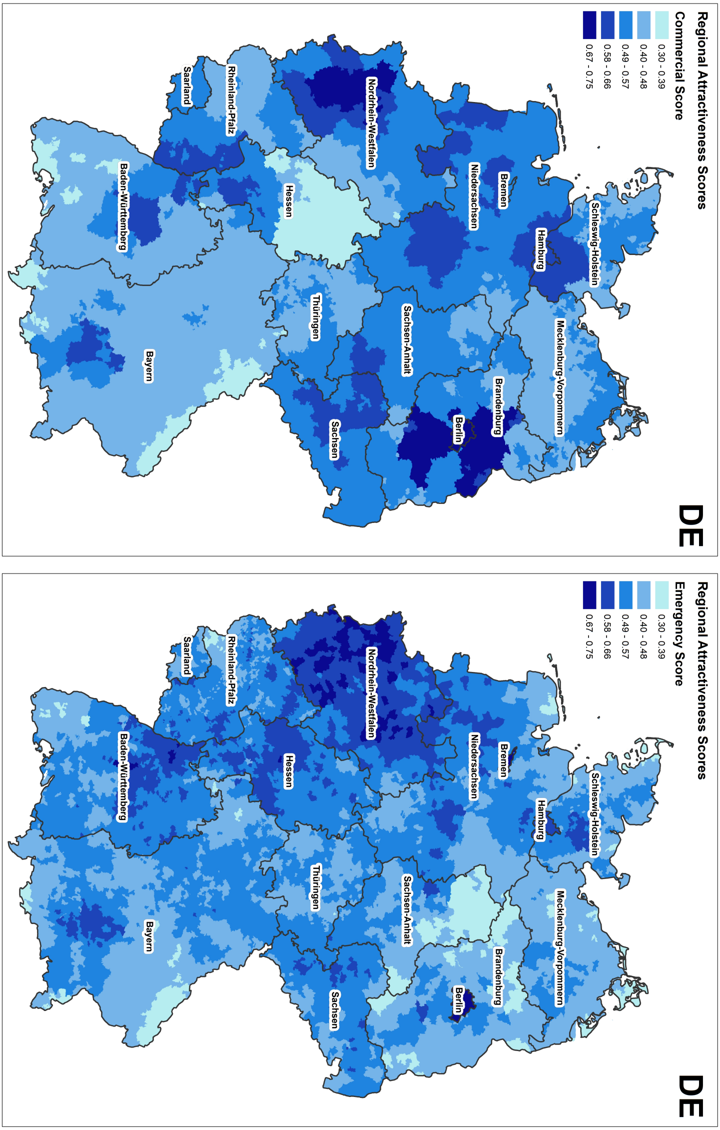
Results and Discussion

The results of the case study underline the possibilities and flexibility of the approach. While the attractiveness score was determined for Germany, the optimization models were restricted to the federal state of Baden-Württemberg to reduce the computational complexity.

Figure 4.2 highlights the scores that result from a total of thirteen interviews with experts from the private sector, authorities, NGOs, and consulting firms.[1] These experts assessed nine criteria for their importance. Combined with more than thirty metrics, the final scores for the attractiveness of a region as a location for a warehouse from the perspectives of the private sector (Figure 4.2a) and relief authorities (Figure 4.2b) result.

While the criteria *"Market in Proximity"* and *"Availability and Skills of Labor Force"* have the highest influence on the commercial attractiveness score, *"Availability of Transport Equipment"* and *"Transport Infrastructure Reliability and Resilience"* influence the emergency score most. Even though regions' attractiveness differs significantly, it is possible to identify some areas of high attractiveness for both actors. For example, large parts of the federal states of

[1] Accounting for inconsistencies in the data, the results of six commercial and six emergency experts were considered in the study.



(a) Commercial scenario

(b) Emergency scenario

Figure 4.2: Final attractiveness scores for Germany (DE) per LAU2 unit (see also Figure B.4).

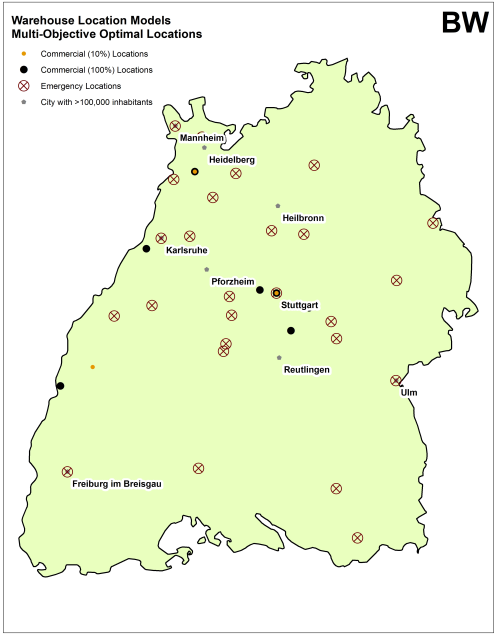
Nordrhein-Westfalen or Baden-Württemberg seem to be promising options for both actors.

Moreover, the scores are an input of various optimization models. These models determine optimal warehouse network set-ups, considering logistics costs and attractiveness (commercial scenario), or logistics costs, deprivation costs, and attractiveness (emergency scenario). Figure 4.3a highlights the different networks. In the commercial scenario, two different subscenarios are considered to reflect the potential target markets. A market share of 10% represents a situation in which one large food retail chain tries to set-up a network. On the other hand, a market share of 100% represents a hypothetical monopolist representing the entire market supply. It follows that a municipality close to Stuttgart is included in each scenario's network, while various locations are a component of two different networks. These locations could be candidate locations if both actors wanted to open a new jointly used warehouse.

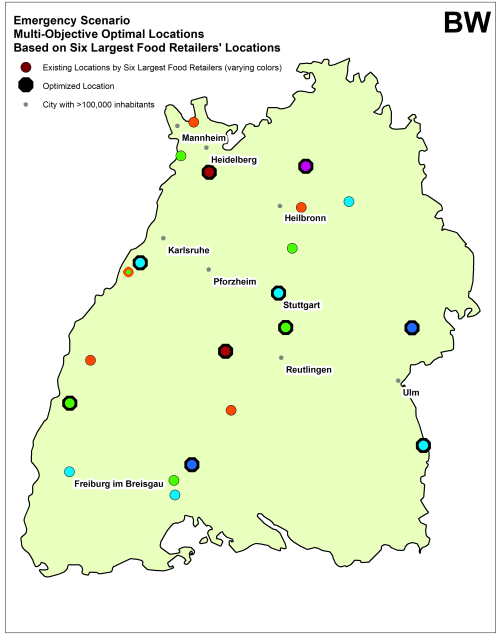
Furthermore, the flexibility of the approach is highlighted with the help of two different extensions. In Extension I, the twenty-one warehouses of the largest six German retailers are considered as candidate locations. Figure 4.3b presents the selected locations. Moreover, Extension II regards the hypothetical case that one retailer wanted to extend its network by one warehouse that can be used as an emergency warehouse.

Comparing the results of the extensions, it becomes evident that the number of candidate locations significantly affects the network's operational performance (measured in costs and deprivation). The network that is based on all retail chains' locations (Extension I) leads to better results than an extension of the warehouses of one chain (Extension II). It can be followed that authorities should aim to increase their flexibility by collaborating with multiple chains. Furthermore, this also minimizes market interference by avoiding to "pick winners."

The study comes along with multiple limitations. For example, establishing an entirely new distribution network is a thought experiment that is not likely to happen in reality. Structures develop over a long period and organically, making the extensions considering existing infrastructure more relevant for a practical application of the model. Moreover, individual companies might have different strategies and objectives, leading to more complex optimization problems, if applied in practice. Furthermore, disaster dynamics are not included. If, for example, critical infrastructure damage comes with a disaster,



(a) Optimal locations for commercial and emergency scenarios.



(b) Optimal locations for the emergency scenario based on existing warehouses.

Figure 4.3: Selected locations for different types of networks. Figure 4.3a highlights the optimal locations in BW for commercial and emergency scenarios. Figure 4.3b highlights the optimal locations in BW for the emergency scenario based on existing warehouse locations (see also Figure B.6).

highways might become blocked and negatively affect a location's suitability. Finally, different legal conditions, including different public administrations and interpretation of responsibilities, are present. Disaster management in Germany is highly localized, while a federal agency runs the emergency warehouses. Therefore, adaptations and adjustments on the country-wide level are only possible if the local disaster plans are adjusted, which will be challenging to coordinate. Nevertheless, the study offers a flexible methodology to identify potential locations of collaborative warehouse locations and, therefore, constitutes an essential contribution to increased resilience.

4.3. Study C: Selecting Locations for Temporary Distribution Centers

The following section refers to the content of the article "A Novel Approach to Include Social Costs in Humanitarian Objective Functions." This article was written in collaboration with Patrick S. Hiemsch, Marcus Wiens, Markus Lüttenberg, and Frank Schultmann, and was published in the KIT-IIP *Working Paper Series in Production and Energy* as Diehlmann, Hiemsch, et al. (2020).

Study context and contributions

The study's objective is to advance the original approach to use *social costs* (SC) in humanitarian objective functions.

This approach was introduced by Holguín-Veras, Jaller, et al. (2012) and Holguín-Veras, Pérez, et al. (2013), who define SC as the sum of logistics costs and deprivation costs (DeC). In this context, DeC represent a monetary approximation of human suffering (Holguín-Veras, Pérez, et al. 2013), which is often measured via the willingness to pay for a critical good, assuming there is a lack of this good after a disaster (Shao et al. 2020). For example, a person with a water demand of 2 liters per day may survive without water for a limited time. However, it would not be sufficient to supply this person with 20 liters of water after 10 days since this person will most likely be dead by then. Moreover, the longer the person is undersupplied, the more severe the physiological implications and the higher the willingness to pay for water. *Deprivation cost functions* (DCFs) reflect these effects and are, therefore, "monotonic, non-linear, and convex with respect to the deprivation time" (Holguín-Veras, Pérez, et al. 2013, p. 267). Consequently, this concept represents a powerful approach to include the escalating suffering of the affected population in considerations. Due to the expression of DeCs in monetary units, they can be combined with logistics costs and allow decision-makers to optimize decisions in terms of both components.

Some disadvantages come along with the application of DCFs in relief optimization models. For example, the functions are susceptible to the local economic context and complex to assess (Shao et al. 2020). Wang et al. (2017) introduce the concept of *Deprivation Levels* (DL) to solve some of these issues. In contrast to DCFs, *Deprivation level functions* (DLFs) capture the suffering of the population on a dimensionless interval of $[0; 10]$. While this approach is universal and does not depend on the local economic situation, it is very complex to determine (Shao et al. 2020). Moreover, DLFs cannot be compared to or combined with logistics costs.

Considering this background, a novel method is suggested in Study C. It is based on a normalized weighted sum approach, in which deprivation and logistics cost are normalized with nadir and ideal points (see also Figure C.2). The objective of the resulting optimization problem is to minimize the normalized weighted sum. Therefore, this approach allows decision-makers to include DCFs (or DLFs) and logistics costs into their decisions fast and efficiently. Furthermore, the approach allows prioritization of one of the two cost components, dependent on the decision-maker's preferences. An example of such a preference could be an international NGO that can spend every euro saved in one country in another disaster context. Therefore, they might regard reducing human suffering as essential but strategically prefer a stronger focus on monetary components in the context of a specific disaster. Consequently, the approach increases transparency regarding decisions and consequences effectively and offers much flexibility to decision-makers.

The approach is applied to a case study for hypothetical water contamination in the city of Berlin. Water stored in large warehouses outside the city is distributed at schools all over Berlin. Following Cotes and Cantillo (2019), small temporary distribution centers (DiCs) are opened to distribute the goods (for instance, as cross-docks, as an additional buffer, or to merge deliveries from different sources). Decision-makers need to select the number and location of these DiCs from a set of twelve candidate locations (large commercial stores or warehouses). This decision is approached with a mixed-integer linear program that suggests different combinations of opened DiCs dependent on decision-makers' preferences. A presentation of the main results and points of discussion of the study follows.

Results and Discussion

The discussion of the results shows the benefits of the approach. Figure 4.4 highlights the selected DiCs, dependent on the decision-maker's preference for logistics costs ($\alpha \longrightarrow 1$) or deprivation ($\alpha \longrightarrow 0$).

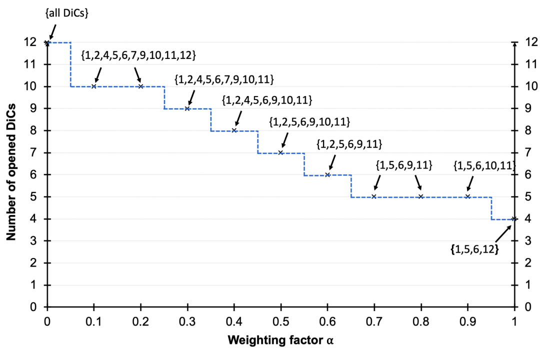
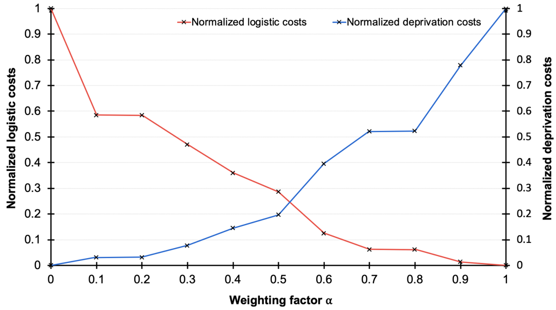


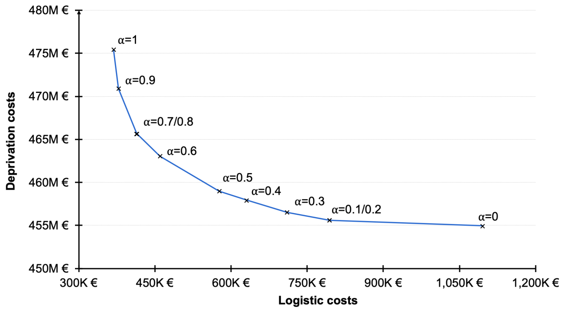
Figure 4.4: Opened DiCs for different values of α (see also Figure C.5).

The figure indicates the importance of different DiCs. For example, DiCs 1, 5, and 6 are robust solutions and should be opened in any case. Moreover, DiC 11 is featured in a large number of solutions. On the other hand, DiCs 3 and 8 only become relevant in case of a strong preference for deprivation ($\alpha \leq 0.1$). Furthermore, Figure 4.4 shows the variety of the selected location combinations. Therefore, decision-makers need to understand the consequences of different levels of α more thoroughly to make a decision.

Figure 4.5 can support this process. Figure 4.5a presents the course of the normalized costs and Figure 4.5b the Pareto-Front. As indicated in Figure 4.5a, deprivation does not significantly change for $\alpha \leq 0.5$, while logistics costs almost double in this interval. Simultaneously, logistics costs are comparably stable for $\alpha \geq 0.6$, while the contribution of the deprivation component does not significantly change. Figure 4.5b further highlights the total costs,



(a) Normalized values.



(b) Pareto-Front.

Figure 4.5: Normalized values and Pareto-Front of the cost components for different values of α (see also Figures C.6 and C.7).

indicating that DeC are much higher than logistics costs. Consequently, a reduction of DeC in the range of 1% already reduces the shadow price of the population's suffering on a level above the total logistics costs, which could lead decision-makers towards prioritizing deprivation. At the same time, the highest possible deprivation value is only about 4% above the lowest value, indicating that the decision does not strongly influence deprivation in absolute terms. On the other hand, the highest logistics costs are almost three times higher than the lowest, indicating that the decision strongly affects logistics costs. Moreover, logistics costs would have negligible effects in the location selection process without the normalization. Since the decision mostly affects logistics costs, normalization could lead decision-makers towards prioritizing logistics costs.

The results highlight the extremely challenging task decision-makers face in disasters and the necessity to support them in making their decision. While the developed approach can increase transparency and suggest locations, the decision and consequences need to be accepted by as many people as possible. Therefore, a broad public debate should be striven for.

Furthermore, the approach still provides opportunities for further improvements and adaptations. While it allows making decisions without defining a new DCF that fits the local economic context, it still requires a DCF or DLF as an input parameter. Even though the concept of deprivation is widely accepted, there is still only a limited number of functions available (Shao et al. 2020), inhibiting the application in case of a demand for extraordinary goods. Moreover, the dependency on the preferences of the decision-maker increases the risk of power abuse. Therefore, it is essential to assess the whole set of options and discuss the implications of selections with multiple stakeholders. Despite these limitations, the case study highlighted possibilities to deepen the understanding of the consequences of disaster relief decisions. Consequently, the new approach can contribute to better decisions in future disasters and support decision-makers effectively.

4.4. Study D: Selecting Locations for Mobile Water Distribution Systems

The following section refers to the content of the article "On the combination of water emergency wells and mobile treatment systems: a case study of the city of Berlin." This article was written in collaboration with Christoph Stallkamp, Markus Lüttenberg, Marcus Wiens, Rebekka Volk, and Frank Schultmann, and was published in the journal *Annals of Operations Research* as Stallkamp et al. (2020).

Study context and contributions

The study's objective is to develop a tool to support decision-makers in selecting locations for mobile water purification systems.

The German disaster management authorities have around 4.800 grid-independent emergency wells at their disposal (BBK 2008). These wells can be activated in case of contamination in the water supply system, e.g., caused by a terrorist attack. Beneficiaries visit the wells, pick up water for their immediate demand, and carry the water back home. Consequently, the distance between the beneficiaries and wells should be as short as possible. Since the wells' locations were selected and built before Germany got reunited, they do not reflect the demographic properly. This applies especially in areas of the former GDR (BBK 2008), leading to large distances between beneficiaries and wells. Therefore, an intervention based on wells alone seems to be not sophisticated enough to account for the population's suffering.

While different technologies could be facilitated to increase the supply of water further (e.g., household-based ceramic water filters (Clasen and Boisson 2006)), *mobile water treatment systems (WTS)* offer the chance to start a large scale intervention fast and with a limited number of required components.

Figure 4.6 provides an overview on the study's components. While module A aims to determine the water demand, the focus of module B is to provide an overview of the collection and pre-processing steps for wells and WTS. Moreover, module C contains the development of a mixed-integer linear optimization problem to select locations, together with various possibilities to better understand the trade-offs of decisions and, therefore, offer decision support to authorities.

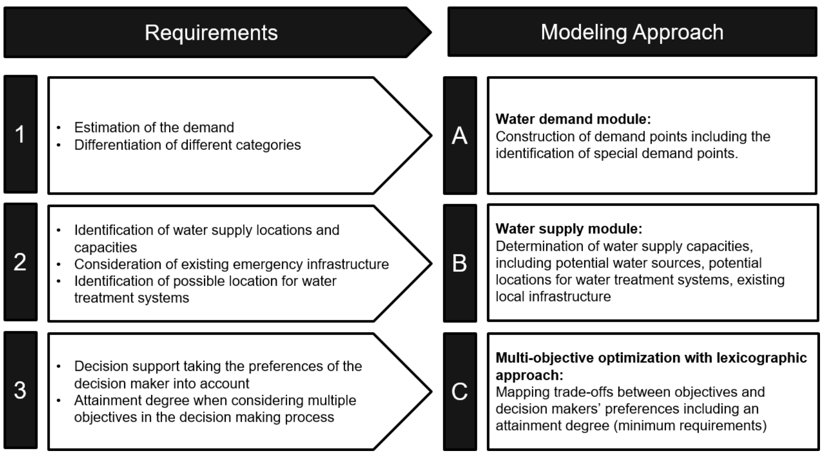


Figure 4.6: Overview of Study D's model requirements and modules with the chosen modeling approaches (modules A, B, C; see also Figure D.1).

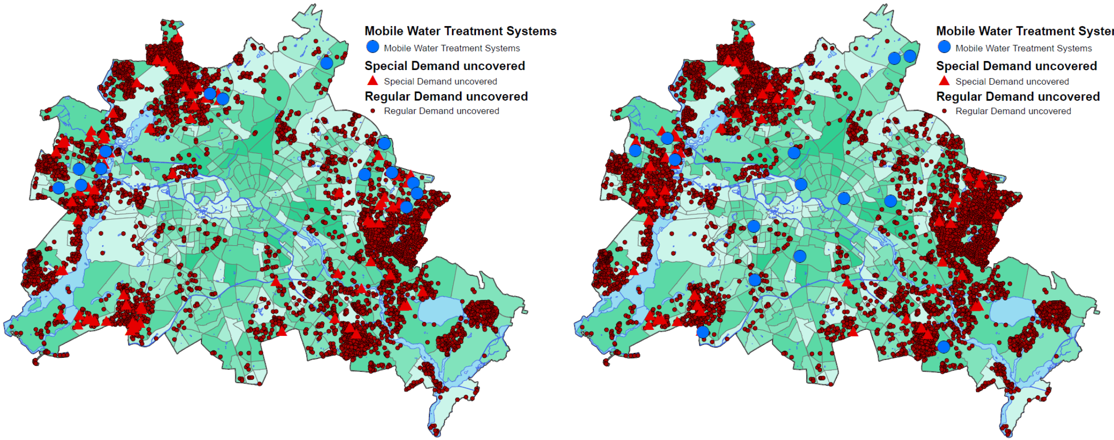
From an academic perspective, the study offers three main contributions to the body of literature. First, the introduced structure can be followed when determining the capacities of an existing well system. Second, a maximum covering model to support the process of location selection for WTS is introduced. Third, the comparison of different trade-offs allows decision-makers to deepen their understanding of relief interventions more thoroughly and, thus, can improve both preparedness for disasters and the response after future disasters.

The application of the model to a case study highlights the power of the approach. Within the case study, the response to hypothetical water contamination in the city of Berlin is analyzed. The German Federal Agency for Technical Relief (THW) owns 14 large-scale UF-15 WTS that are considered potential water sources complementing Berlin's wells. These UF-15 systems can purify up to 300,000 liters of water per day to drinking water quality. A presentation of the main results and points of discussion of the study follows.

Results and Discussion

The case study highlights the importance of extending emergency water supply beyond the limits of emergency wells. Under the selected assumptions, emergency wells can only offer water to up to 77% of the population's demand. On the other hand, this number can increase to up to 84% if WTS complement the wells. However, the selected locations differ strongly if decision-makers prioritize parts of the population – e.g., vulnerable groups such as people in hospitals or nursing homes. The maximization of total supply leads to WTS-locations that are mostly located on the outskirts of Berlin. On the other hand, a lexicographic maximization approach, in which vulnerable groups are prioritized over the general population's demand, suggests installing WTS at more central locations. Figure 4.7 highlights the selected locations. Furthermore, trade-offs regarding the maximum length of the supply route, the required number of WTS to fulfill a certain coverage level, and between cost and coverage are discussed in the published article.

The study efficiently highlights the importance of improving the emergency water distribution system and extending the available resources. Even though the currently available WTS increase the attainable degree of coverage, it is not possible to supply water to 16% of the population.



(a) Maximization of total coverage

(b) Prioritization of vulnerable population

Figure 4.7: Selected locations for WTS (blue dots), uncovered demand of regular (red dots) and vulnerable (red triangle) demand points (see also Figures D.5 and D.6).

Moreover, the study sheds light on the trade-offs decision-makers have to consider when facing disaster relief decisions. Even though these decision-makers are usually experienced logisticians, elected politicians, or both, having expert knowledge in their field, decisions like prioritizing parts of the population or investing in specific technologies come with drastic consequences for society. Therefore, it is necessary to provide people in charge with as much support as possible. This could be done both with studies like the present one, complemented with public debates. For example, one component of the study was to understand the effects of an increased number of WTS and to analyze the effects of a more cost-efficient deployment of expenditures (in favor of other strategies to use available money). Therefore, considering debates, the general society needs to start forming a consent about the degree to which vulnerable people should be prioritized or if it is possible to determine a limit of tolerable consequences for the general population. Similar debates also influenced decisions during the COVID-19 pandemic response, e.g., regarding tolerable contact restrictions during the Christmas holidays or the tolerable economic burden due to the large financial aid volume.

Consequently, the developed approach increases transparency significantly and provides decision-makers with valuable information.

4.5. Study E: The Value of Accurate Demand Information in PPECs

The following section refers to the content of the article "On the Value of Accurate Demand Information in Public-Private Emergency Collaborations." This article was written in collaboration with Miriam Klein, Marcus Wiens, Markus Lüttenberg, and Frank Schultmann, and was published in the KIT-IIP *Working Paper Series in Production and Energy* as Diehlmann, Klein, et al. (2020).

Study context and contributions

The study’s objective is to introduce a framework to quantify the value of accurate information and the planning error due to incorrect information in disaster relief.

Private actors supply goods to the population during ordinary times and interact with their customers regularly. Therefore, they understand the market better than authorities do, which are mainly during disaster relief. Consequently, authorities are motivated to collect more accurate information. For example, this can be done by purchasing market data (similar to the US FEMA, which recently spent 3.6 million USD on market information (Federaltimes 2019)) or, more drastically, by a state-ordered release of demand information during a disaster. However, these measures represent intense market interference and should, therefore, be assessed carefully in advance. To support this assessment, a framework to quantify the value of this information was developed and introduced in the study.

Figure 4.8 highlights the framework. Assuming a demand spike in the aftermath of a disaster, supermarket capacities are exceeded, leaving parts of the population without supplies. Consequently, authorities try to distribute essential goods to the people who cannot be supplied by the companies anymore. This is achieved by opening or remodeling facilities for the distribution, e.g., schools.

While authorities only have access to general demographic information, they cannot distinguish between different characteristics of demand points (DPs) representing beneficiaries. Therefore, they need to treat every DP equally (grey boxes). On the other hand, private actors understand different demand patterns better. If, for example, people living on a block did not increase their water purchases during a minor water contamination a couple of months ago, they most likely will have water stored at home. Therefore, their water purchases will most likely not increase again, leading to a more specific assessment of the same people's demand (green boxes).

Including such information into authorities' school selection decisions leads to different outcomes (*ED-Scenario* (Equal Demand) and *I-Scenario* (Information)). Moreover, the combination of the locations selected with inaccurate information and the real demand points leads to the so-called *CO-Scenario* (Combined Outcome), which can be interpreted as the realization of a plan based on inaccurate information. Consequently, the difference between CO-Scenario and ED-Scenario (in terms of a selected key performance indicator) represents the planning error. Furthermore, the difference between I-Scenario and CO-Scenario represents the value of accurate information. Moreover, the frameworks' flexible set-up allows decision-makers to analyze multiple addi-

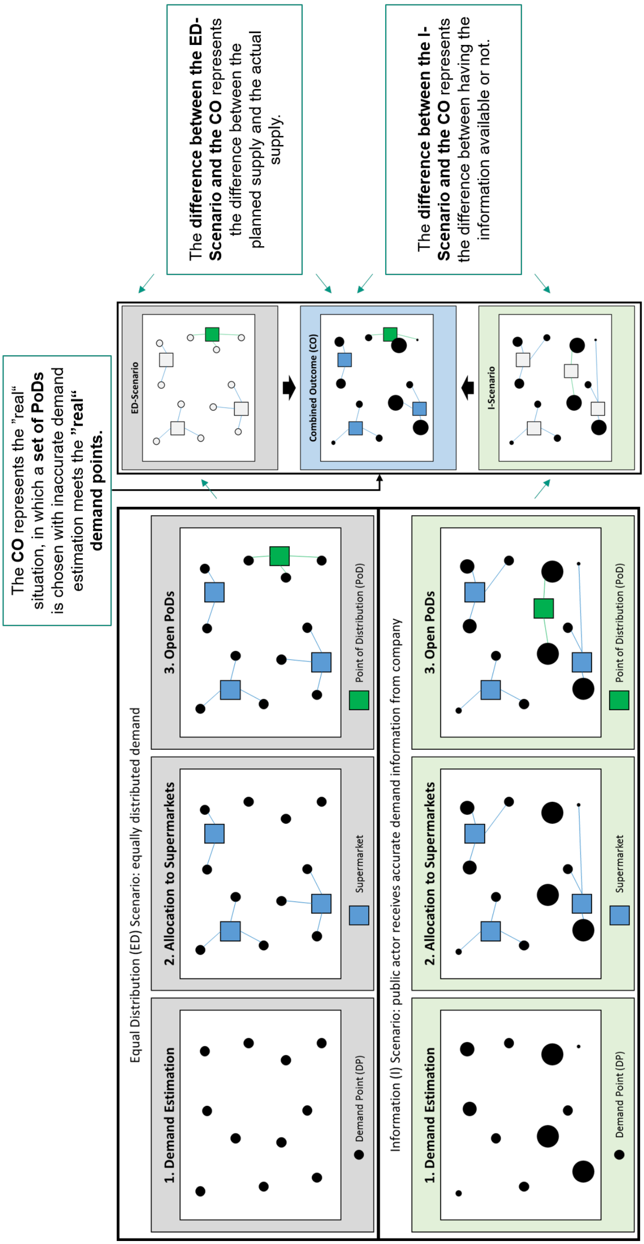


Figure 4.8: Overview of the framework (see also Figure E.1).

tional situations and, therefore, offers a valuable contribution for planners, decision-makers, and researchers.

The framework is applied to a case study of hypothetical water contamination in the city of Berlin. Assuming a short time spike of water demand, authorities need to select schools as temporary water distribution points. In the present case study, these schools' selection is conducted with a mixed-integer linear program maximizing the delivered water. Following the framework described above, authorities can only plan with publicly available census data. Simultaneously, supermarkets have more detailed data available.[2] A presentation of the main results and points of discussion of the study follows.

Results and Discussion

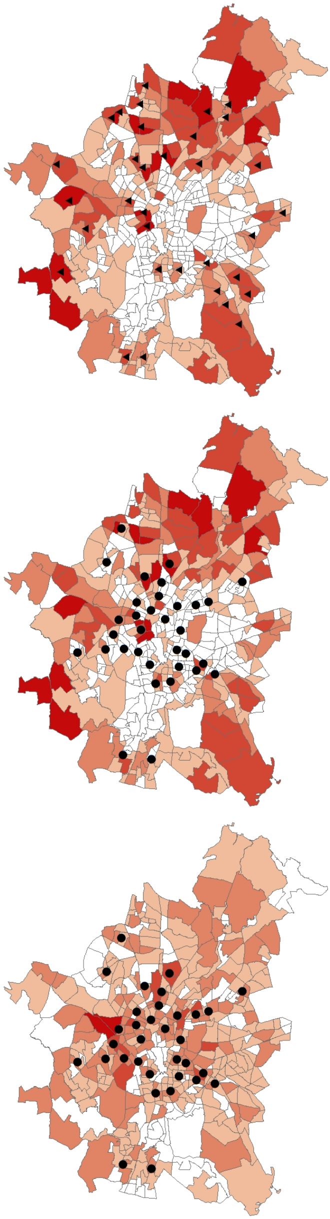
Figure 4.9 highlights the selected schools to open within the three scenarios (ED, CO, and I) in case authorities have the capabilities to open 33 schools.[3]

In the ED-Scenario, the mixed-integer linear program selected schools mostly located in Berlin's center. However, merging the actual demand distribution with these locations indicates that the locations are not selected adequately (CO-Scenario). Consequently, 23% fewer goods than planned can be distributed, representing the planning error. On the other hand, total supply increases by 19% in case authorities base their plan on accurate demand, representing the value of information (I-Scenario).

Furthermore, the framework allows for analyzing two extensions. The first extension aims towards a better understanding of the intervention's starting time. While authorities started operating their school-based distribution after supermarkets had run out of goods in the basic version of the framework, extension I regards simultaneously operated schools and supermarkets. Furthermore, the second extension aims to better understand the competition between supermarkets and school-based distribution centers. In the basic version of the framework, school locations were selected considering the demand that cannot be covered by the supermarkets. In extension II, authorities regard the whole population's demand and operate the schools simultaneously

[2] The study's market data was simulated due to confidentiality reasons.

[3] The sum of the capacity of 33 schools and Berlin's supermarkets roughly equals the total demand.



(a) Selected schools in the ED-Scenario.

(b) Previously selected schools are not optimal to match the real demand in the CO-Scenario.

(c) Selected schools in the I-Scenario.

Figure 4.9: 33 selected school locations and demand in the different scenarios. The darker the color of the polygon the higher the demand (see also Figures E.6 - E.8).

to the supermarkets. Consequently, crowding-out effects are more likely to occur.

Figure 4.10 presents the amount of water distributed via the different distribution channels for the basic version of the framework and the two extensions. In contrast to the intuitively expected result, crowding-out effects are weaker in the case of a more intense market intervention. By selecting schools that maximize the total supply through supermarkets and schools, authorities implicitly consider the maximization of supermarkets' supply into their optimization models. Consequently, supermarkets benefit from stronger interventions and are recommended to collaborate with authorities if they expect an intervention. If, for example, authorities reached out and asked for information on areas that are expected to become undersupplied by the private sector, they could consider sharing additional information on the whole supply. However, it has to be noted that crowding-out cannot be avoided. Consequently, supermarkets still need compensation for the intervention.

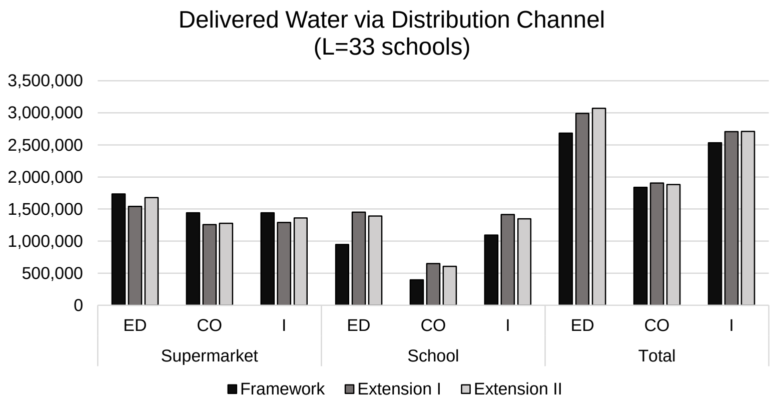


Figure 4.10: Overview of the amount of water distributed via schools, supermarkets, and total within the different model extensions.

The study offers multiple directions for future research. First, the assumption of a static disaster context might not hold in reality. Examples of potentially dynamic parameters are demand and supply, which might increase fast or unfold slowly. Consequently, multi-period approaches might shed light on ways to optimize the order to open schools or the importance of anticipating demand information in disasters. Second, the study assumes equal treatment for every beneficiary. As shown in Stallkamp et al. (2020), the prioritization of vulnerable parts of the population might be necessary, though it can significantly reduce total supply. Considering different demand types might offer the chance to distinguish the value of information for different types of demand information, leading to a deeper understanding of prioritization consequences. Third, the operationalization of the collaboration requires further preparation. If, for example, supermarket chains were to share information with authorities, questions on the data format, requirements for IT-interfaces, data protection issues, and many more would arise and take much time to agree on. Consequently, disaster response exercises could help identify such problems and handle them prior to the disaster, leading to better-defined processes and, thus, an increased speed of the disaster intervention.

5. Managerial Implications

After summarizing the studies' results, the managerial implementations for the four cross-study topics introduced in chapter 2.4 – Information Management, Company Involvement, German Specifities, and Trade-offs – follow.

5.1. Collect Information Before the Start of the Disaster

Studies A, B, D, and E provided valuable insights into the importance of information in disasters. Study A identified asymmetric information as a challenge for collaboration in disaster relief. Study B stressed how information is interpreted differently by the respective relief actors. Furthermore, Study D underlined that decisions might change by including precise information regarding, e.g., a person's vulnerability. Finally, Study E shed light on the importance of accurate information and highlighted the complexity of approximating demand information from publicly available resources.

The diversity of potentially helpful information indicates that a variety of actors could contribute important information. However, the majority of relevant datasets are critical from a business confidentiality or data protection perspective. Consequently, these actors either need compensation for sharing data or guarantees that sharing data will not negatively affect their organization. In case they agree to share data, issues such as data format, granularity, or the selection of an exchange platform may arise.

Creative solutions can facilitate collaboration and information exchange. In this context, blockchain technology might be a promising option since it "provides an integrity protected data storage and allows to provide process transparency" (Wust and Gervais 2018, p. 45). Therefore, blockchains could work as a single platform of communication in disasters, connecting donors and transportation companies or ensuring the verification of the authenticity of relief goods (SCB 2019). Other application concepts include using blockchains for victim identification via sensitive dental data (AlQahtani et al. 2019) or coordinating the information exchange between ground vehicles and unmanned aerial vehicles scanning disaster areas (Su et al. 2020).

Nevertheless, it becomes evident that the information required for an efficient relief decision is too complex to be collected without preparation in the aftermath of a disaster. Decision-makers must address ways to obtain a comprehensive set of information before the disaster started. In addition to complex state-of-the-art technologies, traditional (open-source) databases might already provide sufficient information for dedicated decision support models. For example, the city of Berlin publicly shares georeferenced data (Berlin 2019). This data can be further used in studies addressing different disaster components, increasing the understanding of local characteristics for disaster response. The fact that most of the companion articles for the present dissertation were conducted using Berlin's publicly available data underlines this further.

5.2. Organize Training Exercises With Companies

Studies A, B, C, and E addressed the involvement of companies in disaster relief. Study A offered multiple examples of PPECs, as well as guidelines for modeling these collaborations. Study B underlined the challenges of identifying options that both actors benefit from, while Study C shed light on selecting commercial buildings as temporary distribution centers. Moreover, Study E emphasized the potential effects of authorities' interventions on the private sector.

Together with the current developments in the COVID-19 pandemic, the results of the studies highlight that companies are already heavily involved in relief logistics. Despite authorities' formal responsibility during disasters, companies significantly reduce the affected population's suffering by keeping their distribution channels open (for commercial and altruistic reasons). Thus, increasing the private sector's resilience reduces the burden on authorities. Moreover, authorities implicitly rely on companies' resources – for example, transportation capacities, buildings, or goods. Therefore, joint exercises are highly recommended to improve interoperability by ensuring that access to and operation of the potentially required resources, as well as the related communication processes, work properly. For instance, this could be addressed in one of the upcoming LÜKEX[1] campaigns, in which authorities practice collaboration between different ministries and bureaus during a large scale disaster intervention. Standardization and practicing of processes can speed up the disaster intervention and provide necessary relief.

5.3. Adjust the German Disaster Management System

Different aspects of the German disaster management system were analyzed in Studies B, D, and E. Study B highlighted the potential of closer collaboration of public and private actors during the storage of goods that might be demanded in a disaster. Study D addressed available infrastructure for water supply and Study E Berlin's local school network as potential PoDs.

The studies hint towards slightly outdated structures that require modernization. For example, Study B highlighted that it is not possible to supply Berlin's population in a disaster with wells alone. Even though the emergency wells are maintained and new wells built from time to time, it is highly unlikely that the well system is sufficient during disaster relief, considering that almost 20% of Germany's emergency wells are located in Berlin (Fischer and Wienand 2013). Moreover, maintaining and extending the well system requires high financial and organizational effort. On the other hand, during one of the NOLAN-workshops, experts stressed that emergency wells only serve as the "last resort," and other means of supply might be helpful during small-scale disruptions. Consequently, further investments in mobile treatment systems or other flexible solutions might be reasonable options for decision-makers that want to increase water supply resilience in disasters.

Another essential aspect to consider, which is closely connected to the issue of Information Management, is the high degree of coordination effort. Authorities need to activate and communicate with diverse public ministries, bureaus, and organizations, which will slow down response speed (especially

[1] "Interministerial and Interstate Crisis Management Exercise," in German: "**L**änder- und Ressort**ü**bergreifende **K**risenmanagementübung (**Ex**ercise)."

if legal factors and procedures have to be followed in the context of Amtshilfe). Furthermore, informing beneficiaries about the relevant details of authorities' operational plans is challenging – for example, the location of the allocated PoD. Moreover, the COVID-19 pandemic and the development of the German *Corona-Warn-App* stressed the high priority of data protection in Germany (DW 2020c). Consequently, creative solutions are required to prevent bureaucracy and data protection from slowing down the response speed. These creative solutions could include blockchain technologies and the transfer of the recently developed Corona-Warn-App to other application options. An example could be anonymously tracking the frequency a PoD is visited via the application's interfaces, as well as using the application to distribute food stamps, or collect voluntarily shared information in a crowdsourcing initiative.

5.4. Initiate Public Debates About Prioritization During Disaster Relief

Studies A, B, C, and D highlighted the importance of understanding trade-offs in disaster relief. Study A discussed the different objectives in disaster collaborations, while an approach to identify potential compromises in location selection was introduced in Study B. Moreover, Study C focused on the trade-off between human suffering and financial aspects during a relief intervention, while Study D addressed the trade-offs that come along with prioritizing vulnerable parts of the population.

It is almost impossible to make relief decisions without (explicitly or implicitly) considering trade-offs. Financial trade-offs have been highly debated in commercial literature and attracted some attention in relief logistics in the context of deprivation costs. However, the implications of non-monetary trade-offs should be further investigated. For example, sustainability topics, such as minimizing waste or emissions while maximizing supply, could also become important for decision-makers. Moreover, trade-offs that arise by prioritizing one part of the population over another need to be investigated further. It might be reasonable to prioritize vulnerable groups (for example, people in special care facilities) from a philosophical or moral perspective. On the other hand, Study D highlighted the drastic consequences for the non-prioritized groups. Consequently, there should be a public debate about if, how, and at which cost authorities should prioritize parts of the population.

An example of such a discussion is the COVID-19 vaccine distribution debate. A group of experts from various German organizations[2] opened the debate by suggesting a general vaccination-prioritization strategy for the German population (Ethikrat 2020). Afterward, this strategy was open for debate long before the vaccine distribution was expected to start. Similar debates on critical issues, such as: "who should receive water in case there is not enough water?" or "who should get access to critical goods first if there is hypothetically enough for everyone, but everyone needs them at the same time?" could therefore be initiated by authorities. However, starting these kinds of debates will be challenging and needs to be prepared thoroughly to avoid the risk of a debate based on panic and fears. Nevertheless, besides probably increasing the acceptance of these measures during an upcoming disaster, transparently communicating a strategy agreed upon by the majority of the population might lead to better disaster preparation of non-prioritized groups and, thus, less suffering of the whole population.

[2] The German Permanent Vaccination Commission, German Ethics Council, and the German National Academy of Sciences Leopoldina.

6. Conclusion

Relief logistics aims to deliver goods to beneficiaries in the aftermath of a disaster. During this process, three different types of facilities are essential: warehouses, distribution centers, and distribution points. The selected locations of facilities significantly affect the outcome of disaster response. Therefore, decision-support models improving the process of location selection increase resilience towards disasters.

The dissertation contributes to the literature with five studies, increasing the understanding of disaster relief logistics and supporting decision-makers during different facility location decisions. Thus, it provides valuable insights into making relief interventions more efficient. Study A stresses the importance of addressing differences in resources, capabilities, and strategies in PPECs. Moreover, power differences, information sharing, and partner selection are essential to consider. Study B indicates that, even though both types of actors follow different strategies and goals, it is possible to identify candidate locations with the help of a new approach based on multi-objective mixed-integer optimization models. Study C highlights that decision-makers could better understand the implications of their decisions with the help of a normalized weighted sum approach. Study D indicates that a combination of wells and mobile systems could improve humanitarian water supply chains in disasters. Selected locations change significantly if vulnerable parts of the population are prioritized. Study E introduces a framework that allows determining the value of information and the planning error due to inaccurate information. Consequently, the studies contribute to an increase in the efficiency of the relief system.

Furthermore, implications for four cross-study topics – Information Management, Company Involvement, German Specifities, and Trade-offs – were derived. Information should be collected before a disaster stroke since the complexity of collecting and exchanging information will significantly slow down relief efforts otherwise. Furthermore, the need to exercise with companies became obvious since authorities already strongly rely on company resources. Moreover, adjustments to the German disaster management system are recommended. This includes, inter alia, investments into mobile water treatment systems or creative solutions for more efficient coordination during disasters. Finally, a public debate on the consequences of implicitly or explicitly prioritizing parts of the population has the potential to increase the public acceptance of a prioritization strategy and, thereby, reduce the burden on authorities significantly. Initiating research projects preparing these debates could be a first step to approach this issue.

Future studies aiming to improve location planning further may, in addition to the opportunities mentioned in chapter 4, address these cross-study topics. For example, developing a data exchange interface can increase the available input data for location optimization models. Guidelines to standardize PPECs and a toolbox for exercises can ensure efficient implementation of plans in case of a disaster. A holistic analysis of the German disaster warehouses' location under consideration of the private sector might reduce authorities' warehousing costs. Similarly, a shift from stockpiling grains towards storing ready-to-eat meals can reduce the complexity of the distribution, bypassing the preprocessing steps currently required before distributing food to the population. However, the accompanying adaptations to the warehouse system need to be studied thoroughly first. Moreover, future studies could aim to improve the communication of location decisions. For example, a disaster dashboard highlighting selected PoDs could ensure that prioritized beneficiaries receive their goods. The implementation into an already existing mobile application might facilitate this process.

Despite the opportunities to improve disaster relief further, statistics indicate that, from a global perspective, disaster management is developing in a promising direction. An example of such a promising development is the ongoing century-wide decline of average deaths per year caused by disasters while the total number of disasters increases (Forbes 2020). The COVID-19 pandemic is likely to stop this trend and revealed that there is still much room for improvements. Moreover, the increasing probability of disasters like zoonoses caused by the effects of Globalization (Gibb et al. 2020) or an increasing number of hurricanes caused by Global Warming (Webster et al. 2005) indicates that the number of disasters is likely to keep increasing in the future. Nevertheless, the promising long-term trend highlights that disaster management continuously improved over the last century, allowing disaster managers to face the upcoming challenges with optimism. The present dissertation can contribute to this positive long-term development, improve the response towards upcoming disasters and, therefore, reduce the suffering of affected people in the future.

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Part II.

Companion Articles

Overview of Related Publications

Study A

Diehlmann, F.; Lüttenberg, M.; Verdonck, L.; Wiens, M.; Zienau, A.; Schultmann, F. (2020). Public-Private Collaborations in Emergency Logistics: A Framework based on Logistical and Game-Theoretical Concepts. KIT-IIP Working Paper Series in Production and Energy.

Study B

Löffel, M.[1]; Diehlmann, F.[1]; Zienau, A.; Lüttenberg, M.; Wiens, M.; Wagner, S. M.; Schultmann, F. (2020). Identifying Joint Warehouse Locations in Public-Private Emergency Collaborations. Submitted to a Scientific Journal.

Study C

Diehlmann, F.; Hiemsch, P. S.; Wiens, M.; Lüttenberg, M.; Schultmann, F. (2020). A Novel Approach to Include Social Costs in Humanitarian Objective Functions. KIT-IIP Working Paper Series in Production and Energy.

Study D

Stallkamp, C.[1]; Diehlmann, F.[1]; Lüttenberg, M.; Wiens, M.; Volk, R.; Schultmann, F. (2020). On the combination of water emergency wells and mobile treatment systems: a case study of the city of Berlin. Annals of Operations Research [in Press].

Study E

Diehlmann, F.; Klein, M.; Wiens, M.; Lüttenberg, M.; Schultmann, F. (2020). On the Value of Accurate Demand Information in Public-Private Emergency Collaborations. KIT-IIP Working Paper Series in Production and Energy.

[1] These authors contributed equally to the manuscript.

A. Public-Private Collaborations in Emergency Logistics: A Framework Based on Logistical and Game-Theoretical Concepts

Abstract[1]

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 could contribute to a more efficient supply of goods given their resources and existing communication networks. Based on this research gap, this paper develops a logistical and game-theoretical modeling framework for public-private emergency collaborations. We characterize both public and private actors' possible roles in emergency logistics based on literature research and real cases. Furthermore, we provide an overview on existing PPECs and the challenges they are confronted with. The concluding framework contains aspects from humanitarian logistics on the governmental side and from business continuity management (BCM) or corporate social responsibility (CSR) on the commercial side. To address the challenge of evaluating different objectives in a collaboration, we add a game-theoretical approach to highlight the incentive structure of both parties

[1] This chapter includes the preprint of the article "Public-Private Collaborations in Emergency Logistics: A Framework based on Logistical and Game-Theoretical Concepts" by Markus Lüttenberg, Lotte Verdonck, Marcus Wiens, Alexander Zienau, Frank Schultmann, and myself (Diehlmann, Lüttenberg, et al. 2020).

in such a collaboration. In this way, we contribute to the research field by quantitatively evaluating public-private collaboration in emergency logistics while considering the problem-specific challenge of the parties' different objectives.

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 (UNDRR 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, companies can still dispose over most of their capabilities to respond to the disaster, while established supply chain structures are severely interrupted during catastrophes (Holguín-Veras, Jaller, et al. 2012). Higher resilience provided by public and private actors, cooperatively involved in disaster relief, can therefore 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.

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, Arslan, and Demiroz 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, Gutierrez, and Keskinocak 2011; Gatignon, van Wassenhove, and Charles 2010; Pedraza-Martinez and Van Wassenhove 2013; Saputra et al. 2015; 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.

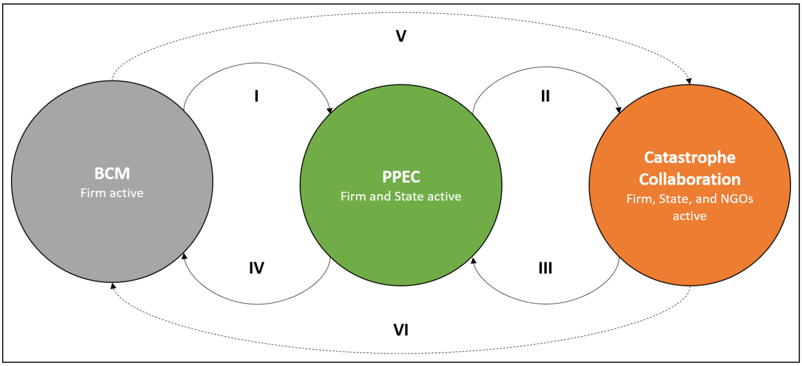

Figure A.1: Classification of phases or activities for different types of actors during a crisis.

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, Arslan, and Demiroz 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 2019). 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, Gronalt, and Hirsch 2016; Nurmala, Vries, and Leeuw 2018; Tomasini and Van Wassenhove 2009), the body of literature on PPECs remains scarce (Chen et al. 2013; Gabler, Richey, and Stewart 2017; Stewart, Kolluru, and M. Smith 2009; Swanson and R. J. Smith 2013; Wang, Wu, 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, Flores, and Soylu 2016; Nagurney, Salarpour, and Daniele 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 R. J. 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, Giese, and Mohn 2012), in the healthcare sector, for schooling projects, or in waste management (Spoann et al. 2019). Saussier and 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, Costantino, and Pellegrino 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 (WEF) 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, Leeuw, and Wout Dullaert 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, Richey, and Stewart 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, Chong, and Saussier 2013).

In principle, most of these mechanisms can also be transferred to collaboration in crisis management (Solheim-Kile, Lædre, and Lohne 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, Fiksel, and Croxton 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 (at least partly) structured as a public-private collaboration for crisis management. One 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 fascilitate 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.

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, Marr, and Garnevska 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 (SBA 2020)) 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, Vries, and Leeuw 2018; Wang, Wu, et al. 2016) or access to logistical competences (Qiao, Nan, and Kang 2010; Tomasini and Van Wassenhove 2009).

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 2020). 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, Lau, and Castillejos 2018; Pettit, Fiksel, and Croxton 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, Vries, and Leeuw 2018).

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 (Elliott, Swartz, and Herbane 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, Tetrault Sirsly, and Ronen 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, Lee, and Dai 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 two real-life examples, where the private sector faced a crisis. The first 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, Vries, and Leeuw 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).

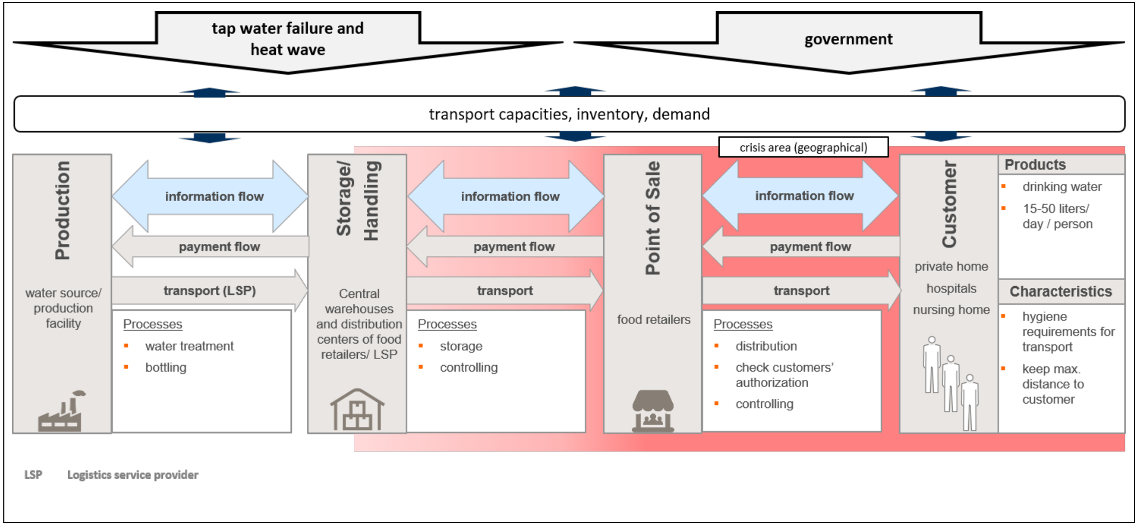

Figure A.2: Exemplary visualization of commercial water supply chains in case of tap water failure (based on Dani and Deep, 2010).

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.

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, Sharkey Scott, and Fynes 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, Fiksel, and Croxton 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.

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, W. Dullaert, and Fleuren 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, W. Dullaert, and Fleuren 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, Sharkey Scott, and Fynes 2014; Snyder et al. 2016; Swanson and R. J. Smith 2013; Tukamuhabwa et al. 2015) and second category (Scholten, Sharkey Scott, and Fynes 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.

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, Jaller, et al. 2012). This is

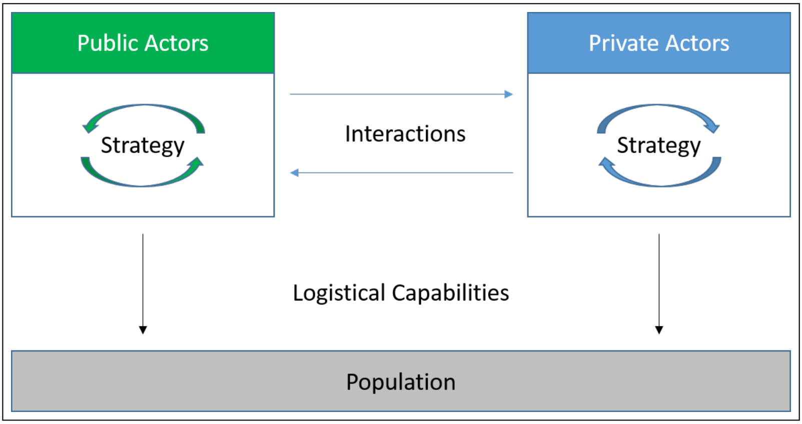

Figure A.3: Interdependencies in Public-Private Emergency Logistics.

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, Jaller, 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, Pérez, 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, Pérez, 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, Jaller, 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, Ramesh, and Arshinder 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 M. 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 and Van Wassenhove 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, Ramesh, and Arshinder (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, Fernández Barrera, and Mansouri (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, Jaller, 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 (M. A. 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, Jaller, 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, Jaller, 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, Jaller, 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.

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, Devine, and Zhuang (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, Flores, and Soylu (2016) and Nagurney, Salarpour, and Daniele (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, Flores, and Soylu (2016) and Nagurney, Salarpour, and Daniele (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).

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, Goentzel, and Montibeller (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, Fernández Barrera, and Mansouri 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. Collaboration can avoid cost and provide the requirements for a 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".

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. 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 ($T_{S,F} \longrightarrow \infty$ 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):

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

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 $\mu \longrightarrow \infty$ 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 $\theta_S\ \theta_F$.

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.4 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.

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.

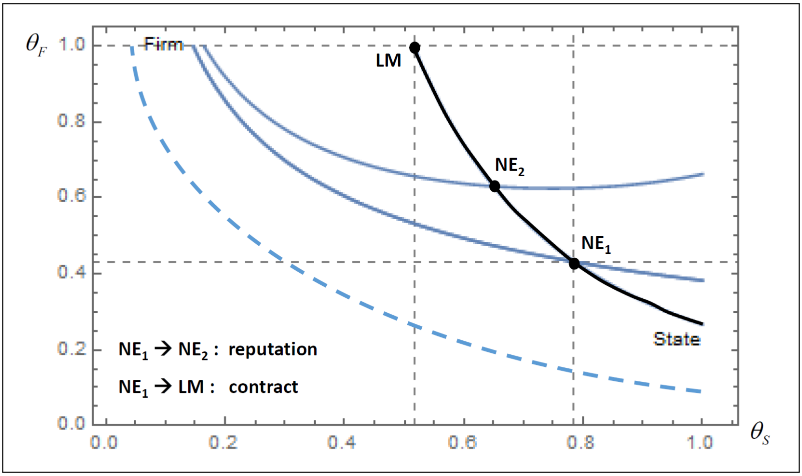

Figure A.4: Best-response functions.

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^* $(\theta_S^*\ \theta_F^*)$. 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.4 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.4 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, Kolluru, and M. Smith 2009; Donia, Tetrault Sirsly, and Ronen 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 π^* (θ_S^*, θ_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):

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

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 2020)) 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.

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. Identifying Joint Warehouse Locations in Public-Private Emergency Collaborations

Abstract[1]

The private sector regularly ensures the efficient supply of food for the population. However, public authorities have legal obligations to ensure food supply and might have to take over responsibilities during times of emergencies. Existing procedures and supply chain structures for crisis preparedness and public emergency food supply are often antiquated and costly. In this study, we consider Public-Private Emergency Collaborations as an innovative approach to improve emergency food preparedness.

We delineate a novel approach and the benefits of deploying private warehouse infrastructure and collaborative warehouse sites for public emergency food supply. The proposed approach provides an attractiveness score for warehouse locations and, as a consequence, increases transparency. Furthermore, the multi-objective optimization considers logistics costs, deprivation, and regional attractiveness. Therefore, it combines relevant but diverse objectives for warehouse location decisions and enables efficient trade-off solutions between objectives. We apply data pertaining to the state of Baden-Württemberg in Germany to determine and demonstrate the application of our approach and the benefits for actors in the private and public sector.

[1] This chapter includes the preprint of the article "Identifying Joint Warehouse Locations in Public-Private Emergency Collaborations" by Maximilian Löffel, Alexander Zienau, Markus Lüttenberg, Marcus Wiens, Stephan M. Wagner, Frank Schultmann, and myself, which has been submitted to a scientific journal.

B.1. Introduction and Problem Description

Food supply is regularly organized through private actors where grocery chains have built highly efficient supply chains. In times of crisis (e.g. due to failed harvest, disruption of international supply chains, or lockdowns due to pandemics), the responsibility to ensure food supply might shift to the public sector. Therefore, the responsible public authorities regularly have preparedness measures and infrastructure in place to ensure responsiveness. The German Federal Government, for example, maintains a large emergency stock of grains and legumes in emergency warehouses (BMEL 2020b).

Public and private actors follow different supply chain strategies with varying requirements regarding warehouse locations. The private sector aims for high inventory turnover (Zentes, Morschett, and Schramm-Klein 2017). Fast Moving Consumer Goods (including food) are usually shipped from production plants and manufacturer distribution centers via warehouses and retailer distribution centers to stores and other Points of Distribution (PoDs; Kellner, Otto, and Busch (2013)). For example, supermarket chain Lidl has approximately 40 regional warehouses and 3.200 retail stores in Germany (LIDL 2020) and Tesco around 30 warehouses and 3.500 retail stores in the UK (Zentes, Morschett, and Schramm-Klein 2017). In contrast, the large and costly stocks in public emergency warehouses are rarely needed (if at all), and the inventory turnover is low. This triggers the question of whether a closer collaboration between private and public actors could maintain the security of food supply in case of crises and increase the emergency supply's efficiency.

Public-Private Emergency Collaborations (PPECs) are not entirely new. However, they are usually restricted to the disaster relief and humanitarian aid context. The humanitarian operations and supply chain management literature discusses and promotes joint crisis management via a voluntary exchange of knowledge or resources (van Wassenhove 2006; Kovács and Spens 2007; Wiens et al. 2018). While some countries consider PPECs in their emergency plans (e.g. Sweden; Kaneberg (2018)), this issue has not been thoroughly addressed in the German context.

Both public and private actors significantly benefit from closer collaboration in this area. On the one hand, the government could substantially reduce the number of unused goods at hand for emergency supply by utilizing private supply chains that store specific goods in well-positioned warehouses, thereby saving taxpayer money. Approximately €20 million are currently spent per year for food supplies that have never been used domestically (Rexroth 2010).

On the other hand, private actors could benefit from additional sales in crises when having essential goods (LZ 2020b) and additional storage space for spikes in demand available (LZ 2020a), e.g. due to improved information sharing with public authorities and supported by public compensation within the collaboration. Moreover, firms could be perceived as an important actor for people's well-being through increased media coverage (Focus 2020; MDR 2020) and achieve reputational gains (Wiens et al. 2018).

Despite expected gains from closer collaboration, public and private actors pursue different objectives and operate in different environments (Holguín-Veras, Jaller, et al. 2012). Therefore, long-lasting collaborations are only feasible if chosen locations are useful and attractive for both actors to fulfill their individual objectives. In particular, we determine regional attractiveness with specific location criteria and evaluate a logistics network from the commercial and emergency perspectives through monetary logistics costs and monetized deprivation.

In the context of this study, we consider a PPEC that facilitates the combined use of warehouses for commercial and emergency food supply. To the best of our knowledge, no approach exists that compares the attractiveness of regions from both perspectives and derives potential candidate locations for collaboration. We close this gap, develop a tool that supports the process to find such locations, and contribute to the body of literature in two ways.

First, we increase transparency regarding the attractiveness of geographical regions for commercial and emergency strategies. Attractiveness can firstly differ due to divergent assessments of the importance of certain location criteria, e.g. salary levels or the quality in local IT infrastructure. Moreover, some criteria might only be relevant for one of the two actors (e.g., local taxes). Comparing regions from either perspective, we further identify regions which can be suitable for both actors.

The differences in the regions' scores provide useful insights for both regional planners and commercial decision makers aiming to contribute to an increased resilience towards crises in the context of their Corporate Social Responsibility initiatives. For example, authorities can select and support less attractive and, probably, less expensive regions they want to develop into emergency logistics hubs.

Second, we develop an optimization model that combines multiple objectives: costs, suffering of the population in crises, and attractiveness of the regions for warehouse locations. The outcome of this model is an array of warehouse networks from different perspectives. The locations that are selected in multiple scenarios can serve as another starting point for a PPEC: If both actors benefit from a new warehouse at the location, common contingency measures could be installed. This may include public actors' access to critical goods and the power to influence their distribution at the beginning of a crisis. On the other hand, companies could for example receive tax-benefits or subsidies for investments in the local infrastructure.

Our study is structured as follows. In Section B.2, we provide an overview on relevant literature. Following, we present our approach in Section B.3, before we apply the approach in the context of a case study in Section B.4. We discuss the results of the case study in Section B.5 and conclude our study with an outlook for future work.

B.2. Theoretical Background

Approaches to identify warehouse locations have been discussed in the literature for a long time (see for instance Akinc and Khumawala (1977), Lee, Green, and Kim (1980), and Yoon and Hwang (1985) as examples of early work). Furthermore, the attractiveness of different regions as a potential warehouse location and the corresponding selection of locations are broadly studied in the commercial and humanitarian logistics literature. A wide selection of criteria, frameworks, and programming approaches have been developed.

Regarding the general process of warehouse location selection, van Thai and Grewal (2005) introduce a three-stage framework. Steps include the identification of a geographical area, a collection of potential locations, and the final selection of a distribution center location. We follow the structure of this approach within our study.

Recognizing that location decisions should be based on different criteria, Badri (1996) is one early example to apply multi-objective programming and optimization. The work ranks various goals according to their importance and uses lexicographic optimization accordingly. Furthermore, Chuang (2002) uses quality function deployment (QFD) to establish useful location criteria, considering nine criteria and expert knowledge. The type of facility is not specified to a warehouse, but several established factors broadly apply to location decisions, such as the quality of transportation infrastructure. Similarly, Dekle et al. (2005) analyze the location of disaster recovery centers in a county in Florida from the humanitarian perspective. Although disaster recovery centers play a different role in relief operations than warehouses, the applied location criteria are generalizable and repeatedly found in comparable publications on location decisions (e.g., Roh, Pettit, et al. (2015) below).

Roh, Jang, and Han (2013) develop specific criteria for humanitarian relief warehouse locations, making use of the Analytic Hierarchy Process (AHP) and semi-structured interviews for first- and second-level criteria. First-level criteria include cooperation, national stability, cost, logistics, and location. In a follow-up study, Roh, Pettit, et al. (2015) deal with important location factors for pre-positioning, several of which are similar to the ones used by Dekle et al. (2005). Their goal is to identify a suitable macro- and later micro-location for a case study warehouse. Applied methods include expert interviews and the ranking of location alternatives. Both methods are also used in this study. Jahre et al. (2016) present an approach to specifically include so-called contextual factors for warehouse decisions, and apply it to the UNHCR warehouses. Their work showed that, when applied properly, further contextual factors for demand, logistics, political, and security aspects can improve existing warehouse networks and preparedness.

In another commercial application by Rikalovic et al. (2017), location criteria are evaluated with the use of a Geographic Information System (GIS). Following the evaluation of various location criteria, the utility value of the macro-location is determined, similar to the (broad) region identified in the first step by van Thai and Grewal (2005). While the specific location criteria are less relevant for our work, the methodology to determine criteria values using GIS and their processing showcases advancements to analyze locations' attractiveness through the use of geographic information. Similarly, Onstein, Tavasszy, and van Damme (2019) combine geographic sources and criteria with typical economic factors to provide a wide range of relevant factors for location decisions.

Various other publications stress the importance of single location criteria, either specifically for food logistics (Fredriksson and Liljestrand 2015; Koster

2002) or for location decisions in general (Hesse 2004; Helm, Gleißner, and Kreiter 2012). While commercial and humanitarian applications are usually regarded separately, it is frequently mentioned that various cross-learning and partnering opportunities exist (van Wassenhove 2006; Kovács and Spens 2007; Cozzolino 2012).

In addition to the studies identifying location criteria, Kovács and Spens (2007) specifically highlight the linkage of business and humanitarian logistics and discuss similarities such as risk management and continuity planning. They argue that humanitarian or emergency logistics can and should learn from business logistics. Early (van Wassenhove 2006) and later works (Cozzolino 2012; Wiens et al. 2018) suggest dedicated public-private cooperations.

Carland, Goentzel, and Montibeller (2018) model the value for private actors in humanitarian supply chains, aiming to address private preferences and facilitate involvement of these actors in humanitarian operations.

Nevertheless, commercial and humanitarian operations have also widely different characteristics, be it in the environment (Kovács and Spens 2007; Holguín-Veras, Jaller, et al. 2012) or specifically in objectives (Holguín-Veras, Pérez, et al. 2013), and it is widely accepted that these must be acknowledged for successful implementation. In this context, Gutjahr and Nolz (2016) specifically stress the importance of multi-objective decisions in the humanitarian environment in a dedicated literature review on the subject. They acknowledge both the cited work that has been done in the field and the need for future research in the domain.

Multi-objective optimization in the humanitarian context is, for instance, applied by Tzeng, Cheng, and Huang (2007), including three objectives: Total cost, total travel time, and minimal satisfaction. The combination aims to consider efficiency and fairness attributes in optimization. Görmez, Köksalan, and Salman (2011) combine different objectives to locate disaster response facilities and allocate demands to these.

The transfer of established Operations Research models to the humanitarian context is considered as critical, arguing that models should instead be tailored to the specific situation (Besiou and van Wassenhove 2015). For example, Rawls and Turnquist (2010) develop a location-inventory model to preposition emergency supplies for disaster response under uncertainty. Similarly, Charles et al. (2016) regard uncertainties in the context of the identification of locations based on different sourcing scenarios. Cotes and Cantillo (2019) and

Paul and Xinfang Wang (2019) moreover identify optimal locations for the pre-positioning of goods to minimize social costs, which are defined as the sum of logistics costs and a proxy for human suffering (so-called *deprivation costs*).

To the best of our knowledge, no approach highlights the differences in the relevant location criteria of private and public actors in a PPEC in a comparative way. Moreover, no study supports the decision making process to identify locations for common warehouses. Lastly, the integration of both public and private applications with the combination of specific costs and criteria does not exist in the literature.

B.3. Methodology

Our approach is designed as follows. We first determine a score for the attractiveness of a region (e.g. a municipality, district, or federal state; upper panel in Figure B.1). To this end, we identify criteria, determine weights and metrics, and calculate the final score. While criteria can include items such as "Market Proximity", a related metric could be the number of potential customers within a certain distance. Second, we develop optimization models to select warehouse locations for both actors. These enable optimization of single objectives and integration of actor-specific cost objectives and regional attractiveness. Consequently, various sets of locations exist. They provide decision makers with the chance to select starting points for PPECs from different perspectives (lower panel in Figure B.1). We briefly describe the components of our approach in the following sections before we apply the approach in a case study in Section B.4.

B.3.1. Regional Attractiveness Score

We assess the attractiveness of a region with the help of a utility analysis (Zangemeister 2014). Within the analysis, we determine relevant 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 performance of the region regarding the respective criteria.

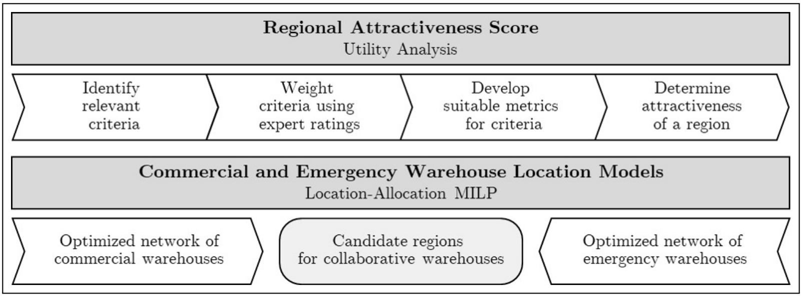

Figure B.1: Overview of the approach. Upper panel: Process for utility analysis to determine attractiveness; Lower panel: Combination of suitable locations for collaborative warehouses.

B.3.1.1. Criteria for Attractiveness

The first step is to identify relevant criteria for each actor. Potential sources are literature as described above, interactive workshops with the decision makers, or a mix of both. We want to emphasize that the selection can be adjusted towards any context that our general approach shall be applied to. The approach thereby provides a high degree of flexibility for decision makers.

B.3.1.2. Weighting of Criteria

Weights are a crucial component of the utility analysis. We derive them with the help of the Analytical Hierarchy Process (AHP), which builds upon pairwise comparison of all criteria (T. L. Saaty 1977). For each pair of criteria, the relative importance of one criterion over the other is evaluated using a scale from 1 (equal importance) to 9 (extreme importance of one criterion over the other; R. W. Saaty (1987)). The weight per criterion results from several minor calculations.

B.3.1.3. Determination of an Attractiveness Score per Region

In a next step, suitable metrics that represent the chosen criteria need to be identified. These metrics depend profoundly on the size and local characteristics of the regions as well as available data. Although this approach does not require any specific geographic classification of a region, the chosen unit of analysis eventually affects the choice of the metrics. If, for instance, a company wants to compare the attractiveness of certain countries, it will select different metrics than for a comparison of smaller units (e.g., states) within a country. While some criteria can be measured purely quantitatively (e.g., net labor costs), others are evaluated using both quantitative and qualitative data. Consequently, it is necessary to transform and standardize all metrics to the same range of numeric values to obtain a single score (Drobne and Lisec 2009).

We furthermore distinguish between *benefit criteria* and *cost criteria*. In this context, benefit reflects a criterion where a high value is desired, while for cost criteria a low value is preferred.

Finally, we compute regional attractiveness from the (criteria-)weighted sum of the normalized metrics. While these results offer to draw a variety of conclusions, they are furthermore used as one input for the following optimization models. These are necessary to evaluate warehouse locations from a network perspective, which is crucial to understand interdependencies between multiple locations. Therefore, we extend the attractiveness analysis with the determination of warehouse locations through optimization models.

B.3.2. Commercial and Emergency Warehouse Location Models

Regardless of the objectives in detail, the location models aim to establish warehouses at analyzed locations and enable deliveries to all demand points. Thus, the solution contains (a) locations where warehouses are opened and (b) the allocation of demand points to warehouses. So-called location-allocation problems were introduced by Cooper (1963). Optimization aims to find a solution with minimal costs 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. Thus, a third result from the model is (c) the optimal number of warehouses to be established.

Table B.1 presents our modeling and optimization approach. We use this structure since it allows to understand the individual components in more detail and points out trade-offs more clearly than a pure multi-objective optimization. We, therefore, developed three models for both types of actors and their respective scenario: 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. Table B.2 provides an overview of all sets and variables in the models.

Optimization sequences						
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 B.1: 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.

Symbol	Explanation	Remark/ Details
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)
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	$U_{WH} \in [0; 1]$
F^t	Fixed costs for warehouse type t by daily depreciation	[€]; $t \in T$
$tp_{i,j}^s$	Daily transport costs between i and j in Scenario s	$tp_{i,j}^s = D_{i,j} \cdot \frac{c_{truck}}{1000} \cdot P_j^s \cdot W^s$ [€]; $s \in S$, $i \in I$, $j \in J$
$dp_{i,j}$	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	$s \in S$, $i \in I$
$x_{i,j}$	Share of j's demand that is supplied from location i	$i \in I$, $j \in J$
y_i^t	Warehouse of type t is opened at location i	$t \in T$, $i \in I$
d_{LC}^+, d_{LC}^-	Slack variables for logistics costs	
d_{SC}^+, d_{SC}^-	Slack variables for social costs	
d_{AT}^+, d_{AT}^-	Slack variables for average attractiveness	
$LC^{opt,s}$, $LC^{max,s}$, $LC^{nad,s}$	Optimal/ Maximum/ Nadir logistics costs 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	

Symbol	Explanation	Remark/ Details
$AT^{opt,s}, AT^{min,s}$	Optimal/ Minimal average attractiveness in scenario s	$s \in S$
$\hat{y}^{s,b}$	Fixed number of warehouse locations in scenario s (to iterate)	$s \in S, b \in T$
$\bar{A}^s$	Average attractiveness for scenario s	$s \in S$

Table B.2: Variables and sets used in the optimization models.

B.3.2.1. Cost Optimization

Minimization of Logistics Costs

Logistics costs (LC) usually consist of direct transportation costs, costs for warehousing, commissioning, and related services. Furthermore, planning, administrative, and order processing costs as well as investment costs, interest, and depreciation are considered (DSLV 2015).

$$\min \quad \sum_{i=1}^{m} \sum_{j=1}^{n} x_{i,j} \cdot tp^s_{i,j} + \sum_{i=1}^{m} \left(y_i^b \cdot F^b + y_i^l \cdot F^l \right) \tag{B.1}$$

s.t.

$$\sum_{i=1}^{m} x_{i,j} = 1 \quad \forall j \in J \tag{B.2}$$

$$y_i^l \leq y_i^b \quad \forall i \in I \tag{B.3}$$

$$\sum_{j=1}^{n} x_{i,j} \cdot P_j^s \leq y_i^b \cdot C^b + y_i^l \cdot C^l \quad \forall i \in I \tag{B.4}$$

$$\sum_{i=1}^{m} y_i^b \cdot C^b + y_i^l \cdot C^l \leq \sum_{j=1}^{n} P_j^s \cdot \frac{1}{U_{WH}} \tag{B.5}$$

$$x_{i,j} \geq 0 \quad \forall (i,j), i \in I, j \in J \tag{B.6}$$

$$y_i^b, y_i^l \in \{0; 1\} \quad \forall i \in I \tag{B.7}$$

The first term of the objective function (B.1) describes transportation costs 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 from opening small (y_i^b) and large (y_i^l) warehouses.

Equations (B.2) ensure that the whole demand is fulfilled, and Equations (B.3) restrict opening a large warehouse to locations where a small warehouse is already located. For modeling reasons, their capacity technically adds up for this location. Following, (B.4) allow allocation only until the capacity of a warehouse is reached. In turn, if no warehouse exists at a certain location ($y_i^b = y_i^l = 0$), allocation is not possible.

Equation (B.5) 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 (B.6), and warehouses of both sizes are either opened or not, which is reflected by binary variables y_i^b and y_i^l in (B.7).

The optimization determines both optimal LC and the number and location of warehouses.

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, Jaller, et al. 2012, SC). DC occur if people are not supplied adequately, for example with food, medical treatment, or shelter. The application of DC has been discussed widely in literature (Holguín-Veras, Pérez, et al. 2013; Cotes and Cantillo 2019; Xihui Wang et al. 2017).

To apply DC in real-world application, deprivation cost functions (DCFs) must be determined specifically for the present scenario and country (Shao et al. 2020). However, since no DCF is available for Germany, we use a cost function developed for identical products in a similar situation in Colombia (Cotes and Cantillo 2019) to transfer the course of the function and normalize it whenever combined with local cost units.

We standardize components with *Ideal* and *Nadir Points*, which are widely used in multi-objective optimization. Ideal and Nadir Points are obtained from the set of efficient points, i.e. the set of function values from all Pareto optimal solutions. 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 B.1). As such, the points represent upper and lower bounds for the set of efficient solutions (Ehrgott and Tenfelde-Podehl 2003).

$$\mathbf{min} \quad \frac{\left[\sum_{i=1}^{m}\sum_{j=1}^{n} x_{i,j} \cdot tp_{i,j}^{s_e} + \sum_{i=1}^{m}\left(y_i^b \cdot F^b + y_i^l \cdot F^l\right)\right] - LC^{opt,s_e}}{LC^{nad,s_e} - LC^{opt,s_e}} + \frac{\left[\sum_{i=1}^{m}\sum_{j=1}^{n} x_{i,j} \cdot dp_{i,j}\right] - DC^{opt}}{DC^{nad} - DC^{opt}} \tag{B.8}$$

s.t. Eq. (B.2), Eq. (B.3), Eq. (B.4), Eq. (B.5), Eq. (B.6), Eq. (B.7)

The standardization of LC and DC through Ideal and Nadir points is applied in objective function (B.8). It combines LC (Eq. (B.1)) and DC objectives. Due to the standardization, the objective value is between 0 and 2 ($SC^{opt} \in [0; 2]$).

B.3.2.2. 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.

$$\mathbf{max} \quad \sum_{i=1}^{m} y_i^b \cdot A_i^s \tag{B.9}$$

s.t.

$$\sum_{i=1}^{m} y_i^b = \hat{y}^{s,b} \tag{B.10}$$

Eq. (B.2), Eq. (B.3), Eq. (B.4), Eq. (B.5), Eq. (B.6), Eq. (B.7)

While optimizing the average attractiveness of all warehouse locations, explicit cost considerations are disregarded. Consequently, the objective function (B.9) only considers locations of opened warehouses and their respective attractiveness values for scenario s ($s \in S$). Average attractiveness is computed afterwards.

Equations (B.2) to (B.7) are unchanged from the former models. We introduce Equation (B.10) to keep the optimization linear. The model is iterated over all possible numbers of warehouses as $\hat{y}^{s,b}$, ensuring computation of the optimal solution.

Average attractiveness $\bar{A}^s$ 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.

B.3.2.3. Multi-Objective Optimization

Competing goals can be combined for optimization, leading to multi-objective models (Kallrath 2013). Different objectives in humanitarian aid and logistics make multi-objective optimization utmost important and thus widely used in the field (Gutjahr and Fischer 2018). Besides different goals between actors as described in the introduction, we also consider multiple goals one decision maker aims to satisfy.

Goal programming is one method 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 pre-emptive 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 important. The optimization then minimizes deviations between the optimal value for each objective and the value determined within the multi-objective optimization (Kallrath 2013).

Commercial Scenario: Logistics Costs and Attractiveness

The following optimization model generates the optimal locations and allocations in the commercial scenario.

The objective function (B.11) captures deviations in LC and attractiveness compared to their optimal values. Equation (B.12) sets standardized LC in relation to optimal $LC^{opt,c}$ through slack variables d^+_{LC} and d^-_{LC}. $LC^{opt,c}$ standardized is 0, since: $\frac{LC^{opt,sc}-LC^{opt,sc}}{LC^{max,sc}-LC^{opt,sc}} = 0$. Equation (B.13) standardizes attractiveness similarly. Again, the optimal reference value on the right side must be standardized. Following, the right side is: $\frac{AT^{opt,sc}-AT^{min,sc}}{AT^{opt,sc}-AT^{min,sc}} = 1$. Slack variables must be positive (Equations (B.14), (B.15)). 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.

$$\mathbf{min} \quad d^+_{LC} + d^-_{LC} + d^+_{AT} + d^-_{AT} \tag{B.11}$$

s.t.

$$\frac{\left[\sum_{i=1}^{m}\sum_{j=1}^{n} x_{i,j} \cdot tp^{s_c}_{i,j} + \sum_{i=1}^{m}\left(y^b_i \cdot F^b + y^l_i \cdot F^l\right)\right] - LC^{opt,s_c}}{LC^{max,s_c} - LC^{opt,s_c}} + d^+_{LC} - d^-_{LC} = 0 \tag{B.12}$$

$$\frac{\sum_{i=1}^{m}\left(y^b_i \cdot A^{s_c}_i\right)/\hat{y}^{s_c,b} - AT^{min,s_c}}{AT^{opt,s_c} - AT^{min,s_c}} + d^+_{AT} - d^-_{AT} = 1 \tag{B.13}$$

$$d^+_{LC}, d^-_{LC} \geq 0 \tag{B.14}$$

$$d^+_{AT}, d^-_{AT} \geq 0 \tag{B.15}$$

Eq. (B.2), Eq. (B.3), Eq. (B.4), Eq. (B.5), Eq. (B.6), Eq. (B.7), Eq. (B.10)

Emergency Scenario: Social costs and Attractiveness

The following optimization model generates the optimal locations and allocations in the emergency scenario.

$$\textbf{min} \quad d^+_{SC} + d^-_{SC} + d^+_{AT} + d^-_{AT} \tag{B.16}$$

s.t.

$$\left[\frac{\left(\sum_{i=1}^{m} \sum_{j=1}^{n} x_{i,j} \cdot tp_{i,j}^{s_e} + \sum_{i=1}^{m} \left(y_i^b \cdot F^b + y_i^l \cdot F^l \right) \right) - LC^{opt,s_e}}{LC^{nad,s_e} - LC^{opt,s_e}} + \frac{\left(\sum_{i=1}^{m} \sum_{j=1}^{n} x_{i,j} \cdot dp_{i,j} \right) - DC^{opt}}{DC^{nad} - DC^{opt}} \right] \cdot \frac{1}{2} + d^+_{SC} - d^-_{SC} = \frac{SC^{opt}}{2} \tag{B.17}$$

$$\frac{\sum_{i=1}^{m} \left(y_i^b \cdot A_i^{s_e} \right) / \hat{y}^{s_e,b} - AT^{min,s_e}}{AT^{opt,s_e} - AT^{min,s_e}} + d^+_{AT} - d^-_{AT} = 1 \tag{B.18}$$

$$d^+_{SC}, d^-_{SC} \geq 0 \tag{B.19}$$

Eq. (B.2), Eq. (B.3), Eq. (B.4), Eq. (B.5), Eq. (B.6), Eq. (B.7), Eq. (B.10) Eq. (B.15)

The objective function (B.16) includes the deviation of social costs and attractiveness from their optimal values. Equation (B.17) connects LC and DC through slack variables d^+_{SC} and d^-_{SC} to the optimal value for social costs (SC^{opt}). As mentioned in Section B.3.2.1, standardized SC is between 0 and 2 due to its two components. Both terms on the left and right side of the equation are, therefore, divided by 2. Otherwise, slack variables were to be larger than for attractiveness, giving an unintended overweight to SC in the objective function.

Equation (B.18), similar to equation (B.13) 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.

In the following chapter, we apply the presented methods and models on a case study in Germany. As described before, German authorities maintain a large and costly number of emergency warehouses. This network could be extended or partially substituted by commercial actors who agree to participate in a PPEC.

B.4. Case Study

We approach our case study on a "per municipality" base, with municipalities classified as LAU2 regions by the European Union (EU 2020). The scope is different between the attractiveness analysis and the optimization models for warehouse location: The attractiveness analysis includes all 11,087 German municipalities (marked as "DE" in the following). Due to capacity restrictions, however, we limit the optimization models to the federal state of Baden-Württemberg (marked as "BW" hereafter) and identify locations for potential warehouses of public and private (i.e., commercial) actors.

B.4.1. Attractiveness Scores in the Case Study

Based on the literature described in Section B.2, we identified 18 relevant criteria for our analysis, which were furthermore validated by the experts who agreed to participate in our survey (see Table B.3 for an overview).

We asked seven experts with experience from the commercial sector (supply chain consulting, management, and logistics service provider) as well as six experts in the field of emergency logistics (from several public authorities on local, regional, and federal level besides NGOs and consulting firms) to compare the criteria within their field.

Following, we selected metrics that represent the respective criteria. 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 that represent 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 important 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 which are identified using standard tools such as a boxplot (Williamson, Parker, and Kendrick 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 criteria. Benefit criteria 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 criteria (e.g., tax rates; Voogd (1982)). Consequently, scores for cost criteria are transformed by subtracting the standardized score from 1.

Table B.3 highlights the selected metrics and their respective normalization components. Due to limited space, we provide the data sources in the Supplementary Material.

Code	Criterion	Metrics	Description	Cost/ Benefit	Weight
C.1	Market in Proximity	Population within 50km	Overall population in all NUTS3 units within 50km distance	b	1
C.2	Producer Proximity	Regional food producer density	Food and drink producers and companies per NUTS2 unit relative to its area	b	1
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
		Street network density	Street network length per NUTS3 unit relative to its area	b	0.25
		Bridge conditions	Share of bridges graded "not sufficient" or worse per NUTS3 unit	c	0.25
		Street conditions	Share of streets with conditions rating for intensive inspection per NUTS1 unit	c	0.25
C.4	Availability of Different Transport Modes	Distance to port	[a]Street network distance to next port per LAU2 unit	c	0,65[a]
		Distance to station	[a]Street network distance to next cargo train station per LAU2 unit	c	0,34[a]
		Distance to airport	[a]Street network distance to next airport per LAU2 unit	c	0,01[a]
C.5	IT and Telecommunications Infrastructure	Broadband availability	Share of households with broadband access per NUTS1 unit	b	0.33
		Internet speed	Average internet speed per NUTS1 unit, rural and urban areas distinguished according to no. of inhabitants	b	0.33
		4G availability	Share of households with 4G access per NUTS1 unit	b	0.33
C.6	Availability and Skills of Labor Force	Job vacancy times	Average job vacancy times in logistics per NUTS1 unit	c	0.33
		Population	Population between age 15 and 64 per NUTS3 unit	b	0.33
		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

Code	Criterion	Metrics	Description	Cost/ Benefit	Weight
C.7	General Labor Costs	Net labor costs	Net labor costs in transportation and logistics per hour per NUTS1 unit	c	1
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
		Price for new industry property	Average price for industry property between 2014 and 2017 per NUTS1 unit	c	0.5
C.9	Local Taxes	Business tax	^{b}Business tax ("Gewerbesteuer") collection rate per LAU2 unit	c	0,79^b
		Property tax	^{b}Property tax ("Grundsteuer B") collection rate per LAU2 unit	c	0,21^b
E.1	Proximity to Beneficiaries	Reachable population	Population reachable within 60min by truck per LAU2 unit	b	1
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
		Street network density	Street network length per NUTS3 unit relative to its area	b	0.5
E.3	Airport proximity	Distance to airport	Street network distance to next airport per LAU2 unit	c	1
E.4	Transport Infrastructure Resilience and Quality	Street network density	Street network length per NUTS3 unit relative to its area	b	0.25
		Highway accesses	Number of highway junctions within 20km radius	b	0.25
		Bridge conditions	Share of bridges graded "not sufficient" or worse per NUTS3 unit	c	0.25
		Street conditions	Share of streets with conditions rating for intensive inspection per NUTS1 unit	c	0.25
E.5	IT and Telecommunications Infrastructure	Broadband availability	Share of households with broadband access per NUTS1 unit	b	0.33

Code	Criterion	Metrics	Description	Cost/ Benefit	Weight
		Internet speed	Average internet speed per NUTS1 unit, rural and urban areas distinguished according to no. of inhabitants	b	0.33
		4G availability	Share of households with 4G access per NUTS1 unit	b	0.33
E.6	Availability of Transport Equipment	Origin freight traffic	Domestic annual road freight traffic in tons per originating NUTS3 unit	b	0.25
		Destination freight traffic	Domestic annual road freight traffic in tons per destination NUTS3 unit	b	0.25
		Transit freight traffic	Average freight traffic density in vehicles per hour per NUTS2 unit	b	0.25
		Logistics firm density	Warehousing and logistics firms per NUTS2 unit relative to its area	b	0.25
E.7	Minimum Distance to Critical Facilities	Nuclear power plants	Euclidean distance to next nuclear power plant per LAU2 unit	b	0.33
		Refineries and chemical sites	Euclidean distance to next refinery or other chemical industry site per LAU2 unit	b	0.33
		Airport	Euclidean distance to next (major) airport	b	0.33
E.8	Vulnerability to Natural Risks	Storm hazard	Hazard for winter storm (50 year event) per LAU2 unit	c	0.33
		Earthquake hazard	Hazard for earthquake (475 year event) per LAU2 unit	c	0.33
		Water proximity	Euclidean distance to sea or next river per LAU2 unit	b	0.33
E.9	Minimum Distance to Large Cities	Type of region	Type of region per LAU2 unit according to RegioStaR 7 typology	b	1

[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 (2020))

Table B.3: Overview of Selected Criteria and Metrics

B.4.2. Optimization Models in the Case Study

Being limited to BW as one federal state in Germany, considered deliveries for the two scenarios differ in the number and type of locations to be supplied. In the commercial scenario, only supermarkets are supplied directly through regional warehouses. On the other hand, the emergency scenario regards numerous different locations to be supplied. Schools or other public buildings are possible emergency PoDs in addition to stores. This is especially important since commercial stores are only located in places with sufficient demand,[2] leading to gaps in demand that need to be supplied more locally in emergencies. Originally 1,102 municipalities in the federal state of BW reduce to 502 candidate locations in the commercial scenario. The remaining demand is allocated to larger municipalities in proximity. All municipalities are candidate locations in the emergency scenario however.

Moreover, emergency supply must reach all 11 million potentially affected people, while commercial actors only supply a part of the market. This is reflected in two sub-scenarios: For one, we consider a commercial actor with a total market share of 10%. The second assumes a fictive monopolist (100% market share) to analyze the effects of cooperation on a larger scale. Thus, demand points and total demand differ largely between the two commercial and the emergency scenario. In the following, we provide an overview on selected input parameters for the optimization.

B.4.2.1. Demand

Commercial demand per person is determined using annual per capita consumption of food in Germany (Henrich 2017). Official ministry recommendations for daily emergency food reserves are the basis for emergency demand respectively (BMEL 2020a). Daily volumes, 3.64kg in the commercial scenario and 3.20kg in emergency, include food and beverages.

[2] Food retailers exclude municipalities that are below a certain threshold of inhabitants as possible locations. We assume a value of 5,000 people for our case study, which is used by several German food retailers (e.g., Rewe (2019) and LIDL (2019)).

B.4.2.2. 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 of €0.0583 per ton and km for a 24t full truck load with an utilization of 100% from a German logistics service provider.

B.4.2.3. Warehouse Costs and Utilization

Fixed warehouse costs include a variety of factors, e.g., acquisition of land, investment in local infrastructure, building construction cost, and equipment. We base our cost estimation on recent projects by German food retailers (e.g., Flemming (2017) and NWZ Online (2016)) and have it validated by logistics experts from the field. Similarly for capacity estimation, we use mentioned data on warehouse projects in combination with market shares and numbers of stores to supply (LZ 2018).

We eventually consider two types of warehouses: The standard warehouse offers sufficient capacity to satisfy the demand of 300,000 people at an investment of €40 million. 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 furthermore assume a depreciation period of 20 years and an interest rate of 7% p.a.

Without a defined minimum utilization of the warehouses, objectives in e.g. attractiveness optimization would lead to unrealistic solutions with numerous warehouses in excess, thus hampering comparability of scenarios. We therefore restrict the number of warehouses by setting a minimum average warehouse utilization U_{WH} of 80%.

B.4.2.4. Deprivation Costs

Deprivation costs can be determined in various ways (see e.g., Shao et al. (2020) for a recent overview). For the present work, we include 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:[3]

$$dc(t_{i,j})\ [€] = 0.0063 \cdot t_{i,j}^3 - 0.2555 \cdot t_{i,j}^2 + 5.8403 \cdot t_{i,j}$$

Under the assumption of uncapacitated transport equipment and personnel (e.g., due to seizure), waiting time is calculated before the optimization through distance and truck speed. In addition to the distances described above in this section, we assume an average speed of 45 km/h, which is based on an analysis of travel times within the attractiveness score.

B.4.2.5. Attractiveness Scores in Optimization

Attractiveness is considered a distinct input for the optimization. To avoid an overlap of certain criteria in the score with costs regarded in the models, we slightly modify the score for the optimization. For the commercial score, two criteria are excluded: *Market in Proximity* and *Land Availability and Price Level.* The former is clearly considered in local demands and resulting transportation costs, the latter is explicitly included in fixed location costs per warehouse.

Considering emergency attractiveness, we exclude only *Proximity to Beneficiaries* from the score. This factor is directly considered in DC, since it is represented by the population reachable within a certain time.

B.5. Results and Discussion

Results for the attractiveness analysis are for all German municipalities (marked "DE"), unless indicated otherwise. Optimization results show the federal state of Baden-Württemberg (BW) only.

Data for the attractiveness score was processed with the help of ESRI ArcGIS Desktop 10.8 and Microsoft Excel. The optimization models were implemented in GAMS and solved with CPLEX.

[3] Converted with an exchange rate of COP 3,706 per EUR (Finanzen.net 2020).

B.5.1. Results of the Attractiveness Score Analysis

B.5.1.1. Criteria and Weights

Before analyzing weights for the criteria, it is necessary to assess the consistency of the survey responses with the help of so-called *Consistency Ratios* (CRs) (T. L. Saaty 1977).

According to T. L. Saaty and Ozdemir (2003), a large number of criteria negatively influences consistency. Therefore, we select a rather high threshold for CR of 0.3, leading to the exclusion of one rating for the commercial criteria. Consequently, six ratings are considered as valid within both perspectives.

Figure B.3 and Figure B.2 highlight the resulting criteria weights for both scenarios and show the composition of both attractiveness scores. The most important criteria (i.e., those with largest criteria weights; shown with grey bars) should be considered first by single municipalities and authorities seeking to increase attractiveness. In the commercial scenario, *Market in Proximity* ($w = 0.19$) and *Availability and Skills of Labor Force* (0.19) are regarded most important. *Availability of Transport Equipment* (0.18) and *Transport Infrastructure Reliability and Resilience* (0.16) are rated most important for the emergency scenario. Notably, *IT and Telecommunications Infrastructure* is considered in both scenarios, but weighted more than twice as important for emergencies (0.13) than for the commercial scenario (0.06).

Depending on the actual contribution of the criterion scores and metrics, criteria are either *overrated* or *underrated* in the score (relative to criteria weights). Criteria with lower average values in their metrics are *underrated*, those with higher values *overrated*. For example, *Market in Proximity* is responsible for 8.6% of the commercial score, while the weight of the criterion is 19.1% (grey bar), leading to a (negative) deviation of 10.5% (red bar). Thus, the criterion is relatively *underrated*.

B.5.1.2. Resulting Attractiveness Scores

Table B.4 shows descriptive statistics for the resulting attractiveness scores. The original scores for Germany are shown alongside adjusted scores for the federal state of BW, which are used as inputs for the optimization model (see Section B.4.2.5).

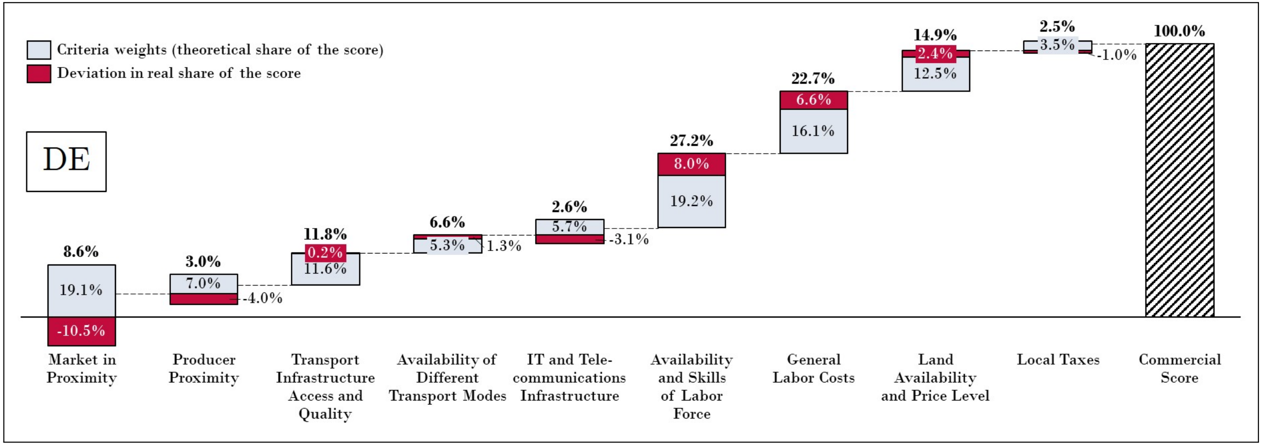

Figure B.2: Criteria weights (grey) and deviations (red) of the share in the commercial attractiveness score for Germany (DE). The number above each bar is the criterion's overall share in the score.

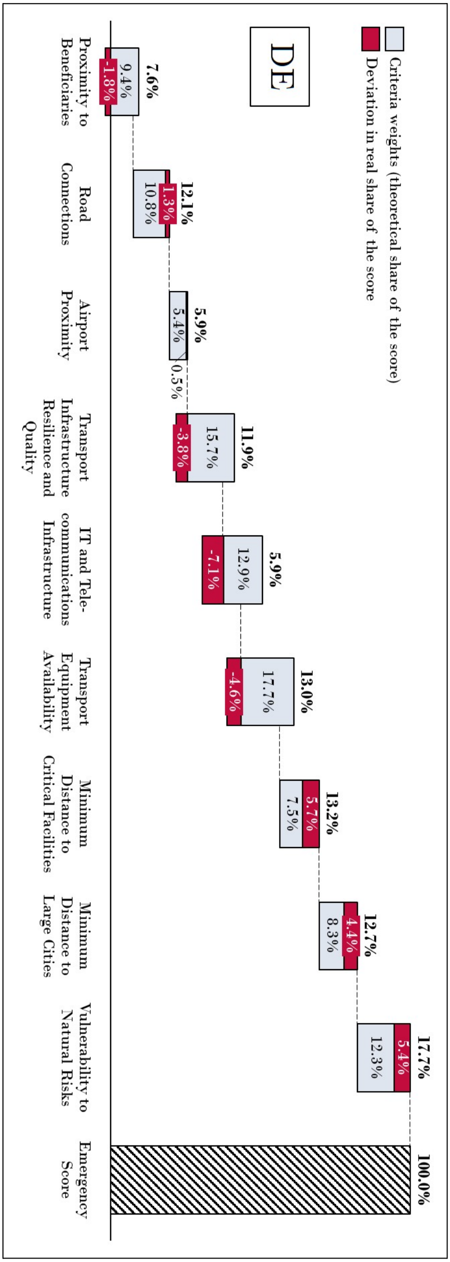

Figure B.3: Criteria weights (grey) and deviations (red) of the share in the emergency attractiveness score for Germany (DE). The number above each bar is the criterion's overall share in the score.

	Germany Original Score		**Baden-Württemberg Adjusted Score**	
Characteristic	Commercial	Emergency	Commercial	Emergency
Minimum	0.30	0.31	0.47	0.36
25% quartile	0.45	0.46	0.54	0.50
Median	0.49	0.50	0.57	0.53
Mean	0.50	0.50	0.57	0.53
75% quartile	0.54	0.54	0.61	0.57
Maximum	0.75	0.75	0.67	0.68

Table B.4: Statistics for the attractiveness scores in Germany (DE) and Baden-Württemberg (BW).

Commercial and emergency scores for Germany are in similar ranges, from 0.30 to 0.75 and 0.31 to 0.75, respectively. Median and mean are close for both scenarios, showing no large influence by outliers.

Figure B.4 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.

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. Least attractive regions are in Northern Saxony-Anhalt, areas of Brandenburg, and in 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

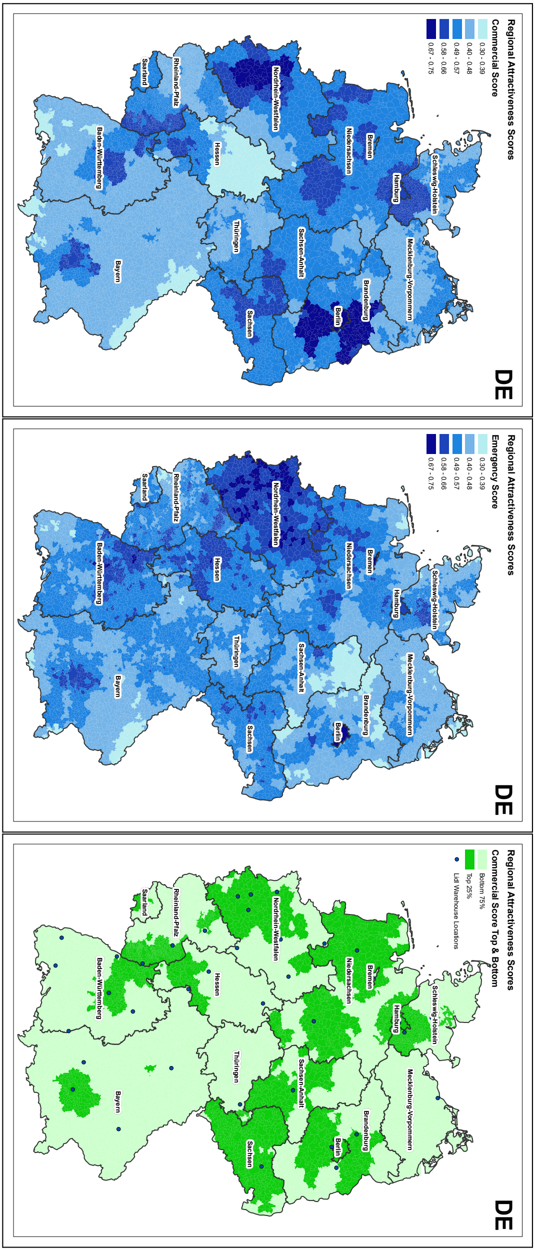

Figure B.4: Final attractiveness scores for Germany (DE) per LAU2 unit; left: Commercial attractiveness; middle: Emergency attractiveness; right: 25% commercially most attractive regions and publicly available Lidl warehouse locations.

(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, which implies a large market. For emergencies, however, its overall transport and IT infrastructure as well as 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.

The score, moreover, 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 B.4, 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 was 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 border-regions of neighbouring countries, the results suggest that the score and its criteria are in fact suitable to identify more attractive locations.[4]

Table B.4 shows descriptive data for the adjusted scores in BW used in the optimization models. Ranges for the scenarios in the adjusted and locally restricted case are considerably smaller. Median and mean are nevertheless very close, underlining that no extreme outliers exist. Both median and mean are considerably higher for the adjusted score in BW compared to the original score in both scenarios. More detailed analysis shows that the federal state has slightly below-average scores for the commercial scenario before adjustment. Consequently, the adjustment, i.e. leaving out two criteria that

[4] Note that, due to public authorities' confidentiality, we cannot validate the emergency score similarly.

are considered in the location model, improves the score dramatically since the state has comparatively low scores for *Market in Proximity* and *Availability and Price Level for Land*. In contrast, BW has above-average scores for the emergency scenario before score adjustment already. Here, adjustment has only minimum influence.

B.5.1.3. Identification of Suitable Regions with the Help of Attractiveness Scores

The attractiveness scores allow to define regions *suitable* from one or both perspectives. Figure B.5 shows a map of (un-)suitable regions in Germany (assuming that regions above the 75% quartile are considered *suitable*). Four types of regions are distinguished: Unsuitable from both perspectives (*not suitable*), above the threshold only in the emergency scenario (*emergency suitable*), above the threshold only in the commercial scenario (*commercially suitable*), and within the Top 25% in both scenarios (*fully suitable*).

Fully suitable regions are clearly unevenly spread over Germany. While parts of Hesse, Northrhine-Westphalia, and Baden-Württemberg show several *emergency* or *fully suitable* regions, almost all municipalities in Northern Bavaria, Thuringia, or Mecklenburg-Vorpommern are considered *unsuitable*.

Regions marked as *emergency suitable* are candidates public actors might want to "make more attractive" for commercial use, e.g. through commercial incentives or subsidies. Differences between average criteria scores for emergency and fully suitable regions are shown in Figure B.5 on the right. Most significant differences occur for *Market in Proximity* and *Producer Proximity*. *Transport Infrastructure Access and Quality* and *Local Taxes* show only minor differences.

Combining suitability results with composition of the score (see Figure B.2), it becomes clear that *Market in Proximity* is the most effective parameter to make regions more attractive for commercial actors. It is, however, obvious that the market itself cannot be influenced directly. Medium- to long-term measures may include efforts to attract more people to live in the region and more upstream suppliers to settle locally. This would in turn grow the market, a local supplier base, and local labor force. On the other hand, public actors could easily provide cheap land and tax discounts for firms. Although they differ less between the groups of regions, both measures directly affect costs.

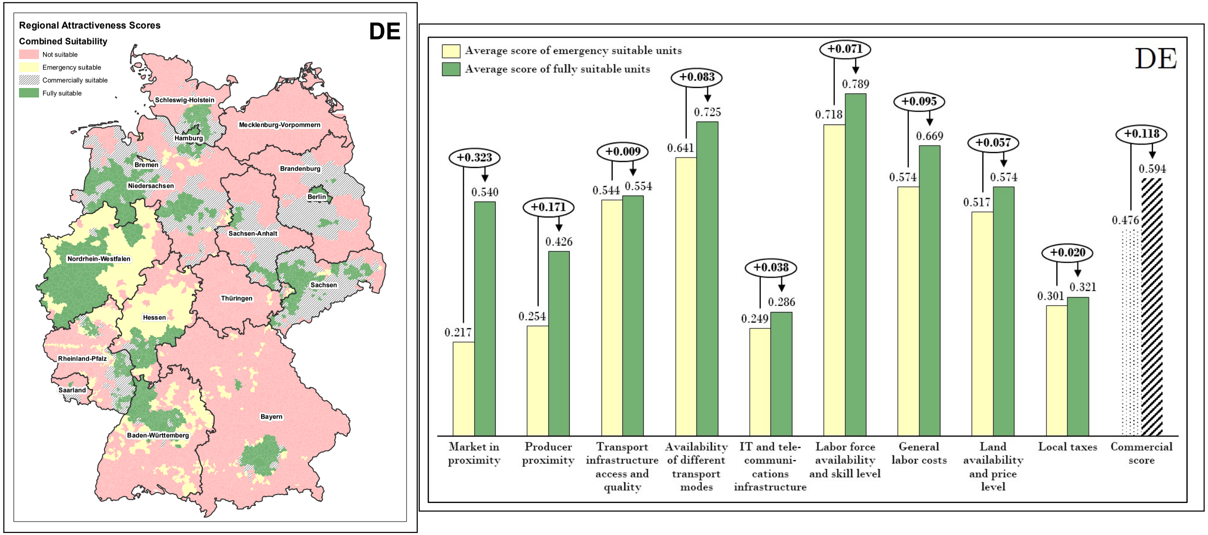

Figure B.5: Left: Combined scores suitability map of Germany (DE); right: Comparison of average criteria scores between partly and fully suitable LAU2 units in Germany. Red highlights indicate that the region is not within the best 25% of the locations in all scenarios and grey highlights that it is only in the best 25% for the commercial scenario. Moreover, yellow regions and bars represent areas that are within the best 25% in the emergency scenario and lower ranked in the commercial scenario. Green regions and bars represent areas that are within the best 25% for both scenarios.

Moreover, authorities of individual regions can use the score to understand their own attractiveness more thoroughly and identify individual areas for improvement.

Since private actors cannot set incentives to directly influence criteria scores, we do not discuss their score manipulation possibilities separately.

It can be concluded that attractiveness scores provide insightful regional differences for the commercial and emergency application. In addition to increased transparency, decomposition of the scores and analysis of different types of suitable regions provide a basis for factors that public actors could address to incentivize combined warehouse locations in PPECs.

B.5.2. Results of the Optimization Models

In this section, we present the results of the warehouse location optimization in the federal state of BW. Table B.5 contains the results from the optimization models for both scenarios. For each (sub-)scenario, results are shown for a pure cost optimization (left), optimization of attractiveness (right), and the combined multi-objective problem (center). As mentioned above, we integrate attractiveness as one way to take more qualitative criteria into account. These are tailored to the priorities of either decision maker. Consistently, costs are always lowest in the dedicated optimization and attractiveness is always highest in its specific optimization.

The multi-objective optimization provides solutions for the trade-offs between both objectives. In the commercial 10% sub-scenario for example, LC are 3.3% higher compared to the solution when only optimizing for LC. Similarly, attractiveness is 1.2% lower in the multi-objective than in the dedicated optimization. On comparison, LC are 24% higher than optimal when optimizing for attractiveness and attractiveness 8.5% lower vice versa. Numbers of locations show less gradual differences between the optimizations which we discuss more specifically in the following. However, the results overall clearly show the advantage of multi-objective optimization.

Considering LC, opening costs are regularly higher than transportation costs. Based on publicly available information on LC in the food retail sector, the costs we report are considerably lower than overall costs in practice. This is due to our exclusion of any costs (e.g., for equipment or staff) aside specific transportation and opening costs. However, other costs do not directly differ

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 €]									
Logistics costs	41,824	43,189	51,841	204,714	231,837	357,122	273,099	283,018	313,748
Transportation costs	10,184	11,549	20,201	78,148	105,271	218,690	31,841	41,760	175,316
Opening costs	31,640	31,640	31,640	126,566	126,566	138,432	241,258	241,258	138,432
Deprivation costs							21,572,703	28,058,579	109,614,008
Average attractiveness	0.6009	0.6485	0.6565	0.5870	0.6487	0.6540	0.5268	0.6124	0.6682

Table B.5: Model solutions for commercial and emergency scenarios optimized for costs, attractiveness, and combined in multi-objective optimization (BW only).

for different locations and therefore do not need to be considered in this case.

The overall number of warehouses is the same for all optimizations in both commercial sub-scenarios, four and seven respectively. Exact locations are different between the different optimizations except for Stuttgart as the state's largest city and capital. Between sub-scenarios, Figure B.6 (left) shows that three out of four locations in the 10% sub-scenario match locations from the 100% sub-scenario. 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 leads to 26 locations spread widely across BW (see Figure B.6, left), 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. While we constrained its direct influence through standardization, the cost behavior (for larger distances) remains the same and leads to an increased number of selected locations. Only one location overlaps with those from the commercial scenario. Among the optimizations for the emergency scenario, the multi-objective optimization shares four optimal locations with the SC and attractiveness optimizations respectively.

Both types of actors (firms and authorities or public planners) have different objectives. Therefore, we introduce an optimization model that is easily adaptable. Having determined the optimal solutions for both actors separately, we can compare solution quality and establish solutions that could be more practically and cooperatively implementable. Moreover, other strategies than pre-positioning for preparedness are discussed in the literature. Kunz, Reiner, and Gold (2014), for instance, argue that a combination of pre-positioning and building management capabilities leads to best results for disaster response. One practical approach for public actors is to make use of existing warehouses and warehouse locations instead of pushing entirely new locations in either scenario (greenfield approach). Thereby, no high investments for new locations would be needed and existing locations could instead e.g. be adjusted or enlarged for emergency supplies and commercial actors be integrated in exercises for immediate response to disasters.

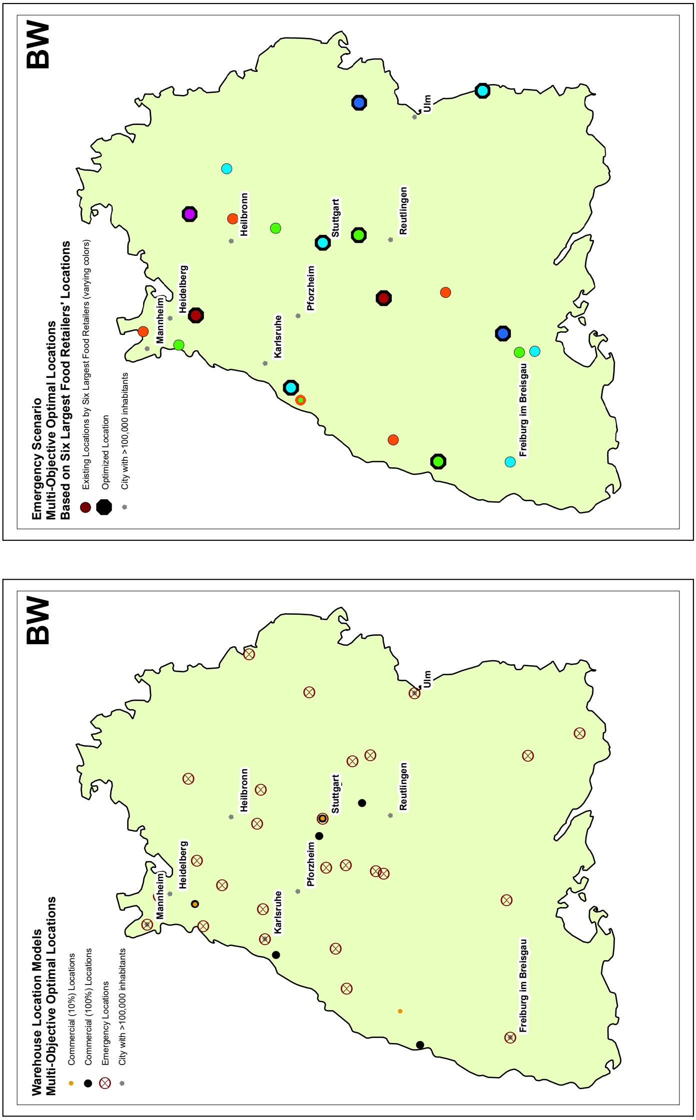

Figure B.6: Left: Multi-objective optimal locations in BW for commercial and emergency scenarios; right: Multi-objective optimal locations in BW for the emergency scenario based on existing warehouse locations.

To this end, we designed two model extensions: Extension I takes existing locations of the six largest food retailers, which overall account for approximately 55% market share (LZ 2018), as candidate locations in the emergency scenario. Extension II makes use of only one retailer's locations and compares results when adding a single new location to the network. We discuss the main results in the following and provide exact numbers in the Supplementary Material.

In Extension I, 10 out of 21 candidate locations in BW are selected (see Figure B.6, right). Candidate locations are all closely tied to the network of highways, highlighting the importance of access to the transportation network. LC are 20% lower than in the greenfield approach (€227,492 per day) due to the smaller number of locations. Moreover, opening costs are expected to be significantly lower in reality since warehouses already exist at all candidate locations.[5] Chosen locations are spread throughout the federal state and include five different retailers. Attractiveness is 6% lower and DC 54% higher compared to the optimization with new locations. However, DC is far from the worst values achieved in former optimizations. It is important to note that, due to the lack of information concerning real emergency warehouse locations, we can only compare DC to our (optimal) solutions, not to the setup in place. Presumably, waiting times and thus deprivation costs would currently be higher if supplies were to be delivered from existing emergency-only warehouses that have been set up over the last decades.

In Extension II, we exclusively use food retailer Lidl's locations, which comprises the largest network of warehouses in the study area. One potential advantage of only one partner is less complex coordination with authorities while still being able to access the retailer's network of six locations spread throughout the state (Figure B.4, right). However, results for the emergency scenario are mixed: While LC is lower than in any optimization before, DC is almost 130% higher and the attractiveness considerably lower (-12%) compared to greenfield. When adding one additional location to choose freely, all parameters improve but still remain worse for DC and attractiveness. Significant overall improvements nevertheless indicate promising opportunities for public actors in future. As one possible approach, they could plan

[5] We still regard opening costs in our model without further adjustment since the private sector will demand a substantial payment as compensation and certain costs accrue to transform existing locations.

a well-optimized network of warehouses based on existing and new locations. Chosen new locations would then be proactively promoted for future commercial warehouse locations. Such measures could lead to a significantly improved base of locations for emergencies without having to construct several new warehouses solely for that purpose.

Summarizing the results of the extensions, we highlight the following conclusions: Attractiveness and DC are considerably better when all municipalities are candidate locations within the model. However, LC are much lower for existing locations, presumably even more so in practice. Results are overall better when several large retailers are potential partners. While this may add more complexity for public actors in the first place, they avoid a lock-in with one partner and having to 'choose a winner', which would otherwise interfere with their neutrality towards businesses. Lastly, cooperation with several partners to enable pre-positioning in existing locations, building partner capabilities with exercises, and joint development of emergency procedures is clearly in line with the mixed approach for preparedness found to be optimal by Kunz, Reiner, and Gold (2014).

Regarding attractiveness of (existing) locations, public actors could also specifically check for criteria that lead to the exclusion of certain locations and accept all others as candidates. The provided attractiveness score facilitates such analyses.

Moreover, it should be noted that theoretically optimal solutions are not overly sensitive towards changes in single locations. For example, a neighboring municipality might be chosen without drastically changing overall costs if there is no space available in the initially selected municipality. We noted similar changes during the course of optimization which did not change overall results. The number of locations in the emergency model is clearly driven by deprivation costs as the comparison of single- versus multi-objective optimizations shows. However, Extension I showed no such behavior, including less locations in the final network than theoretically available. Overall, various optimization runs have not revealed significant sensitivity towards any factor. Assumptions and inputs should nevertheless be carefully chosen for each specific application.

B.6. Conclusion and Future Work

Including the private sector's warehouses more extensively into authorities' disaster preparedness plans offers multiple benefits for both sides. However, selecting candidate locations for collaborative sites is a challenging process that requires a deepened understanding for the requirements of both actors, as well as their objectives.

To support the selection and facilitate an increase in collaboration, we combined two analytical approaches: In the first step, we identified location criteria for public and private actors and ranked them with expert interviews and AHP. Following, we selected suitable metrics to assess municipalities in terms of the location criteria and determined a score for each municipality's attractiveness. In addition to providing information and transparency, the score was one key component of the different optimization models developed in our approach's second step. These models reflect the actors' individual objectives and strategies and identify individually optimal networks of locations. While logistics and deprivation costs were also optimized individually, attractiveness was considered within multi-objective optimization models. We were able to show that, even though the networks differed significantly between actors, our approach can identify locations for collaboration.

In addition to the models described above, we took a deeper look into two model extensions that more directly combine existing private networks and public objectives and are thus presumably more easily realizable: While Extension I considered the locations of the six largest food retailers in the investigated region, Extension II analyzed the case where only the locations of one retail chain could be used as collaborative sites. Even though it is more complex to collaborate with multiple partners in practice, the increased number of potential locations leads to significantly better results. Moreover, market interference is minimized and the long term balance not put at risk.

Nevertheless, the study comes along with some limitations that affect the transfer of the methodology into practice. To start with, networks are usually not built from scratch but over a long time and adaptations therefore only follow gradually. Consequently, changes either require a high investment (e.g., by public actors) or only follow selectively (this aspect is reflected in Extensions I and II). We moreover acknowledge that even within groups of actors, priorities and even criteria may vary. This can be rooted in both different strategic priorities and perception of certain risks. However, our approach is widely flexible. Firstly, it allows to force a couple of locations to be opened and secondly it is easily able to include case- or institution-specific criteria (e.g., regarding infrastructure) or objectives (e.g., types of costs).

Our model only indirectly addresses pre-positioning, while we discuss the locations and direct transports for emergency supplies. We argue with Kunz, Reiner, and Gold (2014) to combine pre-positioning and building capabilites for efficient response, but acknowledge that more direct planning for stock items and levels is needed to implement our approach in practice. Aspects that directly influence pre-positioning locations, such as vulnerability to natural risks, are included in our analysis. Stocking details are however not included in particular, but are decisive parameters in planning and cost modeling as discussed by Campbell and Jones (2011).

Other crisis dynamics are likely to influence the networks. This could for instance include damage to the infrastructure (Ahmadi, Seifi, and Tootooni 2015), uncertainty regarding data (Tofighi, Torabi, and Mansouri 2016), 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 in general. Consequently, future studies that include these uncertainties and dynamics in warehouse location planning are promising to deepen the understanding of efficient collaboration.

Another limitation and opportunity for future research lies in the very restrictive scope of our optimization which includes only one federal state in Germany. This clearly neglects the use of (existing) warehouses across state borders and characteristics of other regions. Results nevertheless show that networks reflect population density and integration of attractiveness allows to take e.g. infrastructural factors into account.

Lastly, federal and regional authorities have very distinct responsibilities, making it more difficult to implement country-wide supply networks for emergencies. Recent exchange with a state ministry in BW, however, has shown significant interest in respective warehouse locations and networks for emergency supply, indicating public actors' awareness for this problem and their motivation to develop useful solutions.[6]

[6] Personal communication of the authors with representatives of the Federal Ministry of Rural Affairs and Consumer Protection, 28th July 2020.

To conclude, the developed approach increases transparency and assists in location selection. Due to its flexibility, it supports manifold ways to improved preparedness towards future crises.

B.7. Acknowledgements

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Supplementary Material

Code	Criterion	Metrics	Source
C.1	Market in Proximity	Population within 50km	Eurostat (2019e)
C.2	Producer Proximity	Regional food producer density	Eurostat (2019f) and Eurostat (2019a)
C.3	Transport Infrastructure Quality and Reliability	Travel time to highway	BBSR (2012)
		Street network density	BKG (2019) and Eurostat (2019a)
		Bridge conditions	BAST (2018b)
		Street conditions	BMVI (2018)
C.4	Availability of Different Transport Modes	Distance to port	BKG (2019)
		Distance to station	BKG (2019)
		Distance to airport	BKG (2019)
C.5	IT/Telecommunications Infrastructure	Broadband availability	Eurostat (2019b)
		Internet speed	Verivox GmbH (2016)
		4G availability	BMVI (2019a)
C.6	Availability and Skills of Labor Force	Job vacancy times	BA (2019)
		Population	Eurostat (2019e)
		Formal education	Eurostat (2019d)
C.7	General Labor Costs	Net labor costs	Destatis (2016)
C.8	Availability and Price Level for Land	Availability of new industry property	Destatis (2019) and Eurostat (2019a)
		Price for new industry property	Destatis (2019)
C.9	Local Taxes	Business tax	Destatis (2018)
		Property tax	Destatis (2018)
E.1	Proximity to Beneficiaries	Reachable population	openrouteservice.org (2020)
E.2	Road Connections	Travel time to highway	BBSR (2012)
		Street network density	BKG (2019) and Eurostat (2019a)
E.3	Airport Proximity	Distance to airport	BKG (2019)
E.4	Transport Infrastructure Resilience and Quality	Street network density	BKG (2019) and Eurostat (2019a)
		Highway accesses	BKG (2019)
		Bridge conditions	BAST (2018b)
		Street conditions	BMVI (2018)
E.5	IT/Telecommunications Infrastructure	Broadband availability	Eurostat (2019b)
		Internet speed	Verivox GmbH (2016)

Code	Criterion	Metrics	Source
		4G availability	BMVI (2019a)
E.6	Availability of Transport Equipment	Origin freight traffic	Eurostat (2019c)
		Destination freight traffic	Eurostat (2019c)
		Transit freight traffic	BAST (2018a)
		Logistics firm density	Eurostat (2019f) and Eurostat (2019a)
E.7	Minimum Distance to Critical Facilities	Nuclear power plants	GLOBAL 2000 (2019) and BKG (2019)
		Refineries and chemical sites	VCI (2019) and BKG (2019)
		Airport	Flughafenverband ADV (2020) and BKG (2019)
E.8	Vulnerability to Natural Risks	Storm hazard	CEDIM (2019)
		Earthquake hazard	CEDIM (2019)
		Water proximity	BKG (2019)
E.9	Minimum Distance to Large Cities	Type of region	BMVI (2019b)

Table B.6: Overview of Sources for Selected Metrics.

BW	**Largest Six Retailers' Locations**			**All Municipalities**		
Emergency Scenario	Costs	Multi-Objective	Attrac-tiveness	Costs	Multi-Objective	Attrac-tiveness
Locations						
Number of warehouses	13	10	7	26	26	7
Thereof large	6	7	7	3	3	7
Thereof small	7	3	0	23	23	0
Costs [per day, in €]						
Logistics costs	232,717	227,492	359,370	273,099	283,018	313,748
Transportation costs	58,691	65,330	220,938	31,841	41,760	175,316
Opening costs	174,026	162,162	138,432	241,258	241,258	138,432
Deprivation costs	39,078,894	43,332,979	134,513,305	21,572,703	28,058,579	109,614,008
Average attractiveness	0.5452	0.5739	0.5960	0.5268	0.6124	0.6682

Table B.7: BW: Model solutions for scenarios optimized for costs, attractiveness, and combined in multi-objective optimization. Left: Optimization based on largest six food retailers' locations; Right: Original Optimization.

BW Emergency Scenario	Lidl Locations						All Municipalities		
	Six Existing Locations			Existing Locations + One					
	Costs	Multi-Objective	Attrac-tiveness	Costs	Multi-Objective	Attrac-tiveness	Costs	Multi-Objective	Attrac-tiveness
Locations									
Number of warehouses	6	6	6	7	7	7	26	26	7
Thereof large	6	6	6	7	7	7	3	3	7
Thereof small	0	0	0	0	0	0	23	23	0
Costs [per day, in €]									
Logistics costs	217,846	217,846	369,293	215,502	217,285	374,107	273,099	283,018	313,748
Transportation costs	99,190	99,190	250,637	77,070	78,853	235,675	31,841	41,760	175,316
Opening costs	118,656	118,656	118,656	138,432	138,432	138,432	241,258	241,258	138,432
Deprivation costs	64,464,152	64,464,152	151,130,951	50,882,797	52,003,829	142,815,380	21,572,703	28,058,579	109,614,008
Average attractiveness	0.5383	0.5383	0.5383	0.5423	0.5579	0.5583	0.5268	0.6124	0.6682

BW Commercial Scenario 10% market share	Lidl Locations						All Municipalities		
	Six Existing Locations			Existing Locations + One					
	Costs	Multi-Objective	Attrac-tiveness	Costs	Multi-Objective	Attrac-tiveness	Costs	Multi-Objective	Attrac-tiveness
Locations									
Number of warehouses	6	6	6	7	7	7	4	4	4
Thereof large	0	0	6	0	0	7	0	0	0
Thereof small	6	6	0	7	7	0	4	4	4
Costs [per day, in €]									
Logistics costs	56,602	56,602	137,153	64,022	64,022	156,929	41,824	43,189	51,841
Transportation costs	9,142	9,142	18,497	8,652	8,652	18,497	10,184	11,549	20,201
Opening costs	47,460	47,460	118,656	55,370	55,370	138,432	31,640	31,640	61,640
Average attractiveness	0.5797	0.5797	0.5797	0.5857	0.5857	0.5857	0.6009	0.6485	0.6565

Table B.8: BW: Model solutions for commercial scenarios optimized for costs, attractiveness, and combined in multi-objective optimization. Left: Locations based on existing locations of retailer Lidl; Center: Locations based on existing locations of retailer Lidl plus one location determined before for the emergency scenario; Right: Original Optimization.

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C. A Novel Approach to Include Social Costs in Humanitarian Objective Functions

Abstract[1]

Social cost functions in humanitarian operations are defined as the sum of logistics and deprivation costs. They are widely regarded as appropriate objective functions, even though the way they were introduced requires cautiously formulated deprivation cost functions for the analyzed goods and do not allow decision makers to include their individual preferences. We develop this approach further and introduce a normalized weighted sum approach to increase decision makers' understanding of the trade-offs between cost and suffering and, therefore, increase transparency significantly. Furthermore, we apply the approach to a case study of a hypothetical water system failure in the city of Berlin, in which we support authorities preparing for this scenario by identifying critical distribution centers. In this context, our model is able to process both possible supply scenarios - too low and sufficient supply. We show that the normalized weighted sum approach significantly improves transparency and leads to a deeper understanding of the trade-offs during the crisis. Consequently, it proved itself as a powerful tool for decision makers preparing for or navigating through a crisis.

1 This chapter includes the preprint of the article "A Novel Approach to Include Social Costs in Humanitarian Objective Functions" by Patrick S. Hiemsch, Marcus Wiens, Markus Lüttenberg, Frank Schultmann, and myself (Diehlmann, Hiemsch, et al. 2020).

C.1. Introduction and Motivation

The COVID-19 pandemic in the year 2020 distinctly highlights the vulnerability of supply chains to disasters. Despite the unprecedented support by local governments and international organizations, the WHO announced a global shortage of critical goods such as face masks or ventilators (WHO 2020). As a response, multiple companies all over the world stepped forward and supported the population. For instance, the German company Trigema started to produce a large number of face masks (Irishtimes 2020), and General Motors adapted some of their plants to produce ventilators (WSJ 2020).

In case the private sector cannot guarantee sufficient supply in a crisis, actors like governments or NGOs become active and try to reduce the burden to the population (Kovács and Spens 2007). However, setting up humanitarian supply chains is very challenging since they vary significantly from commercial supply chains and often need to be designed from scratch under enormous time pressure (Holguín-Veras, Jaller, et al. 2012). Therefore, researchers developed a large variety of optimization models to analyze and improve decisions in disaster situations.

A very critical component of these models is the objective function (Holguín-Veras, Jaller, et al. 2012). Various different objectives from commercial optimization models were applied, e.g. minimization of cost (Falasca and Zobel 2011), minimization of travel time (Jánošíková et al. 2019), maximization of the covering (Balcik and Beamon 2008), or multi-objective approaches (Ahmadi, Seifi, and Tootooni 2015; Fikar, Hirsch, and Nolz 2018; Nolz, Semet, and Doerner 2011; Rath, Gendreau, and Gutjahr 2016; Schneeberger et al. 2016). In spite of the valuable contributions of these models, the chosen objectives do not reflect the unique nature of humanitarian interventions (Holguín-Veras, Pérez, et al. 2013). Therefore, Holguín-Veras, Jaller, et al. (2012) and Holguín-Veras, Pérez, et al. (2013) introduce *social costs* as an more adequate objective.

They define social costs as the sum of logistics costs (LC) and a monetary representation of the suffering of the population, so-called *deprivation costs* (DC) (Holguín-Veras, Jaller, et al. 2012). Therefore, the concept of DC offers a considerable potential to holistically analyze the system and, in turn, to derive sustainable decisions (Kunsch, Theys, and Brans 2007). Deprivation Cost Functions (DCFs) highlight the development of deprivation over time.

They are "monotonic, non-linear, and convex with respect to the deprivation time" (Holguín-Veras, Pérez, et al. 2013).

Shao et al. (2020) present an overview of the state-of-the-art in DC research. They highlight that DCFs often differ significantly from one another because the values depend on the respective goods, the country under consideration, and the specific crisis situation. Thus, different estimation approaches and data from different countries can lead to significant differences in DCFs. As an example, Shao et al. (2020), present DCFs for water or food-kits. They highlight that, in the course of a crisis, DCFs can differ by factors of 3 and higher. Combined with the "complex" process of data collection (Shao et al. 2020), the simple transfer of DCFs determined for a good and country seems to be not appropriate. Therefore, in theory, every study that uses social cost needs to first determine an appropriate DCF for the selected good and location, e.g. with the help of willingness-to-pay surveys.

Even though it is not difficult to conduct willingness-to-pay surveys (Shao et al. 2020), it requires a lot of time and effort, and, therefore, takes attention and resources away from the operations management aspects of the study. Furthermore, the practical application can be questioned since it can be doubted that decision makers are willing or able to take the time to conduct a survey in the aftermath of a disaster. Consequently, in spite of the powerful implications of the social cost approach, we argue that a more practicable approach to include social cost is favorable in situations where it is not possible to derive an appropriate DCF.

We suggest a normalized and weighted sum approach. After presenting an overview of the theoretical foundation in the next Section, we describe the main ideas and advantages of this approach with the help of an illustrative example in Section C.3. Following, we apply the approach on a case study for a hypothetical tap water contamination in the city of Berlin. Afterwards, we present and discuss the results and the approach in Section C.5.

C.2. Theoretical Foundation

Shao et al. (2020) identified 31 studies that consider DC. The majority of these studies does not regard social costs in the originally defined way, but, for instance, considers proxies for DCFs, such as the number of missing goods

(Serrato-Garcia, Mora-Vargas, and Murillo 2016; Biswal, Jenamani, and Kumar 2018), or a priority function (Rivera-Royero, Galindo, and Yie-Pinedo 2016).

A group of studies considers DCFs without LC. For example, Yushimito, Jaller, and Ukkusuri (2012) use a Voronoi-based approach to identify disaster relief locations, or Keshvari Fard, Eftekhar, and Papier (2019) determine the size and allocation of vehicles that leads to minimized deprivation. However, Gutjahr and Fischer (2018) point out equity problems if optimization models under a fixed budget focus on minimizing DC. To increase equity, the authors suggest an extension similar to the Gini-coefficient.

On the other hand, some studies use social cost in the originally defined way, approaching a variety of aspects of humanitarian logistics. For instance, Khayal et al. (2015) develop a location-allocation model for facilities and resources, Pérez-Rodríguez and Holguín-Veras (2016) introduce an inventory-allocation-routing model to deliver critical supplies to the population, Chakravarty (2018) analyze options to invest in levee infrastructure, Loree and Aros-Vera (2018) select locations and inventory allocated to Points of Distribution, Paul and Zhang (2019) develop a two-stage stochastic program to place capacities within a supply chain for hurricane preparedness, and Cantillo, Macea, and Jaller (2019) identify critical links in a relief network. Moreover, Cotes and Cantillo (2019) locate inventory in anticipation of a crisis, and Paul and Xinfang Wang (2019) propose a robust model for facility location in the context of earthquake preparedness.

Furthermore we want to mention two "hybrid approaches" briefly, in which DC and LC are combined in different ways. Xihui Wang, Fan, et al. (2019) develop an approach to optimize the ratio of reduced deprivation and logistics cost to understand the efficiency of interventions better. Even though this approach provides a valuable basis for efficiency discussions, it only provides the chance to compare different options regarding their efficiency rather than identifying a globally optimal relief decision. Moreno et al. (2018) suggest a location-transportation problem and solve the model for the two objectives with a lexicographic approach. While it might be reasonable to argue that DC are more important than LC, and that the approach also allows to include preferences in a limited way (e.g. by introducing an attainment degree), the optimization is always focused on one objective and only regards the second objective subsequently. Even though both approaches allow decision makers to derive valuable conclusions, they have significant limitations.

In addition to the challenges regarding the sensitivity of DCFs towards local economic conditions, we want to further address another factor that, in our view, inhibits the use of social cost approaches in humanitarian logistics: summing up the two cost components simply assumes that both factors are of equal importance to each actor.

We argue that this does not reflect the real conditions properly since the way social cost functions work already includes an implicit weighting: LC are the dominating component in peace time, when the population is not deprived of goods. In disaster relief, DC significantly increase, leading to a substantially reduced influence of LC (Holguín-Veras, Pérez, et al. 2013). Consequently, LC have only very limited effects on social costs-based decisions in relief logistics. We see this assumption rather critical since different actors might not be able or willing to (more or less) disregard the LC implications of their decisions.

An obvious example is an international corporation that delivers different beverages into a region, which is suddenly affected by a disaster. In spite of a potential altruistic or Corporate Social Responsibility-motivated initiative to set up a humanitarian supply chain and support the population with donations, it is difficult to imagine that the company would not base their decision on costs. Another example is an international NGO that is motivated to support the affected population but also bound to their budget. Even though it would be possible to determine a maximal budget and implement this as a constraint in the optimization model, this simply does not reflect the preference that money directly spent as LC can affect an organization more than shadow prices of suffering.

On the other hand, the argument "costs are less important in disaster relief" comes into play, which is based on the (normative) judgement that money should not matter if lives are in danger. Even though such considerations can be observed in some cases (for instance in the COVID-19 response, when Banks like the US Federal Reserve started huge money creation campaigns to support people and businesses (Forbes 2020)), the assumption neglects alternative measures that could be done with the saved money. These measures could, for instance, be to purchase goods and other resources, or, in case of public actors, pay for social measures like short-term labor for the employees (as for instance happened in Germany due to the COVID-19 crisis of 2020 (DW 2020)). Since system boundaries necessarily lead to neglecting effects outside the system, ignoring the costs seems to be only appropriate in a very limited number of cases.

Following, a social cost approach should allow to include decision makers' preferences.

The normalized weighted sum approach is an approach that solves the problems of difficult transfer of DCFs and lack of included preferences. It is especially powerful in a bi-objective case since it allows to determine normalization values comparably easy. In the following section, we first present an example that highlights the challenges of the original social cost approach and discuss the methodological advantages of our new approach.

C.3. Methodology and Illustrative Example

Before discussing our approach in detail, we want to briefly address the concept of deprivation level functions (DLFs), which were introduced by Xihui Wang, Xiang Wang, et al. (2017) and are regarded as an alternative to DCFs (Shao et al. 2020). DLFs "provide[s] information about the degree — not the economic value — of human suffering" and can, therefore, be "defined as the degree of human suffering caused by lack of access to a good or service" (Xihui Wang, Xiang Wang, et al. 2017). While DCFs are defined in terms of costs, DLFs range on a scale from 0 to 10. Even though this approach also offers a variety of advantages (see for instance Shao et al. (2020)), we will focus on DCFs in the present study since a well defined DCF, in spite of the difficulties from an ethical perspective, provides additional room for discussion of results for decision makers. However, we want to note that our approach can also be applied with DLFs.

We make use of the following example to highlight our concerns with the way social costs are defined and to show the advantages of our new approach (see Figure C.1).

We assume that after a disaster disrupted the tap water supply of cities A and B, a humanitarian organization (HO) becomes active and plans to deliver water to the cities. Therefore, they need to decide at which airport they should land with their airplane full of bottled water for 800 people. They can either land in city A, which is inhabited by 600 people, or in city B, in which 200 people live. The roads that connect the two cities allow traffic in one direction

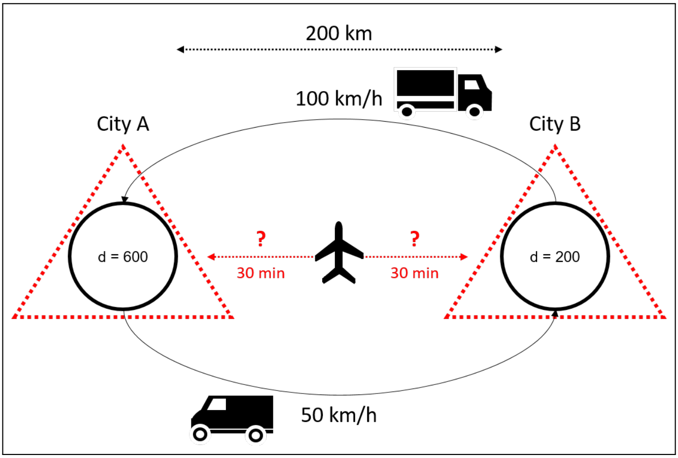

Figure C.1: Overview of the example situation.

and limit the weight and speed of trucks that are allowed to drive on them. The street from A to B is a backroad and only light trucks are allowed to drive on it, while the street in the other direction is well maintained, allowing heavier trucks to drive on it. Hence, goods transported from A to B are transported in two lightly loaded trucks at total costs of 2.80 € per km, while a fully loaded truck can transport all goods in the other direction (at total costs of 1.40 € per km). The heavy loaded truck can drive at 100 km per hour, while the small trucks are only allowed to operate at a speed of 50 km per hour due to the road conditions. The cities are located 200km away from each other, and it takes the airplane 30 minutes to both cities.

From a social cost minimizing point of view, the preferred option offers the minimum sum of LC and DC. The LC are 200 km $*$ 2.8 € = 560 € if the goods are delivered by plane to A first and then delivered by truck to B and 200km $*$ 1.4 € = 280 € if the plane lands in B and the goods are delivered by truck to A afterwards.

DC depend on the number of affected people and the time until the goods reach their city. For example, 600 people would be without water for 0.5 hours and 200 people for 4.5 hours if the plane landed in A. Assuming that it is possible to transfer DCFs from one area to another, we use the DCF of Moreno et al. (2018), in which the DC result in 1,114 € if the plane lands in A and 1,377 € if it lands in B. Consequently, the HO would prefer to land in B since the resulting social costs of 1,657 € are below the 1,674 € of the other option.

However, using a different DCF can obviously lead to different results. As mentioned in Section C.1, the range of DCFs determined for one good and economy compared to the same good and another economical situation can vary at factors of above 3 during a crisis. Let us, therefore, consider an alternative DCF that is three times higher than the DCF of Moreno et al. (2018).

Even though the relative values of the DC stay the same, the net difference between the DC of option A and B triples, leading to social costs that favor landing in city A. Consequently, it can be followed that the social cost approach is only robust if DCFs are defined accurately and implicitly balanced with their corresponding LC, and that the way social costs implemented in the current body of literature needs some adjustments. Consequently, we suggest to adapt the way we use DCFs and LC in social costs objective functions and normalize them.

Multiple ways to normalize exist, which all have their benefits and drawbacks (see for instance Kim and Weck (2005) for an overview). An example in the context of disaster logistics is the approach from Zhu et al. (2019), who normalize logistical, deprivation, and relative DC with the help of its maximum and minimum and use an ant colony optimization algorithm to obtain a solution. Even though this leads to normalization in the interval of 0 and 1, the approach is regarded as "inefficient and not practical" (Mausser 2006). If, for instance, option s_1 leads to the minimal DC at LC of l_1, every option that leads to LC $l_2 \leq l_1$ would be dominated by s_1.

Hence, a more practical way is to normalize with the so-called *Nadir* and *Ideal* Points (see Figure C.2), since they lead to Pareto-efficient solutions (Mausser 2006). The "Ideal Point" can be defined as "the vector composed of the best objective values over the search space," while the Nadir point represents "the vector composed of the worst objective values over the Pareto set" (Bechikh et al. 2015).

The normalization of an objective value z_i follows Kim and Weck (2005):

$$\bar{z}_i = \frac{z_i - {z_i}^{Ideal}}{{z_i}^{Nadir} - {z_i}^{Ideal}} \tag{C.1}$$

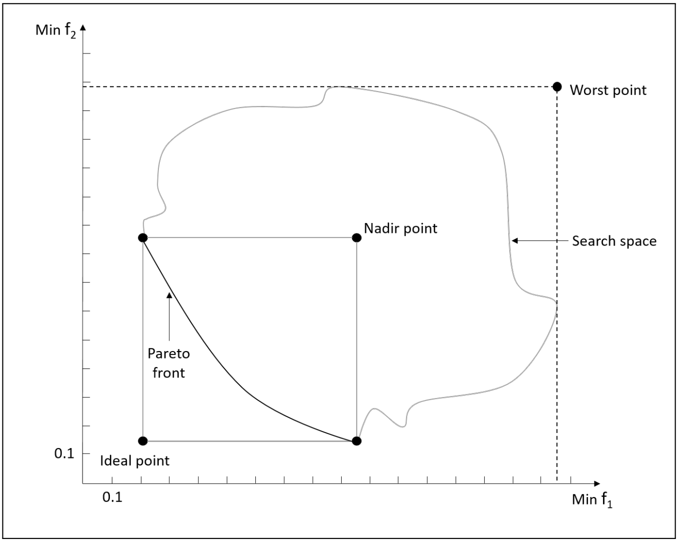

Figure C.2: Visualization of Nadir and Ideal Point (adapted from Bechikh et al. (2015)).

Moreover, the weighting factor α represents the relative value of the DC part of the social costs to allow decision makers to prioritize the two components in a preferred way. It follows that we choose the feasible solution x that leads to the minimal normalized weighted social costs:

$$\min \ \alpha * \frac{LC(x) - LC^{\,Ideal}}{LC^{\,Nadir} - LC^{\,Ideal}} + (1-\alpha) * \frac{DC(x) - DC^{\,Ideal}}{DC^{\,Nadir} - DC^{\,Ideal}} \tag{C.2}$$

In the context of our illustrative example with the DCF from Moreno et al. (2018), the Ideal point is $(280\,€; 1,114\,€)$ and the Nadir point $(560\,€; 1,377\,€)$. Consequently, the normalized social costs result as 1 in case the plane lands in A or B for $\alpha = 0.5$. If the decision maker has a preference towards regarding DC or LC as more important ($\alpha < 0.5$ or $\alpha > 0.5$), a solution that fits to the preferences of the decision maker results.

As we will show in the following section, more complex scenarios lead to more granular variations of solutions. Hence, the sensitivity of a decision towards social costs is reflected in more detail, leading to a significant increase in transparency for decision makers. Our approach can, therefore, provide critical support for decision makers in disaster relief.

C.4. Case Study

C.4.1. Scenario Description

We assume that authorities in Berlin want to prepare for a hypothetical failure of Berlin's tap water system, for instance due to a large-scale water contamination. The tap water cannot be used anymore. Therefore, the population needs to be quickly supplied with bottled water to fulfill their basic needs.

Consequently, public authorities need to become active and install a humanitarian supply chain to provide bottled water to the population, in our case for a time period of 48 hours. We acknowledge the time it takes to set up the supply chain by assuming that deliveries arrive in Berlin 24 hours after the start of the crisis.

The structure of the humanitarian supply chain is in line with Cotes and Cantillo (2019): The bottles enter the system at consolidation centers (CCs), from where they are transported via distribution centers (DiCs) to the demand points (DPs). Figure C.3 highlights the structure of the logistical network.

In the context of our case study, we assume that the set I contains three CCs located on the outskirts of Berlin, from where the required bottles are transported via various transport routes to the city area. The set J of potential DiCs consists of 12 warehouse locations distributed across Berlin, which are currently used from private companies. We assume that the 24 hours between the start of the crisis and the arrival of deliveries is sufficient to modify the warehouses for incoming goods. Moreover, the water is delivered to 631 schools distributed all over Berlin, at which the population can pick up the water. Figure C.4 highlights the positions of the DiCs and CCs on the map of Berlin.

Since CCs and DPs are considered fixed, authorities need to decide which DiCs should be opened. Opening additional DiCs costs money but leads to faster deliveries and reduced deprivation. Hence, authorities face the trade-off

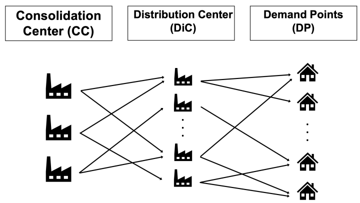

Figure C.3: Structure of logistics network.

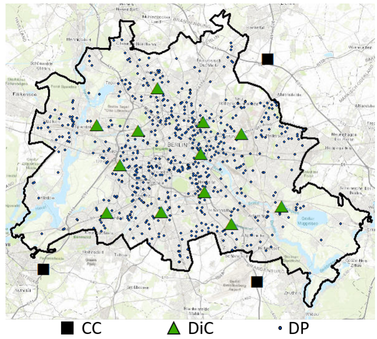

Figure C.4: Locations of CCs, DiCs, and DPs.

between logistics cost and deprivation cost described above by identifying an appropriate set of locations.

We consider two scenarios to cover the potential combinations of demand and supply: In the first scenario, the water arriving at the CCs is sufficient to match the demand of the population (Balanced Scenario).[2] In the second scenario, the demand is not sufficient to match the demand (Unbalanced Scenario).

Hence, deprivation is expected to increase significantly. In the context of our case study, we assume that only 90% of the demand can be fulfilled, even though the calculations can be easily adjusted to fewer deliveries.

C.4.2. Development of a Humanitarian Facility Location Model

As mentioned above, our supply chain and the connected model closely build upon the work of Cotes and Cantillo (2019) and the related literature discussed in their article. We first provide an overview of the nomenclature and the Balanced Scenario. Following, we discuss the adaptions for the Unbalanced Scenario and the necessary steps to calculate the values of parameters.

[2] Note that the developed model can also be applied to a scenario of exceeding supply. Since the results do not significantly differ from the results of the Balanced Scenario, we only focus on two scenarios.

C.4.2.1. Nomenclature

Sets

I:	Set of Consolidation Centers (CCs)
J:	Set of potential Distribution Centers (DiCs)
K:	Set of Demand Points (DPs)

Parameters

α:	Weighting factor for LC (relative to DC), $\alpha \in [0; 1]$
c_{ijk}:	Transport costs from CC i to DP k via DiC j per transported unit
d_k:	Demand in DP k
f_j:	Fixed costs for setting up facility j
$\gamma(t_{ijk})$:	DC as a function of transport time t
t_{ijk}:	Transport time from CC i to DP k via DiC j
q_k:	Population in DP k
LC^{ideal}:	Value of Ideal Point of LC
LC^{nadir}:	Value of Nadir Point of LC
DC^{ideal}:	Value of Ideal Point of DC
DC^{nadir}:	Value of Nadir Point of DC
s_i:	Supply of CC i
cap_j:	Capacity of DiC j

Decision variables

x_{ijk}:	Proportion of demand in DP k, that is provided by CC i via DiC j
y_j:	Binary variable that represents the decision to open a location

C.4.2.2. Mathematical Formulation for the Balanced Scenario

The model for the Balanced Scenario is a capacitated facility location problem with multi-allocation. It can be applied to find an optimal location and transportation plan that minimizes social costs in a post-disaster context.

$$
\begin{aligned}
\min \quad & \alpha \cdot \left(\frac{\sum\limits_{i \in I} \sum\limits_{j \in J} \sum\limits_{k \in K} c_{ijk} \cdot x_{ijk} \cdot d_k + \sum\limits_{j \in J} f_j \cdot y_j - LC^{\,ideal}}{LC^{\,nadir} - LC^{\,ideal}} \right) \\
& + \; (1-\alpha) \cdot \left(\frac{\sum\limits_{i \in I} \sum\limits_{j \in J} \sum\limits_{k \in K} \gamma(t_{ijk}) \cdot x_{ijk} \cdot q_k - DC^{\,ideal}}{DC^{\,nadir} - DC^{\,ideal}} \right) && \text{(C.3)} \\
\text{s.t.} \quad & \sum_{j \in J} \sum_{k \in K} x_{ijk} \cdot d_k \leq s_i && \forall i \in I \quad \text{(C.4)} \\
& \sum_{i \in I} \sum_{j \in J} x_{ijk} = 1 && \forall k \in K \quad \text{(C.5)} \\
& \sum_{i \in I} \sum_{k \in K} x_{ijk} \cdot d_k \leq cap_j \cdot y_j && \forall j \in J \quad \text{(C.6)} \\
& x_{ijk} \leq 1 && \forall i \in I, \; \forall j \in J, \; \forall k \in K \quad \text{(C.7)} \\
& x_{ijk} \geq 0 && \forall i \in I, \; \forall j \in J, \; \forall k \in K \quad \text{(C.8)} \\
& y_j \in \{0, 1\} && \forall j \in J \quad \text{(C.9)}
\end{aligned}
$$

The objective is to minimize the weighted sum of the normalized social costs (as described in Section C.3). As described above, the factor α implements a weighting between the two normalized objectives.

Eq. (C.4) ensures that the total quantity delivered by CC i does not exceed the supply s_i and Eq. (C.5) guarantees complete satisfaction of the demand of each of the DPs.

Constraint (C.6) serves two functions: On the one hand, it ensures that deliveries only flow via a DiC j if it is actually opened ($y_j = 1$). On the other hand, it limits the flows that go through each DiC below the capacity limit (cap_j).

Eq. (C.7) and Eq. (C.8) define the decision variable $x_{ijk} \in [0, 1]$ and Eq. (C.9) the binary decision variable y_j. In contrast to y_j, x_{ijk} is not subject to an integer condition. Therefore, multi allocation is enabled, which allows the model to satisfy the demand of a DP by supplies of several CCs if this is advantageous for minimizing social costs.

C.4.2.3. Modifications for the Unbalanced Scenario

The model described above needs to be slightly adjusted for the Unbalanced Scenario, where supply and demand are not identical (see for instance Girmay and Sharma (2013) for an overview of balanced and unbalanced transportation problems).

It is common practice to transform the unbalanced problem into a balanced problem by adding a dummy supply node that artificially compensates for the lack of supply (Girmay and Sharma 2013; Vasko and Storozhyshina 2011). Compared to the model developed above, this implies an extension of the set I of CCs by an artificial node DK. This node accounts for the unsatisfied demand by representing a fictitious supply, whereby a feasible solution can now be calculated. Thus, the supply of the DF is equal to the amount of the missing quantity of goods.

The transport costs emanating from DK are set to 0 because there is no actual delivery. Therefore, no additional costs for these imaginary transports influence the objective function. Consequently, the people receiving a fictitious delivery from this node are not supplied in reality. To account for their undersupply in the assessment of DC, the transport time t is set to the time horizon t_{max} covered by the model, since these people do not receive any delivery until the end of the planning period.

Moreover, the following applies to the parameters related to DK:

$$
\begin{array}{llll}
\text{Supply:} & s_{DK} & = \sum_{k \in K} n_k - \sum_{i \in I} a_i & \\
\text{Transport costs:} & c_{DKjk} & = 0 & \forall j \in J,\ \forall k \in K \\
\text{Artificial transport time:} & t_{DKjk} & = t_{max} & \forall j \in J,\ \forall k \in K \\
\text{DC:} & \gamma(t_{DKjk}) & = \gamma(t_{max}) & \forall j \in J,\ \forall k \in K
\end{array}
$$

C.4.2.4. Computation of Parameters for Normalization

According to Kirlik and Sayın (2015), the nadir point in bi-criteria optimization "is attained among solutions that minimize the first objective function and vice versa" (p. 82). So DC^{nadir} is the value of the DC that results during computation of LC^{ideal}, and vice versa.

Therefore, the presented models have to be solved twice to determine the values for the normalization. For the calculation of $LC^{\ ideal}$ we use the following function:

$$\min \ \text{LC} \quad = \quad \min \quad \sum_{i\in I}\sum_{j\in J}\sum_{k\in K} c_{ijk} \cdot x_{ijk} \cdot d_k + \sum_{j\in J} f_j \cdot y_j \qquad \text{(C.10)}$$

Simultaneously the following term replaces the original objective function to determine DC^{ideal}:

$$\min \ \text{DC} \quad = \quad \min \quad \sum_{i\in I}\sum_{j\in J}\sum_{k\in K} \gamma(t_{ijk}) \cdot x_{ijk} \cdot q_k \qquad \text{(C.11)}$$

C.4.3. Data Collection

C.4.3.1. Demand and Supply

According to the city of Berlin, 3.754 million people live in Berlin (SSW 2019). In line with the Sphere-Handbook, we assume a water demand of 3 liters per person per day, which represents the absolute minimum for survival (Sphere 2018). During the modeled time horizon of 48 hours, a total demand of 22.526 million liters results. This demand is allocated to the 631 public schools of Berlin, which serve as DPs. The allocation followed the proportion of students per school, obtained from the Berlin Senate Department for Education, Youth, and Sport (BSDEYS 2019). As mentioned above, the supply either matches the demand (Balanced Scenario) or is 10% below it (Unbalanced Scenario). The corresponding amount of water is evenly distributed to the three CCs in both scenarios.

To quantify the suffering of the population in case of water shortage, we use the DCF of Moreno et al. (2018):[3]

[3] Converted into EUR with the 2019 average exchange rate of 0.2268 € per Brazilian Real (ECB 2020).

$$\gamma(t_{ijk})\ [€] \quad = \quad 31,752 \cdot \frac{e^{(1.5031+0.1172 \cdot t_{ijk})} - e^{1.5031}}{e^{(1.5031+0.1172 \cdot 72)} - e^{1.5031}} \qquad \text{(C.12)}$$

$\gamma(t_{ijk})$ depends on the time t_{ijk} that passes until the demand of a person is satisfied. Hence, it consists of the time it takes for the goods to arrive at the CCs (t_i^0) and the transport time from CC i to DP k via DiC j.

We regard an average travel speed in regular road traffic for Berlin to compute the first stage transport time (from CCs to DiCs). According to the German "Zukunft Mobilität", the average travel speed in Berlin is about 24 km per hour (ZukMob 2012). As a consequence of the prevailing state of emergency, we further assume a reduction of speed on the second stage (from DiCs to DPs) by 50%. Since this includes a lot of uncertainty, we discuss different options for the potential speed reduction in Section C.5.3.

C.4.3.2. Infrastructure and Transportation

We assume fixed costs of 1 € per square meter of DiC (the average DiC has a size of 17k m^2). Moreover, we assume that 0.768 pallets of water can be stored on one m^2 storage space, taking into account the size of the pallet (1.2m*0.8m), and a cushion of 20% (e.g. for hallways or common rooms). This is in line with Gudehus (2012), who suggest a range of 0.4-1.8 pallets per m^2 for block storage.[4]

Regarding transportation cost, we distinguish between two different cost components - the transport from CC to DiC (first stage), and the transport from DiC to DP (second stage). All distances are based on linear distances calculated with ArcGIS Desktop 10.6, multiplyied with a tortuosity factor of $\sqrt{2}$ (Diehlmann et al. 2019). We assume that the transport on the first stage is conducted on a sizeable 40t truck with a payload of 24t and space for 33

[4] Note that, even though the DiCs offer these capacities, in reality, not all necessary space would be used since the pallets will not be in the DiCs for a long time. However, it will probably also not be possible to empty the warehouse completely, leaving a part of the area blocked. Within our model, we assume that these two effects even each other out.

pallets. In discussions with a German logistics service provider (LSP), we select a cost rate of 0.058 € per ton and kilometer.[5]

The cost estimation for the second transportation stage is more challenging since the LSP calculates the prices for these kinds of trips on a per-case-base (otherwise, a 5km trip would cost 7 €). Therefore, we cannot use a directly verified kilometer-based rate for short-distance freight transportation.

Consequently, we developed a cost estimation for a truck with a payload of 10 tons, similar to Wietschel et al. (2019), including investment costs, insurance, taxes, maintenance, diesel, tolls, and driver wages. In contrast to the first transportation step, we need to regard the way back as well, resulting in costs of 0.568 € per ton and kilometer. Furthermore, labor costs for the time it takes to load and unload the truck is a large cost driver. A factor of in total 1.33 € per euro pallet is assumed.

These estimations have been validated with the LSP, comparing the costs with the rates they would charge for a selection of comparable trips. Even though our estimations are slightly above the rates of the LSP, we regard them as validated since some "disaster premium" can be expected.

C.5. Results

The models were implemented in GAMS and solved with the CPLEX-solver on an AMD-Ryzen 7 (3.8 GHz, 64 GB RAM). We consider the whole α-interval $[0; 1]$ in steps of 0.1.

C.5.1. Results of the Balanced Scenario

Figure C.5 highlights the optimal number of DiCs dependent on different values for α. The numbers in brackets represent the set of opened DiC locations related to the respective solution. At $\alpha = 0$, when only DC are considered in the objective function, all DiCs are opened. With increasing

[5] Note that this cost rate is based on the one-way distance. Therefore, we do not regard the return journey within this transportation stage.

value of α, the number of DiC locations is gradually decreasing until it reaches its minimum of 4 at $\alpha = 1$, which represents a decision only based on LC.

Taking a closer look at the solutions, some sites are more present than others. Especially the three DiCs 1,5 and 6 should be highlighted in this context since they are included in every solution independent of α. They can be identified as robust locations and should, therefore, be opened, regardless of the decision makers preferences.

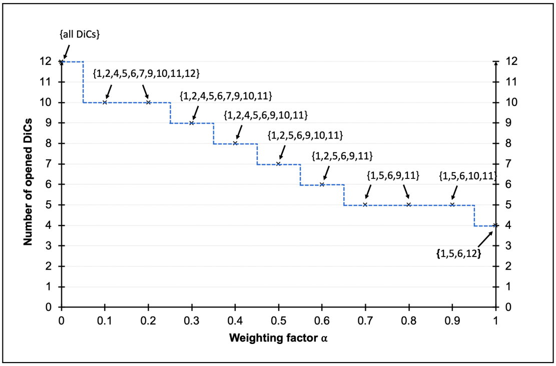

Figure C.5: Opened DiCs for different values of α in the Balanced Scenario.

Figure C.6 illustrates the absolute costs of the solutions. The LC lie within the interval of $[368K €; 1,095K €]$ and decrease as α increases. Hence, they reach their minimum at $\alpha = 1$. The DC fall within the interval of $[455M €; 475M €]$ and in contrast to the LC, they increase as α increases. Consequently, the minimal DC are located at $\alpha = 0$. Furthermore, the figure highlights the need to normalize if decision makers plan to include both aspects of social costs since the DC completely outweigh the LC.

Figure C.7 highlights the value of LC and DC with respect to the related value of α. Hence, the relationship between the two conflicting objectives becomes apparent, since one type of cost decreases if the other one increases and vice versa.

The results in the Balanced Scenario can be summarized the following way: DiCs 1, 5, and 6 are robust locations and should, therefore, be opened in any case. Beyond that, no general recommendation can be made since all of the presented solutions are Pareto-efficient. The decision for one of these

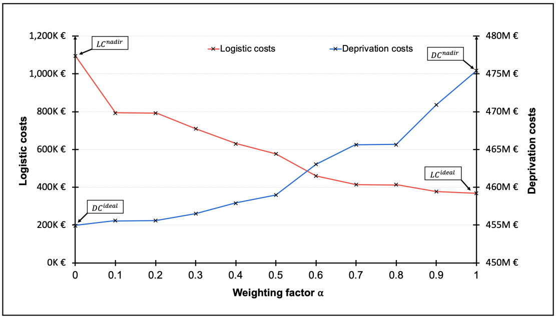

Figure C.6: Logistic and deprivation costs for different values of α in the Balanced Scenario.

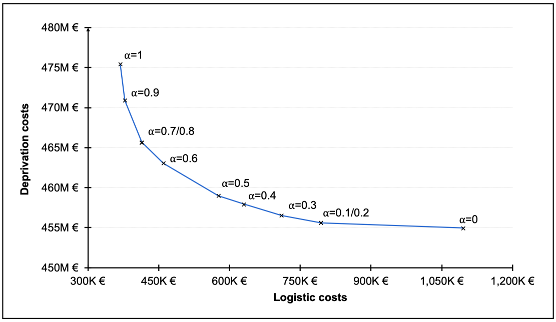

Figure C.7: Pareto-front with an indication of different values for α in the Balanced Scenario.

Pareto-efficient solutions depends on the decision maker and, therefore, the preferred value of α. The preference can be influenced by factors such as the general risk perception of the decision maker, the available budget, or the underlying situation in general.

For example, if a large budget is available, a solution in the α-range between 0.1 and 0.2 could be reasonable since both types of costs remain unchanged in this area. Until $\alpha = 0.1$, the LC rapidly decrease while the DC only slightly increase. On the other hand, with a lower budget, a value between 0.7 and 0.8 could be appropriate as the LC are quite close to their minimal cost while DC are still moderate. In contrast, with α-values greater than 0.8, the DC increase at a disproportionate rate in relation to the small savings regarding the LC.

C.5.2. Results of the Unbalanced Scenario

Figure C.8 highlights the different optimal location decisions with respect to the value of the weighting factor α. The general course of the solutions looks similar to the course of the graph for the first scenario: all 12 DiCs are opened if $\alpha = 0$, and the number of DiCs decreases as α increases. At $\alpha = 1$, only 4 open DiCs are left.

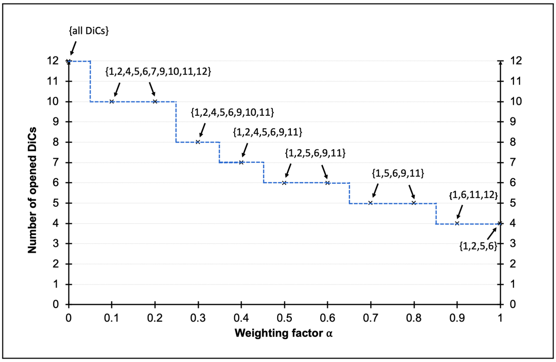

Figure C.8: Opened DiCs for different values of α in the Unbalanced Scenario.

However, a comparison of the solutions reveals differences, not only regarding the number of locations but also the composition of optimal DiC-sets, especially in the higher α range. As in the balanced case, DiCs 1 and 6 are included in every solution and can, therefore, be identified as robust locations. In contrast to the first scenario, DiC 5 is no robust location in the unbalanced case. Compared to the results described above, DiC 5 is not opened in the case of $\alpha = 0.9$, but DiC is 11 opened instead. DiC 11 offers less space at less cost than DiC 5. Since fewer goods flow within the system, the size of DiC 11 combined with the other three open DiCs is sufficient now, allowing to reduce costs.

The costs are illustrated in Figure C.9. They show a similar pattern as in the Balanced Scenario. However, it is noticeable that, compared to the first scenario, DC are much higher. They range from 1,100M€ to 1,124M€. This high number results from the undersupply underlying this scenario. Even though only 10% of supplies are missing, total deprivation more than doubles, highlighting the exponential structure of DCFs.

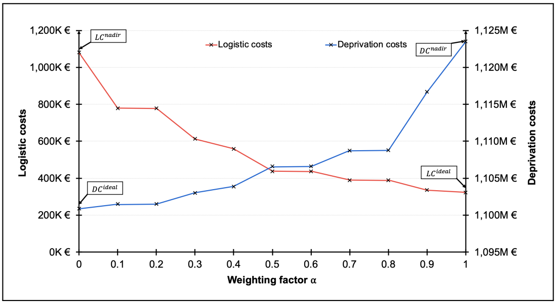

Figure C.9: Logistic and deprivation costs for different values of α in the Unbalanced Scenario.

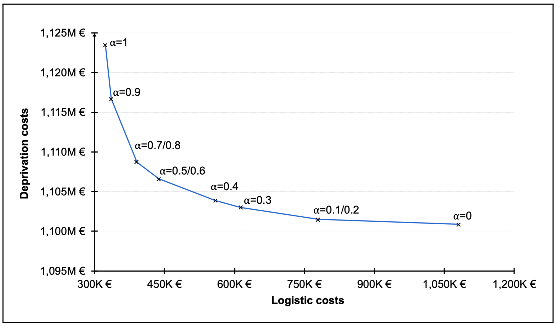

Figure C.10: Pareto-front with an indication of different values for α in the Unbalanced Scenario.

Figure C.10 highlights the Pareto-front and, therefore, the trade-off between LC and DC. Even though the absolute numbers differ in magnitude, the course is very similar to Figure C.7 and, thus, underlines the competitive nature of the two objectives as well.

The results in the Unbalanced Scenario can be summarized in the following way: DiCs 1 and 6 are robust locations and should be opened in any case. As stated before, the final decision depends on the preferences of the decision maker. Similar to the first scenario, α-values between 0.1 and 0.2 could be reasonable for high budgets. On the other hand, α could be set to a value between 0.7-0.8 for low budgets.

C.5.3. Analysis of the Sensitivity Towards Travel Speed and DiC Capacities

As mentioned above, we furthermore want to discuss the sensitivity of the results towards two key assumptions: the travel speed and the number of pallets per m^2 of DiC area.

Table C.1 highlights this analysis for the Balanced Scenario. In addition to the combination discussed in detail above (12 km/h and 0.768 pallets per m^2), the table shows the LC, DC, and number of opened DiCs for different combinations of travel speed and capacity. Note that an equal number of open DiCs does not automatically lead to equal DC or LC. Since the number of pallets that fit in one DiC strongly depends on the capacity of pallets per square-meter, travel distances change within the selected combinations. Moreover, we calculate DCs based on travel time. Consequently, they increase if travel speed slows down.

An increase in travel speed leads to a reduction in both types of costs - LC and DC. However, the significance of the effect differs. The mean drop in LC is on average 0.033% for each percent increase in travel speed in case of 0.768 pallets per m^2 (and 0.036% in case of 2 pallets per m^2). Moreover, the mean DC drop by an average of 0.028% (and 0.032%).

However, an increase in the number of pallets per m^2 comes along with more complex effects. On the one hand, the mean LC decrease by 0.048% for each percent increase in pallet capacity in case of a second stage travel speed of 6 km per hour (0.044% for 12 km per hour and 0.052% for 18 km per hour). On the other hand, mean DC slightly increase in all cases - 0.001% in case of 6 km per hour and even smaller increases for different travel distances. This is unexpected since the increased capacity of DiCs allows for additional options to deliver goods through them. Consequently, it can be followed that the positive effects of the LC significantly outweigh the changes in DC. This, furthermore, underlines the importance of considering both objectives simultaneously and to take a close look at the trade-offs between both objectives.

	speed 2nd stage		6 kmh	speed 2nd stage		12 kmh	speed 2nd stage		18 kmh
	pallets per m2		0.768	pallets per m2		0.768	pallets per m2		0.768
alpha	LC[k€]	DC [k€]	#DiCs	LC[k€]	DC [k€]	#DiCs	LC[k€]	DC [k€]	#DiCs
0	1,093	477,585	12	1,096	454,943	12	1,102	446,967	12
0.1	1,093	477,585	12	794	455,600	10	800	447,134	10
0.2	792	480,343	10	794	455,601	10	744	447,334	9
0.3	792	480,343	10	711	456,543	9	587	448,440	7
0.4	708	482,557	9	631	457,923	8	587	448,440	7
0.5	575	488,730	7	577	458,988	7	535	449,181	6
0.6	418	500,346	6	460	463,073	6	416	452,499	5
0.7	418	500,349	6	414	465,654	5	416	452,499	5
0.8	418	500,365	6	414	465,675	5	416	452,508	5
0.9	369	516,690	4	379	470,913	5	379	457,202	5
1	369	517,023	4	369	475,433	4	369	462,508	4
Mean	640	492,901	7.82	604	461,850	7.36	578	451,337	6.82
alpha	speed 2nd stage		6 kmh	speed 2nd stage		12 kmh	speed 2nd stage		18 kmh
	pallets per m2		2	pallets per m2		2	pallets per m2		2
0	1,093	477,494	12	1,096	454,871	12	1,103	446,885	12
0.1	947	478,508	11	794	455,543	10	744	447,202	9
0.2	792	480,271	10	794	455,544	10	665	447,736	8
0.3	708	482,488	9	616	457,868	8	463	449,230	6
0.4	440	494,049	6	459	460,865	6	423	449,745	5
0.5	440	494,050	6	409	462,809	5	373	450,784	4
0.6	440	494,053	6	408	462,821	5	373	450,784	4
0.7	368	506,882	5	371	465,164	4	373	450,793	4
0.8	331	514,776	4	332	469,839	4	373	450,793	4
0.9	303	529,663	3	303	478,569	3	303	462,905	3
1	298	544,792	2	298	487,092	2	298	469,503	2
Mean	560	499,730	6.73	535	464,635	6.27	499	452,396	5.55

Table C.1: Results for different combinations of travel speeds and pallet per area.

C.6. Discussion

The results of both scenarios underline the wide range of applications and the great versatility of the developed approach. The weighting factor α allows the decision maker to integrate individual preferences into the calculation of an optimal location decision based on the available budget and the particular situation.

In the case of $\alpha = 0$, only the DC are included in the objective function. Accordingly, if α is set to 1, only the LC are considered. Every other value for the weighting factor in between these two extremes represents a weighted mixture of both cost objectives. This allows the decision maker not only to implement a prioritization for one of the cost factors according to the disaster situation but also to identify potentially suitable options for action by examining the entire interval $\alpha \in [0; 1]$.

Moreover, different phases of the disaster can lead to different preferences and, consequently, different values for α. For example, it is possible to use a lower value for α in disaster relief than in preparedness.

Additionally, by examining the entire α-interval, some DiCs can often be excluded entirely from the set of potential DiC locations because they do not occur in any of the calculated solutions. Furthermore, robust DiC locations may be found that appear in each of the solutions and should, therefore, be in the focus of authorities preparing for a disaster.

In contrast to the original definition of social costs in the objective function by Holguín-Veras, Pérez, et al. (2013), this leads to a significant increase in transparency and, therefore, provides valuable support for decision makers. Figures C.11 and C.12 highlight this by presenting the number of opened DiCs and the cost structure for the Balanced Scenario without normalization.

It follows that before we introduced our approach, decision makers would open all DiCs since they would only regard the outcome of $\alpha = 0.5$. Furthermore, the implicit prioritization of DC leads to a comparably rigid function behavior and a sudden drop for α between 0.9 and 1. This drop highlights the benefits of normalization since it allows decision makers to understand the sensitivities of the SCF more thoroughly.

In addition, as shown in our solution analyses of the two scenarios, the model can provide a good overview of the possible trade-offs between different

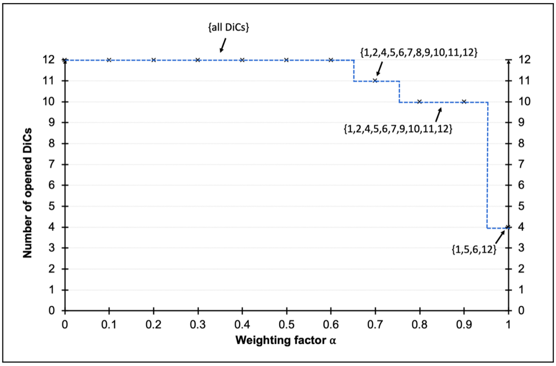

Figure C.11: Opened DiCs for different values of α without normalization in the Balanced Scenario.

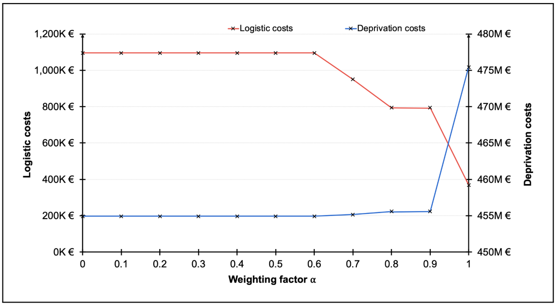

Figure C.12: Logistic and deprivation costs for different values of α without normalization in the Balanced Scenario.

options by analyzing the Pareto-front in respect to $\alpha \in [0, 1]$. Therefore, it supports the whole decision making process and, thus, facilitates to tailor decisions to the specific disaster context.

C.7. Conclusion

The use of social cost functions in humanitarian logistics depends on well-defined deprivation cost functions. However, only very few of these functions have been scientifically developed. Combined with the lack of transferability due to a strong sensitivity towards local economic conditions, the application of social cost functions is difficult. Moreover, the original definition of social cost functions in humanitarian logistics comes along with two potential weaknesses. First, it does not allow to include preferences of decision makers towards one of the two cost components. Second, it contains an implicit weighting since deprivation costs can completely outweigh logistic costs in disaster relief.

Therefore, we further developed the concept of social costs in humanitarian logistics and introduced a normalized weighted sum approach. After presenting the methodological foundations of the approach, we applied it to a case study for a hypothetical water system failure in the city of Berlin. Assuming that authorities want to prepare for such a scenario, we developed a model that identifies an appropriate distribution network. Since it is not clear if the supply is sufficient, the model needed to be flexible enough to consider both cases (Balanced and Unbalanced), which we investigated in two scenarios. Furthermore, we compared the results with the results of the original definition, highlighting the increase in transparency, in particular with respect to the sensitivity of the decision.

Future studies can complement our approach in many ways. For example, it would be possible to derive "rule-of-thumb factors" for α in a survey of decision makers from different institutions (e.g. private sector, NGOs, authorities). While the approach supports decision makers to understand their decisions better, they still need to decide for an appropriate α by themselves. Therefore, standard values could work as a starting point for discussions with decision makers.

Moreover, the application of the approach in the context of collaboration seems promising. If, for instance, public and private actors work together in a Public-Private Emergency Collaboration (PPEC, Wiens et al. (2018)), different combinations of individual preferences would affect the outcome of the PPEC significantly. Hence, our approach could support them aligning their objectives and finding compromises for long term collaboration. Moreover, it is possible to derive Pareto-fronts for different collaboration scenarios and, therefore, allocate budget to a portfolio that fits the individual preferences best. Consequently, this could enable a better coordination of resources and, thus, likely improve the outcome of future interventions (Maghsoudi et al. 2018).

Despite the potential fields of further investigation, we can conclude that our approach significantly increases transparency for decision makers and allows them to include their preferences into the objective function. Thus, it leads to more substantiated decisions and, consequently, to a more efficient relief logistic.

C.8. Acknowledgements

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D. On the Combination of Water Emergency Wells and Mobile Treatment Systems: A Case Study of the City of Berlin

Abstract[1]

A shortage of water leads to severe consequences for populations. Recent examples like the ongoing water shortage in Kapstadt or in Gloucestershire in 2007 highlight both the challenges authorities face to restore the water supply and the importance of installing efficient preparedness measures and plans. This study develops a proactive planning approach of emergency measures for possible impairments of water supply systems and validates this with a case study on water contamination in the city of Berlin. We formulate a capacitated maximal covering problem as a mixed-integer optimization model where we combine existing emergency infrastructure with the deployment of mobile water treatment systems. The model selects locations for mobile water treatment systems to maximize the public water supply within defined constraints. With the extension to a multi-objective decision making model, possible trade-offs between the water supply coverage and costs, and between the coverage of differently prioritized demand points are investigated. Therefore, decision makers benefit from a significantly increased transparency regarding potential outcomes of their decisions, leading to improved decisions before and during a crisis.

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[1] This chapter includes the final version of the article "On the combination of water emergency wells and mobile treatment systems: a case study of the city of Berlin" by Christoph Stallkamp, Markus Lüttenberg, Marcus Wiens, Rebekka Volk, Frank Schultmann, and myself (Stallkamp et al. 2020). The supplementary material can be found on the journal website.

D.1. Introduction

D.1.1. Motivation

Critical infrastructures are organizations and facilities with great importance to the public. Failure can lead to supply shortages of essential services as well as possible disruption of public safety (BMI 2009; UNISDR 2009). In case of an emergency, it is necessary to limit damages to critical infrastructures and to prevent possible corresponding disruptions of services (Wannous and Velasquez 2017). This objective is particularly relevant due to new security policy risks like international terrorism and significant natural risks that have an enhanced potential to damage critical infrastructures (Bross et al. 2019). Therefore, authorities need to update their continuity plans regularly and make sure that each part of the critical infrastructure is protected.

The water supply system and the sewage system are one of the critical infrastructures of a city (BMI 2009). Potential damage to the system can lead to the unavailability of drinking water. For example, a contamination led to disruptions in Toledo (Redfern et al. 2018) and Flint (Ruckart et al. 2019). Moreover, the system can be affected by natural disasters. For example, an earthquake caused significant disturbance of the water system in Los Angeles in 1994 (Davis 2014), a long-lasting drought put the supply in Kapstadt under heavy pressure (Enqvist and Ziervogel 2019). Moreover, severe flooding led to a collapse of the water distribution of Gloucestershire (Rundblad, Knapton, and Hunter 2010) and Simbach am Inn in Germany (Bross et al. 2019). While a lot of measures and contingencies are in place to repair and reestablish water supply, it is important to develop plans to mitigate the consequences of a disruption.

Drinking water is critical for the survival of the population. Therefore, operators of critical infrastructure are obliged to develop contingency plans. For example, German water supply companies need to implement preventive measures for strengthening the safety of public water supply. If companies lack capacities to re-establish normal operations, German authorities need to ensure alternative supply measures (BBK 2016a).

Dependent on the level of the disruption, authorities can activate a variety of specialized disaster management agencies or divisions. Besides safety and security actors like firefighters, police, or the military, authorities can activate the Federal Agency for Technical Relief (THW), which provides technical support in the context of civil protection and disaster assistance (Deutscher Bundestag 1990). The agency consists of volunteers that form different specialist groups, including drinking water specialist groups equipped with resources to establish an emergency water supply. These resources include mobile water treatment systems, water transportation containers, and vehicles (BBK 2016a). Other specialist groups provide emergency repair, supply, or rescue (BBK 2016b).

While the Federal Office for Civil Protection and Disaster relief (BBK) coordinates crisis interventions on a national level (BBK 2016b), each federal state in Germany is in charge of their own disaster measures. In case of water supply disruptions, they can, for example, install mobile pipes from regions with functioning water systems or use transportation trucks (BBK 2016b). In severe cases, when a huge number of people cannot be supplied otherwise, German authorities can activate more than 5,200 independent emergency water wells throughout the country that enable quick access to groundwater (Fischer and Wienand 2013).

However, even though measures to maintain and check the wells are in place, it is not certain that each well works properly (Boehme, Geißler, and Schweer 2012). Moreover, the well system was designed and installed during the cold war (Fischer and Wienand 2013). Even though authorities occasionally install new fountains, it can be debated if the locations reflect the current distribution of the population properly. Therefore, the focus of our study is to analyze the effectiveness of wells in a hypothetical disaster and to investigate, how these wells can be supported by a more flexible technology.

D.1.2. Problem Description and Contribution

Mobile water treatment systems represent a flexible option to complement the emergency supply by wells. However, the decision making on the placement of these mobile systems is highly complex and depends on multiple factors, such as suitable locations, distance to the beneficiaries, or available budget. This is especially complex in disaster relief since parts of the population in different and sometimes critical physical constitution need different types of help (see for instance IFRC (2011), who state that they "prioritize to help the most vulnerable and ensure that immediate emergency needs are being met)." Decision making is especially challenging for authorities responsible for the whole population. While they are focused on maximizing the supply for the vulnerable part of the population, they still need to make sure that the non-vulnerable parts of the population receives sufficient amounts of water or help as well.

Therefore, we developed a multi-criteria decision model to support decision makers in implementing an emergency water supply chain in case of the disruption of the public water supply. This model allows to consider different objectives within the optimization and, therefore, to analyze possible trade-offs (e.g. cost vs. coverage, focus on vulnerable vs. less vulnerable parts of the population).

The model consists of three parts: determination of the spatial demand and the supply of the existing emergency water supply infrastructure, identification of potential locations for mobile water treatment systems, as well as the selection of locations for them.

Consequently, the article contributes to the body of literature in three significant ways. First, we provide a guideline to transparently assess available capacities for the first time to enable decision makers to assess their own systems' conditions and capacities. Second, we develop a novel maximum covering model to support decision makers designing emergency water supply chains. The developed model combines various extensions for the maximum covering location problem. In contrast to previous models, our approach allows to jointly consider existent service infrastructure with additional facilities, while integrating the inventory allocation of facilities to demand points. Third, the importance of considering trade-offs is obvious since authorities need to regard multiple stakeholders and their needs within their decision making. Furthermore, it is necessary to understand the consequences of prioritizing parts of the population. With our methodology, various trade-offs can be identified in a clear-cut way.

The paper is structured as follows. After the review of related literature in the following section, we provide an overview of the model in Section D.3. Following, we apply the model in the context of a case study for a hypothetical terror attack (water contamination) on the public water supply of the city of Berlin, Germany in Section D.4. The results of that case study are highlighted in Section D.5 and discussed in Section D.6.

D.2. Literature Review

D.2.1. Water Emergencies

Jain (2012) highlights the challenge of possible contamination of drinking water sources after an emergency, especially if there is a lack of infrastructure to purify water. He classifies four groups of possible contaminants: (1) microbiological contaminants, (2) chemical contaminants, (3) radiological contaminants, and (4) physical contaminants. Loo et al. (2012) provide a comprehensive overview of water treatment systems that purify water from different contaminants. They also developed a framework to support authorities and relief organizations selecting from the multiple water treatment options in emergencies. Water treatment systems are classified according to their operating principle (Loo et al. 2012) or their capacity, ranging from point-of-use systems for the intervention on a household level to small-scale-systems on community level (Peter-Varbanets et al. 2009).

Several papers analyze the effectiveness of specific water treatment technologies reducing the concentration of water contaminants in different emergency settings. Clasen and Boisson (2006) note that household-based ceramic filters helped to improve the drinking water quality among the population affected by flooding in the Dominican Republic in 2003. Clasen, Smith, et al. (2006) provide an overview of several water purification technologies deployed after the Indian Ocean tsunami in 2004. They highlight that a timely, comprehensive, and effective response to restore drinking water is essential to save lives and outline conditions under which household water treatment technologies are useful to provide relief to an affected population. Dorea et al. (2009) describe the intervention with a clarifier on a community level and provide performance data from the Indian Ocean tsunami. Garsadi et al. (2009) extend the investigated treatment systems in this aftermath by the discussion of the practical experiences of the deployment of mobile water treatment systems. Mahmood et al. (2011) evaluate household sand filters in the aftermath of an earthquake that damaged over 4,000 water and sanitation schemes in northern Pakistan in 2005. Lantagne and Clasen (2013) document the impact of a household intervention with chlorine and filter products distributed after the 2010 earthquake in Haiti.

Since the number of natural and man-made disasters is expected to rise, e.g. due to climate change, migration, diseases or terror attacks, it is necessary to develop holistic concepts to encounter the consequences of the disasters as effectively as possible (Wu et al. 2019). This also includes integrated concepts for drinking water supply and water treatment technologies.

D.2.2. Covering Approaches

According to Church and Murray (2019), public actors' location decisions are often formulated as covering problems to represent the principle of equity while placing public facilities and services. There are two types of location covering models, *Location Set Covering Problems (LSCP)* and *Maximal Covering Location Problems (MCLP)*. While LSCPs seek to cover total demand while minimizing the number of facilities needed, MCLPs maximize the covered demand based on a given number of facilities (Church and Murray 2019).

According to Toregas (1970), an application of the LSCP is placing emergency response services with a maximal accepted service time. Other applications are ensuring the access of services for people with disabilities (Kwan et al. 2003), the siting of bus stops (Murray 2001), or the placing of warning sirens (Current and O'Kelly 1992).

On the other hand, possible applications for the MCLP are the placing of health clinics (Bennett, Eaton, and Church 1982) or fire stations (Murray 2013) in case only a limited number can be set up. Church and ReVelle (1974) suggest that MCLPs for given planning applications can be solved by varying the number of facilities. This allows to create a trade-off between the coverage provided and the investment in facilities (Church and Murray 2019). This additional information allows the decision maker to weigh between service level and cost.

Li et al. (2011) provide an overview of various extensions of the MCLP and LSCP like implementing quality levels of service, multiple types of service, or ensuring back up coverage. Moreover, Church and Murray (2019) mention extensions regarding integrating existing service systems and hierarchical services.

Loree and Aros-Vera (2018) highlight that allocating inventory from facilities to demand points is another important aspect while designing post disaster humanitarian supply chains. Integrating the inventory allocation decision into the facility location decision links the optimization of facility locations with the consequences for the supplied population (Lin et al. 2012). Loree and Aros-Vera (2018) discuss three models with the objective to maximize the covered demand (Jia, Ordóñez, and Dessouky 2007; Murali, Ordóñez, and Dessouky 2012; Hong, Xie, and Jeong 2012). Only Jia, Ordóñez, and Dessouky (2007) and Hong, Xie, and Jeong (2012) base their models on possible facility locations and specify the numbers of facilities that are to be placed. However, none of the models considers multiple facility types to meet the demand and none considers trade-offs.

Consequently, our MCLP differs from available humanitarian location-allocation models by including the following model components: it determines facility locations, while simultaneously considering multiple facility types that combine efforts to provide relief and maximize coverage. In addition, capacity constraints, the allocation of inventory to the demand points, and multiple sourcing are included. Furthermore, we extended the MCLP model to include a multi-criteria perspective, allowing for trade-off analysis.

D.2.3. Multi-objective Approaches

Real-world problems include multiple objectives that decision makers have to consider. The resulting multi-criteria decision making (MCDM) problems combine decisions regarding cost, environmental risk, service level, or other aspects (Clasen, Smith, et al. 2006).

Various studies used MCDM methods to find optimal solutions for different emergency settings. Barbarosoğlu, Özdamar, and Çevik (2002) develop a mathematical model for helicopter mission planning during disaster relief operations. The model has two sub-problems with conflicting objectives leading to the additional development of a multi-criteria analysis. Evaluating another use case, Bastian et al. (2016) create a multi-criteria decision analysis framework to optimize the military humanitarian assistance aerial delivery network.

Emergencies in the context of water are also investigated, including hazards and public water supply. Gigović et al. (2017) evaluate possible flooding areas in urban areas by defining factors that are relevant to the hazard of flooding combining the application of geographical information systems (GIS) and MCDM. Doerner, Gutjahr, and Nolz (2009) investigate the placement of public locations near coasts taking risks of inundation by tsunamis and costs into account. Singh, Jha, and Chowdary (2018) evaluate groundwater potential while Al-Weshah and Yihdego (2018) investigate different approaches to remediate water supply after groundwater pollution. Tscheikner-Gratl et al. (2017) investigate a multi-objective approach for the maintenance of water supply systems, while Zimmermann, Felmeden, and Michel (2018) assess different water infrastructures. Nolz, Doerner, and Hartl (2010) introduce a decision support system for planning water distribution tours with trucks in emergencies. The transportation problem includes a cost criterion based on travel time and a coverage objective.

Boonmee, Arimura, and Asada (2017) provide a comprehensive overview of location-based decision making problems that are related to humanitarian logistics in emergencies. The survey is based on data modeling types and the classification of facility location problems. Furthermore, it examines pre- and post-disaster situations (Boonmee, Arimura, and Asada 2017) and includes multi-criteria problems. None of the mentioned approaches regard the trade-off between differently vulnerable groups of the population.

Furthermore, Holguín-Veras et al. (2013) provide an overview of humanitarian logistics problems with multiple objectives. They discuss incorporating a measure into optimization problems, which represents the suffering of the population experienced from a lack of access to goods or services, and name this external effect *deprivation cost*. Therefore, deprivation cost functions present an opportunity to prioritize parts of the population (Rivera-Royero, Galindo, and Yie-Pinedo 2016). Shao et al. (2020) provide an overview of the recent literature on the concept of deprivation cost and highlight challenges associated with this approach. They conclude that deprivation cost functions are highly sensitive towards the product and the local economic characteristics (Shao et al. 2020).

To the best of our knowledge, no estimation for water deprivation cost functions in Germany is known. Hence, the application of a deprivation cost approach does not seem to be mature enough in our context.

D.2.4. Research Gap

The literature review shows that there are no covering models that provide an integrated concept of combining existing infrastructure with additional mobile water treatment systems. The developed model allows decision makers to consider already existing infrastructure when deciding where to place additional mobile water treatment resources in an emergency or undersupply case.

With the extension of the MCLP model to a MCDM model, comprehensive trade-off analysis with different priorities are enabled. To the best of our knowledge, there is no such model combination allowing for a comprehensive analysis of trade-offs between coverage and length of supply routes, number of deployed water treatment systems or costs. Our approach also provides valuable insights into the prioritization of certain demand points over others, especially if deprivation cost functions cannot be applied."

D.3. Methodology

The model consists of three modules that are described in the following subsections. The modules (A) and (B) feed the module (C) that consists of the optimization model and enables trade-off analysis.

D.3.1. Model Requirements

The introduced model aims to support the establishment of a humanitarian supply chain in the context of an urban water emergency. Modeling an emergency supply chain for a major city involves the definition of model boundaries, the collection of required data, and the formulation of assumptions due to prevailing unknowns and uncertainty.

The main objective is the maximization of the coverage of the public water demand. In covering models, demand is covered and supplied within a predefined service standard. The demand coverage is maximized by placing mobile water treatment systems throughout the city while taking already existing and functioning emergency infrastructure (wells) into account.

The main challenges are estimating demand, identifying and locating water supply capacities, and determining preferences of the decision maker. The model is supposed to fulfill the following requirements:

1. Estimating demand and identify demand centers within the study area. This includes different categories of demand such as the demand

of residents and patients of high vulnerable facilities such as hospitals and nursing homes.

2. A second requirement is establishing the available drinking water within the study area. Possible drinking water sources are already existing emergency infrastructure and location candidates for mobile water treatment systems.

3. Besides optimizing the total water demand covered, the consecutively optimization of secondary objectives should be possible to allow analyzing trade-offs between the attainment of multiple objectives. This enables the decision maker's preferences to be represented. Possible trade-offs could be the maximum coverage at a given budget or at least to gain knowledge on how much a higher coverage would cost.

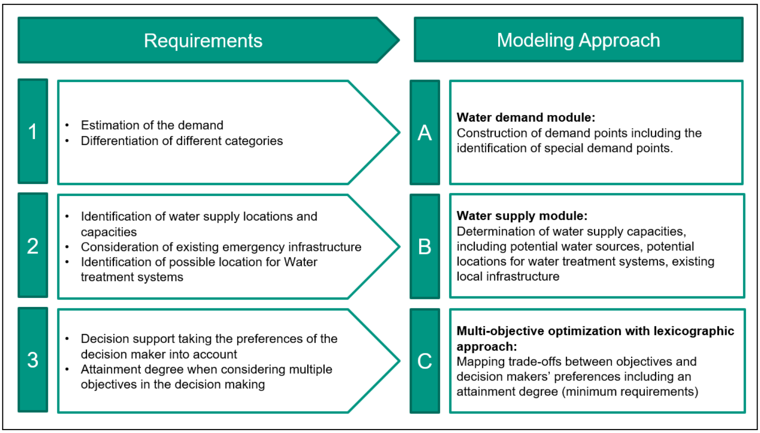

Figure D.1: Overview of model requirements and modules with the chosen modeling approaches (modules A, B, C). The requirements are discussed above and are based on the challenges identified while designing a water emergency supply chain. Three model modules are formulated and described to meet the requirements.

D.3.2. Model Components

Figure D.1 displays an overview of the model requirements and contrasts them with the chosen modelling approaches to meet these requirements. The water demand module (A) and the water supply module (B) are two modules to determine the required data for the optimization module (C). Module (A) locates the water demand by constructing demand points based on collected data while taking two different categories of demand into account. Module (B) evaluates water supply capacities with respect to their locations and costs. Furthermore, existing emergency infrastructure is investigated and possible locations for mobile water treatment systems are defined as solution space. Module (A) and (B) represent the data basis for module (C). The core of module (C) is a lexicographical optimization model comprising two objectives, enabling a consecutive optimization of coverage and associated costs. It allows the mapping of trade-offs between objectives and the impact of the decision maker's preferences. Figure D.2 displays the interdependencies of the different modules that are described in more detail below.

Module (A) determines the demand in case of an emergency. Based on data for population density per building blocks and the water demand per capita, demand centers can be localized and their water demand can be calculated resulting in the water demand of regular residents. Vulnerable patients of hospitals and nursing homes are located at these high care facilities. Their demand is characterized by the number of beds per institution and the per bed demand. Additional demand flows can extend the approach.

The available water supply by existing emergency wells is established by module (B). Data must be identified that locate the existing emergency infrastructure and its capacities. Possible locations for mobile water treatment systems are defined by identifying open areas and by restricting potential candidates based on location criteria such as access to the road network or a water source. The opportunity to supply locations by tank trucks is evaluated.

The decision making process is described, summarized and solved in module (C). The established data from modules (A) and (B) is input for a capacitated maximal covering location problem (CMCLP). A CMCLP was chosen since covering models are typically used to design emergency services (Daskin 2008). Church and Murray (2019) justify this with the goals of the public sector, including the provision of good services and fairness that are implemented through a service level. Moreover, a MCLP is formulated since the number of available mobile water treatment systems is limited in case of an emergency. Demand is regarded as covered if the nearest supply is within a predefined distance and provides a predefined minimum of water.

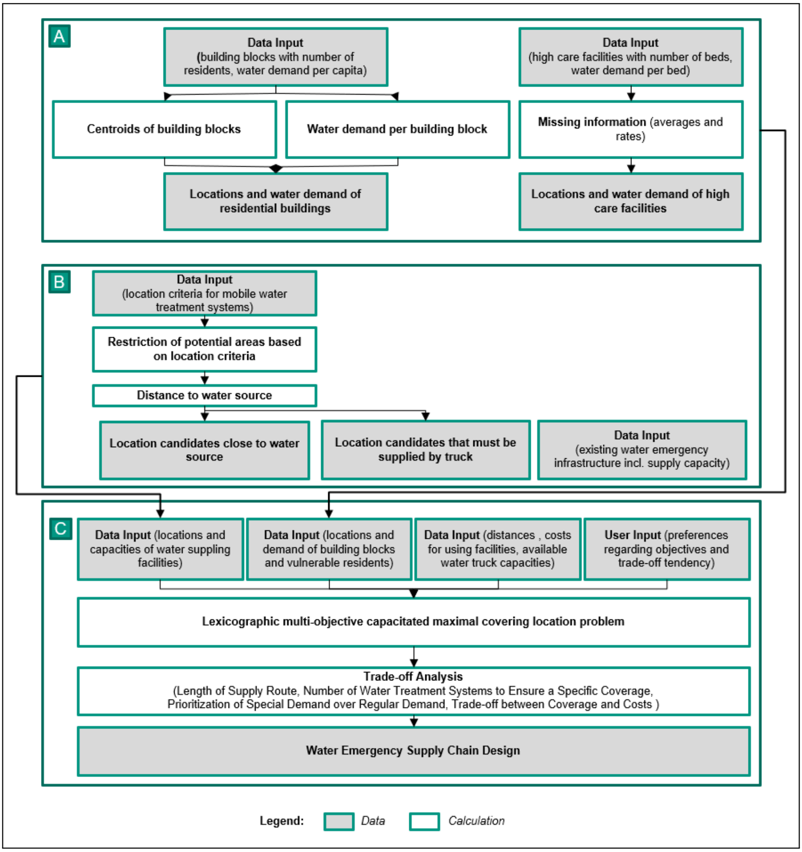

Figure D.2: Overview of the model and the decision making process. Water demand module (A) and Water supply module (B) provide data for the optimization module (C). The decision making process is based on a multi-objective optimization problem and trade-off analysis.

If emergency infrastructure exists, the model extends this by placing mobile water treatment systems. These two different facility types have both specific supply capacities. Multiple facilities can provide service for one demand point.

Chung, Schilling, and Carbone (1983) describe a basic formulation of CMCLP. Their basic formulation was extended by additional constraints leading to the following optimization model (see Table D.1 for a description of the components).

$$\text{maximize} \quad \sum_{i \in I} \sum_{j \in N_i} z_{ij} * a_i \tag{1}$$

$$\text{subject to} \quad \sum_{j \in N_i} z_{ij} \leq 1, \qquad \forall i \in I, \tag{2}$$

$$z_{ij} \geq y_{ij} * fd, \qquad \forall i \in I, \forall j \in N_i, \tag{3}$$

$$\sum_{i \in K_j} a_i * z_{ij} \leq c_j * x_j, \qquad \forall j \in J, \tag{4}$$

$$\sum_{j \in J} s_{jw} \leq c_w, \qquad \forall w \in WS, \tag{5}$$

$$\sum_{w \in W} s_{jw} \leq 1, \qquad \forall j \in J, \tag{6}$$

$$s_{jw} \leq al_{jw}, \qquad \forall j \in J, \forall w \in WS, \tag{7}$$

$$\sum_{w \in WS} s_{jw} \geq x_j, \qquad \forall j \in J, \tag{8}$$

$$\sum_{j \in J} x_j \leq p, \qquad \forall j \in J, \tag{9}$$

$$\sum_{j \in DWT} x_j \leq q, \qquad \forall j \in J, \tag{10}$$

$$z_{ij} \leq x_j, \qquad \forall i \in I, \forall j \in N_i, \tag{11}$$

$$y_{ij} \geq z_{ij}, \qquad \forall i \in I, \forall j \in J, \tag{12}$$

$$y_{ij} \leq z_{ij} * M, \qquad \forall i \in I, \forall j \in J, \tag{13}$$

$$x_j \in \{0, 1\}, \qquad \forall j \in J, \tag{14}$$

$$y_{ij} \in \{0, 1\}, \qquad \forall i \in I, \forall j \in J, \tag{15}$$

$$z_{ij} \geq 0, \qquad \forall j \in J. \tag{16}$$

The objective function of the CMCLP is to maximize the total demand covered (1). It is subject to the constraint that a demand point is satisfied by a water source that is located within a certain distance and receives an amount of water that is lower or equal to its total demand (2). Therefore, an oversupply is not possible. Moreover, constraint (3) establishes that the water allocated to a demand point is higher than a percentage that can be predefined dependent on the context of the case study. Trips for very small quantities of water are

Sets	
i	Index of demand points ($i \in I$)
j	Index of water supplying facilities ($j \in J$)
w	Index of water source ($w \in WS$)
N_i	Set of water sources within service standard of demand point i $\{j \mid d_{ij} < S\}$
K_j	Set of demand points within service standard of water supplying facility j $\{i \mid d_{ij} < S\}$
FT	Set of existing emergency supply locations {j | supplying facility j is part of the existing infrastructure}
WT	Set of available water treatment systems {j | supplying facility j is a water treatment system}
DWT	Set of available water treatment systems that must be supplied by trucks $\{j \mid j \in \text{WT and distance to water} > dW\}$
Parameters	
dW	maximal distance allowed for pump supply of water treatment system
d_{ij}	shortest distance between demand i and supply j
al_{jw}	binary allocation of supplying facility j to water source w
a_i	amount of demand at demand point i
c_j	capacity of water supply facility j
c_w	maximum number of water treatment systems that can be supplied by water source w
S	desired maximum distance between supply and demand
p	maximum number of water treatment systems to be placed in total
q	maximum number of water treatment systems that can be supplied by available trucks
f	minimum percentage of demand that must be supplied by an allocated facility within the service standard
M	Big number with M > 1,000
Decision variables	
x_j	$\begin{cases} 1, \text{ if water treatment system is located at j} \\ 0, \text{ otherwise} \end{cases}$ $\quad j \in WT$
x_j	1 $\quad j \in FT$
y_{ij}	$\begin{cases} 1, \text{ if demand i is allocated to facility j} \\ 0, \text{ otherwise} \end{cases}$
s_{jw}	$\begin{cases} 1, \text{ if location j is allocated to water source w} \\ 0, \text{ otherwise} \end{cases}$
z_{ij}	percentage of demand i assigned to facility j

Table D.1: Notation of sets, parameters and variables used in the optimization model.

thereby eliminated. Therefore, people are sure that if they take a trip to a water supply facility, they will get an adequate amount of water. Due to this combination of constraints, the demand can be covered or partially covered by one or multiple sources within an acceptable distance.

Water supplying facilities have a predefined capacity that must not be exceeded (4). In addition, constraint (5) ensures that the capacities of water sources are not exceeded by the number of water treatment systems placed next to it. Each location is allocated to one water source (6) while the allocation is only possible if it is feasible with respect to other emergency systems placed at the same water source (7). Constraint (8) establishes that if a water treatment system is placed at a location, this location must be allocated to a water source.

A maximal number of p water treatment systems can be sited (9), of which q can be placed further away from water than a specified distance (10). Constraint (11) restricts the allocation of demand to available emergency infrastructure and locations where a water treatment system has been placed.

Constraint (12) defines a lower bound and constraint (13), an upper bound for the decision variable y_{ij}. Constraints (14) to 16 define the range of values of the decision values.

Due to the constraints described above, it is possible that the available resources are not sufficient to supply a desired proportion of the population. In Section D.6.2, we discuss this issue and suggest a model to analyze this further if decision makers want to extend their analysis in this direction.

Furthermore, the problem is extended to a multi-objective problem that is solved using a lexicographic approach, optimizing the objectives coverage and costs in a defined sequence. This enables the investigation of possible trade-offs between different objectives (Farahani, SteadieSeifi, and Asgari 2010). Table D.2 introduces additional parameters to enable the trade-off analysis.

In general, a lexicographic solution approach optimizes multi-objective problems sequentially in a predefined order and, therefore, it is based on the preferences of the decision maker. The present model assumes that the decision maker prioritizes coverage higher than cost in the case of a terror attack or emergency. The coverage is optimized while the cost objective is not considered. If multiple solutions result in an optimal coverage, the cost objective is optimized within the determined solution space (Nickel, Stein, and Waldmann 2011). An objective attainment degree can extend this approach. Table D.2 introduces the parameter *perCov* that represents an objective attainment degree and allow deviation from the optimal solution of the demand covered to enable possible cost savings.

Parameters	
	Multi-Objective Optimization
perCov	attainment degree of optimal coverage solution (percentage)
	Costs
costEW	daily cost of operating existing emergency water supply infrastructure (FT)
costLW	daily cost of operating a water treatment system not supplied by trucks ($WT \setminus DWT$)
costLC	daily cost of operating a water treatment system supplied by trucks (DWT)
	Number of Water Treatment Systems
perTotalCov	percentage of the total demand that must be covered

Table D.2: Extended notation to enable trade-off analysis: Multi-objective optimization approach, inclusion of costs and analysis of water treatment systems needed to achieve a defined coverage.

The following equations (17) to (18) display the additions to establish the subsequent cost minimizing optimization run.

$$\text{minimize} \quad costEW * \sum_{j \in FT} x_j + costLW * \sum_{j \in WT} x_j + costLC * \sum_{j \in DWT} x_j \tag{17}$$

$$\text{subject to} \quad \sum_{i \in I} \sum_{j \in N_i} z_{ij} * a_i = perCov * \text{Optimal Coverage} \tag{18}$$

The first step of the lexicographic solution approach maximizes the demand covered as defined in equations (1) to (16) and the optimization approach described above. The coverage of its optimal solution is then set to the objective attainment degree in equation (18). The second step of the approach is minimizing the associated cost for the given coverage. Therefore, objective function (17) is introduced. Constraint (18) enforces that the set coverage is achieved. The full optimization model for minimizing the total costs also includes constraints (2) to (16).

D.4. Case Study

In the following, the consequences of a hypothetical terrorist attack on the water supply infrastructure of Berlin, Germany, is investigated. The city of

Berlin is assumed to be a prestigious target for a terrorist attack, as it is the capital of Germany, with over 3 million registered residents (Amt für Statistik Berlin-Brandenburg 2019) in the center of Europe. Therefore, the city is a suitable case study for the application of the introduced optimization model and for planning an emergency water supply chain.

D.4.1. Berlin and its Emergency Management Processes

According to the Berliner Wasserbetriebe (2019), the average water consumption of a Berlin resident is a total of 110 liters per day. Drinking water and water used to prepare food are 5.5 liters, whereas most of the water is used for personal hygiene or sanitary facilities. Water supply is ensured by nine waterworks that gain water from bank filtrate, which is extracted indirectly from surface water. Its quality depends on the condition of lakes and rivers next to the waterworks (Hiscock and Grischek 2002). Thus, if the surface water is contaminated, there is a possibility of a disruption of the public water supply (Möller and Burgschweiger 2008).

The responsibility of water supplying companies includes preventive measures for strengthening the safety of the public water supply (BBK 2016a). If a disruption or failure of the public water supply can no longer be controlled by the water supply company, the municipality, district, or state may assist with alternative supply measures (BBK 2016a). In that case, federal agencies like the THW are deployed, and existing emergency infrastructure is activated (BBK 2016b).

The THW can provide mobile water treatment systems to establish an emergency supply. The deployment of these systems results in the need for alternative water sources providing water to gain drinking water. In the city of Berlin, surface water is a valuable water source for purification systems, since it is easily accessible due to significant water surfaces (58.48 km^2) in and around the city (Amt für Statistik Berlin-Brandenburg 2018). Surface water is usually the most polluted water, leading to stricter requirements for purification technologies (Dorea et al. 2009). If there is no time to identify possible contaminants within the water, a purification system that purifies a broad spectrum of contaminants should be preferred. Riley, Gerba, and Elimelech (2011) recommend the use of multi-barrier techniques. This technique is, for instance, included in the *UF-15* system of the THW (Al Naqib 2019).

Consequently, different levels of contamination can be purified simultaneously, allowing supply to the UF-15s from various sources of water around Berlin. Depending on the severity of the emergency, using multiple sources such as lakes, rivers, or even ground water can increase the available capacity while simultaneously not depleting single local water resources.[2]

Groundwater is usually the preferred source due to less exposure to contamination than surface water (Doerner, Gutjahr, and Nolz 2009). Emergency water wells ensure the availability of groundwater in Berlin during disruptions of public life and water supply shortages (Fischer and Wienand 2013). According to Fischer and Wienand (2013), there are more than 900 emergency wells in the city of Berlin.

D.4.2. Emergency Scenario

The investigated emergency scenario comprises the failure of the public water supply of the city of Berlin after a terrorist attack on the waterworks of the city. As time is needed to run different detection methods to identify the contaminants, the water supply is shut down and an emergency water supply network has to be established in the meantime.

We assumed that the groundwater is not contaminated. Therefore, the emergency water wells can be operated. The large water surfaces of the city of Berlin are additional water sources, but treatment systems are needed to ensure drinking water quality. The UF-15 treatment systems of the THW are used to extend the existing infrastructure of emergency wells. The water is distributed at the wells and treatment systems. The locations of the wells are fixed, whereas the UF-15 systems can only be placed at locations that fulfill specific requirements (see Section D.4.3.3).

We assumed that besides the public water supply, no other public infrastructure like roads or power supply was attacked. Roads are accessible and power is available everywhere. The accessible roads imply that neighboring communities or other federal states could provide help by supplying bottled water, water tanks, or other resources. The supply of bottled water is not evaluated since it is not under control of the local authorities. However, knowledge

[2] Note that cities with only one source of water (e.g. Las Vegas with Lake Mead) cannot take advantage of this increased flexibility.

and equipment stationed in other federal states are deployed and increase the available capacities of the authorities. The running power supply implies that wastewater treatment systems can be used for the disposal of sewage. Therefore, the water sources will not get contaminated with wastewater.

During the crisis, all businesses in the need of drinking water stay closed as their constant water supply cannot be guaranteed (e.g. hairdresser, ...). However, food supply, pharmacies, hospitals (critical infrastructure) and businesses in the service sector remain opened. Residents are informed in time so that there is no increase in diseases or other sufferings due to consumption of contaminated water. Since the attack was not expected, we assume that private households did not store additional water to complement the emergency water supply.

D.4.3. Data Collection

The data collected consists of the demand structure, the available emergency wells, location candidates for available water treatment systems and distances between supply and demand. The following subsections provide an overview of the data while details of the collection and processing can be found in the supplementary material.

D.4.3.1. Demand Structure

In Germany, the First German Water Securing Regulation (1. WasSV) determines the amount of water that must be provided to the public in case of an emergency. It distinguishes between regular persons and persons in highly vulnerable facilities. In our context, we regard hospitals or nursing homes as vulnerable facilities, as suggested by the Inter-Agency Standing Committee (IASC 2010) and the Active Learning Network for Accountability and Performance in Humanitarian Action (Sanderson, Knox-Clarke, and Campbell 2012). Regular persons are supplied 15 liters per day while persons in highly vulnerable facilities are supplied 75 liters per day. Residents of vulnerable facilities are provided with 150 liters of water per day if it is an intensive care facility.

Within the attached supplementary material, the collection and processing of the data to establish discrete demand points for the different demand types is described in detail. The emergency water demand of the regular residents is 56.23 million liters per day, whereas the demand of high and intensive care facilities is 6 million liters per day. It has to be mentioned that people also store water at home that, in theory, reduces the required amount of water that authorities need to deliver to ensure the well-being of their population. However, we still regard the full demand of water due to observations made during the first wave of the COVID19-pandemic. Since people panicked and started to purchase goods that the they did not directly need (e.g. toilet paper), we assume that people would still try to receive water if they need it and the state offered it to them for free.

To avoid unnecessary trips, a predefined percentage ensures that, if demand is allocated to a water supplying facility, an adequate amount of water is supplied per person. We assume that a threshold of 20% of the German standard for water quantity is suitable, resulting in 3 liters per person and day. This is in line with Sphere Project (2018), that defines 3 liters as the absolute minimum in the aftermath of a disaster.

The analysis of demand is limited to the stated types of facilities. Water supply for schools, food suppliers, or industry is not investigated due to the assumption that these facilities are closed during the response phase.

D.4.3.2. Emergency Wells

The emergency water supply chain combines existing infrastructure with mobile water treatment systems. The existing infrastructure for water emergencies includes 1,028 emergency wells that are placed throughout the city of Berlin. Their average drinking water output is 90,000 liters per day and well (Langenbach and Fischer 2008).

The supplied water will be disinfected with chlorine if needed (Langenbach and Fischer 2008). It is assumed that the legal maintenance procedures have been followed and that, therefore, all emergency water wells considered in the optimization model can be accessed and operated. If this would not be the case, the model parameters can be easily updated and the optimum locations of water treatment systems for maximum coverage can be recalculated.

The daily costs associated with the operation of an emergency water well are separated into personal costs and costs associated with equipment and consumables. Table D.3 summarizes the estimated expenses that amount to a rounded 10,700 € per day per operated well. Based on the assumption that all 1,028 emergency wells are operated during the maximum of 12 hours per day, fixed supply costs of 11,308,000 € per day arise that can not be influenced by the model. The details of the calculation are outlined in the supplementary material.

Cost Driver	Expenses		Quantity	Sum	Source
		Personal Costs			
Volunteer THW	22.00 €	per hour	12	3,960,00 €	THW (2012b)
		Equipment Costs			
Drinking Water Laboratory	18.20 €	per day	1	18.20 €	THW (2012b)
		Consumables Costs			
Disinfectant	0.075 €	per 1 liter	90,000	6,750.00 €	Träger (2019)
Sum				10,728.20 €	

Table D.3: Daily costs of operating one emergency water well.

D.4.3.3. Mobile Water Treatment Systems

The THW has 14 drinking water specialist groups, each of which has a UF-15 drinking water treatment system.[3] Since the THW is under the control of the German Ministry of Interior, authorities can control the availability and maintenance of UF-15. Therefore, there is no competition with private stakeholders who want to support their processes by purifying water themselves. And, if a water treatment system would be unavailable, e.g. due to an unexpected breakdown, the model parameters can be easily updated and the optimum locations of water treatment systems for maximum coverage can be recalculated.

The UF-15 treats well or surface water using ultrafiltration with a capacity of 15 m^3 per hour (Al Naqib 2019). The operating time of the system is 20 hours per day, which yields 300,000 liters of water per system and day (THW 2012a). The treated water meets the drinking water quality standards of the drinking water ordinance (BRD 2018).

Furthermore, we define the following location criteria (Table D.4):

[3] According to email exchange with THW.

Criterion	Description	Value	Source
Access to water	Ability to feed water treatment systems with water must be ensured. Therefore, it must be possible to bridge the distance between water source and system with a pump. Alternatively, delivery by truck can be ensured by the proximity of the road network.	1,200 meters	Corsten and Gössinger (2016), Feuerwehrschulen Bayern (2018)
Access road network	Transportation of water to the water treatment system must be possible if it can not be supplied water by pump. Therefore, the maximal distance to next road must not exceeded the maximal distance a pump can bridge.	1,200 meters	Corsten and Gössinger (2016), Feuerwehrschulen Bayern (2018)
Distance to demand	Location candidates must be within the maximal allowed supply routes to at least one demand point	2,000 meters	EPA (2011), Fischer and Wienand (2013)
Available area	Operating site must have a minimum size	60 x 60 metres	EPA (2011)

Table D.4: Location criteria for location of water treatment systems.

According to EPA (2011), an emergency response site should have an area of more than 60 x 60 meters in size, which is also used as criterion for the needed water system operating area. The locations must be accessible by road to enable deployment and transportation to and from the site. Since the water treatment system is also used as a distribution station, locations should be close to demand points (EPA 2011).

The location should also have access to a raw water source (Corsten and Gössinger 2016), which can provide a water feed of $15m^3$ per hour. The usage of a maximum of one pump per water treatment system is assumed. It can generate the required flow rate up to the distance of 1,200 meters. The available number of pumps and their pump capacities separates locations into locations that can be supplied by pump only and locations that must be supplied with additional measures. These measures include supplying raw water by tank truck to site. In the supplementary material, we determined that we need two trucks to supply one treatment system. The THW has 14 trucks with the needed capacities, limiting the operable number of water source distant treatment systems to seven.

The criteria described above were used to process data provided by Berlin's Geoportal (Berlin 2019c). The identified location candidates are separated into two sets: the first set is within a distance of 1,200 meters to a water source and can be supplied by one water pump, while locations in the second set need additional measures to be feasible candidates. The set of locations that can be supplied with a pump contains 2,403 locations. The set that contains the locations that need alternative supply measures contain of 157 additional locations.

Cost Driver	Expenses		Quantity	Sum	Source
		Personal Costs			
Volunteer THW	22.00 €	per hour	18	7,920,00 €	THW (2012b)
		Equipment Costs			
Pumps	35.00 €	per day	4	140.00 €	THW (2012b)
Power Generator	4.77 €	per hour	1	95.40 €	THW (2012b)
Water Tanks	7.70 €	per day	12	92.40 €	THW (2012b)
Drinking Water Laboratory	18.20 €	per day	1	18.20 €	THW (2012b)
UF-15	884.00 €	per day	1	884.00 €	THW (2012b)
Sum				9,150.00 €	

Table D.5: Daily costs for operating one mobile water treatment system.

Table D.5 highlights the estimated expenses per day for the operation of an UF-15 system. The estimation includes personal and equipment costs. The total daily operating costs are around 9,200 € per system if it is placed next to a water source. If tank trucks have to be deployed, the costs increase to 10,300 € due to additional personal costs as well as costs for the trucks and fuel. For a detailed overview of the data collection and processing see the supplementary material.

D.4.3.4. Supply Route

We define the distance between supply and demand points as *supply route*. This supply route represents the service standard and is used to select locations for water treatment systems. Within the case study, supply routes between interacting points are calculated using the Euclidean distance. However, the assumption of direct links is not applicable when considering overland routes. Therefore, a tortuosity factor of $\sqrt{2}$ is introduced to embrace real road conditions (Delivand 2011; Diehlmann et al. 2019).

According to Langenbach and Fischer (2008), reasonable supply routes in the context of emergency water wells are between 500 and 2,000 meters.

We assume this also applies for the supply with water treatment systems. Therefore, the maximum service standard is examined for a supply route of 1,250 meters, evaluating an intermediate scenario. A sensitivity analysis for different supply routes lengths follows in the Section D.6.

D.4.3.5. Data summary

Table D.6 provides an overview of the collected data for the case study. It includes the parameter settings for the optimization runs. As already mentioned, the collection and processing of the used data can be found in the supplementary material.

D.5. Results

This chapter summarizes the results of the optimization. The optimization model is implemented in GAMS and solved with the CPLEX-solver.[1]

D.5.1. Computation of Model Input Parameters

Figure D.3 provides an overview of the water demand per planning area of the city of Berlin. The darker the shade of the planning areas or the larger the circles, the higher the demand in the area. The figure highlights that special care facilities are often placed within the city center, while the general demand is distributed rather equally within the city.

Moreover, we identified 2,560 potential locations to place mobile water treatment systems. Of these possible locations, 2,403 are near (<2 km) a water source, so that a water treatment system can directly be supplied. In Figure D.4, these areas are highlighted (green). In addition, there are 157 potential locations that require supplies by tank trucks (red).

[1] With a tolerated MIP-gap of 0.5%.

Parameter	Value	Source
Optimization Parameters		
Distance to water (dW)	1,200 meters	Feuerwehrschulen Bayern (2018)
Desired maximum distance between supply and demand (S)	1,250 meters	Fischer and Wienand (2013)
Number of available water treatment systems (UF-15 units) (p)	14	Email exchange with THW
Maximum number of water treatment systems that can be supplied by trucks (q)	7	Wisetjindawat et al. (2014), Email exchange with fire brigade Berlin and THW
Minimum percent of demand supplied per trip (f)	20%	Sphere Project (2018) BRD (1970)
Operating Costs Water emergency wells ($costEW$)	10,700 € per day	THW (2012b), Träger (2019)
Operating Costs Water Treatment Systems ($costLW$)	9,200 € per day	THW (2012b)
Operating Costs Water Treatment Systems further away from water source ($costLC$)	10,300 € per day	THW (2012b), Statistisches Bundesamt (2019)
Spatial Demand Structure		
Number of regular demand points	14,755	Berlin (2019a)
Number of special demand points (hospitals, nursing homes, sheltered housing)	529	Berliner Krankenhausgesellschaft e.V. (2019), Privatinstitut für Transparenz im Gesundheitswesen GmbH (2019)
Emergency Wells		
Number of operated emergency water wells (FT)	1,028	Geofabrik GmbH (2019)
Daily drinking water supply (c_j)	90,000 liters per well	Fischer and Wienand (2013)
Mobile Water Treatment Systems		
Location candidates next to surface water (WT)	2,403	EPA (2011), Corsten and Gössinger (2016), Fischer and Wienand (2013), Feuerwehrschulen Bayern (2018), Berlin (2019b)
Location candidates that must be supplied by trucks (DWT)	157	Wisetjindawat et al. (2014), email exchange fire brigade Berlin, email exchange THW
Daily drinking water supply (c_j)	300,000 liters per system	THW (2012a)
Distance		
Distance Calculation	Euclidean Distance	Mwemezi and Huang (2011)
Tortuosity factor	$sqrt(2)$	Diehlmann et al. (2019)

Table D.6: Overview of relevant input data for the optimization model.

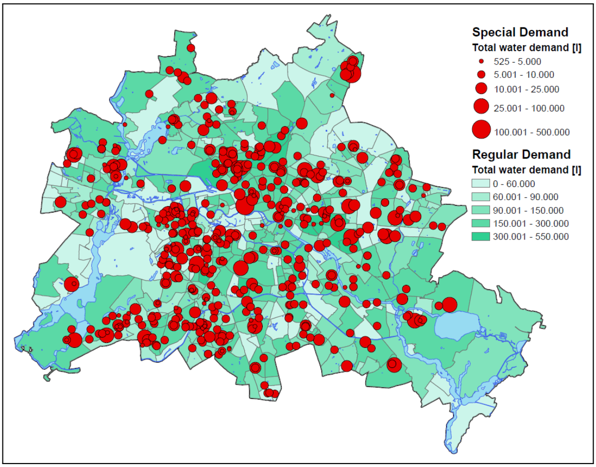

Figure D.3: Map of water demand of regular residents and high care facilities in the city of Berlin. The demand of the residents is aggregated to planning areas of the city. The different colors represent the total water demand in liters [l].

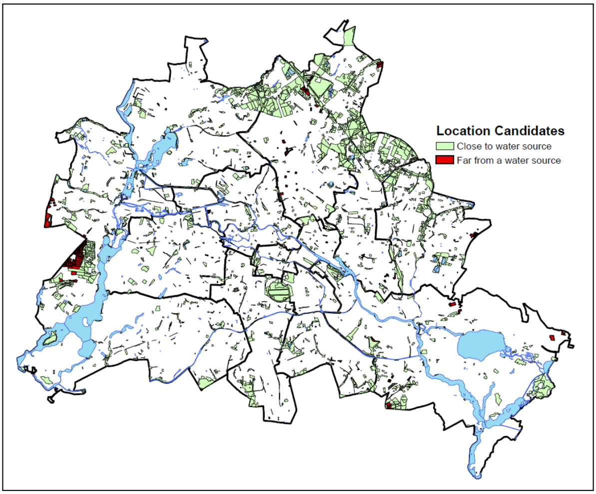

Figure D.4: Map of location candidates for placing water treatment systems in the city of Berlin. The locations are distinguished according to their distance to the closest water source.

D.5.2. Location Analysis

D.5.2.1. Optimal Locations that Maximize Covering

Figure D.5 displays the results of the single objective model with the parameters and input data stated above. The regular demand points as well as special demand points in central areas with a high population density are mostly covered. This is a result of the high number of emergency water wells in this area. Without additional water treatment systems they cover a total demand of 77%.

The treatment systems are placed in the outer districts of Spandau, Pankow, Reinickendorf, and Marzahn-Hellersdorf, where the number of emergency wells is lower. All 14 available water treatment systems are placed within close distance to an adequate water source. The systems increase the demand covered by seven percentage points leading to a coverage of 84% of the total demand.

The total costs associated with the emergency response are 11,128,400 € per day resulting from operating the 1,028 emergency water wells and 14 water treatment systems.These high costs indicate the need of a multi-criteria optimization approach including a cost criterion.

D.5.2.2. Optimal Locations for Cost-efficient Maximum Covering

A cost-efficient emergency supply enables the investment of saved resources in other areas of the emergency response.

The results of the proposed lexicographic two-step approach are comparable to the results of the single objective model with a coverage of 84%. Because other locations in the outer districts of Spandau, Pankow, Reinickendorf, and Marzahn-Hellersdorf have been chosen, the solution space for the optimal coverage does not seem to be bijective. However, within the solution space, no solution is more cost-efficient than the one found with the single objective model. Therefore, the total costs associated with the lexicographic optimization are also 11,128,400 € per day. The high operation costs are caused by the emergency water wells and the assumption that all are operated. These fix costs amount to a rounded 11,000,000 € and cannot be influenced by the model design and decision variables.

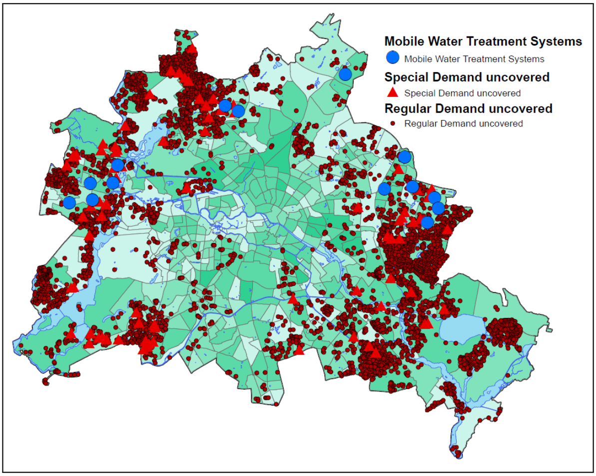

Figure D.5: Map of regular and special demand points left uncovered, considering a maximum supply route of 1,250 meters.

D.5.2.3. Prioritization of Special Demand over Regular Demand

As mentioned above, decision makers try to prioritize the highly vulnerable demand points in disaster relief. To investigate the effects of such a prioritization of demand types, the lexicographic CMLCP is slightly modified: the gradual optimization of coverage and costs is replaced by the gradual optimization of special and regular demand covered. Therefore, the objective function of the CMCLP is split into covering high care facilities and covering regular demand points. The model assumes that the decision maker prioritizes the demand of high care facilities. Therefore, the objectives are optimized in this order.

The result of the modified lexicographic approach is a total coverage of 81% covering 91% of the demand of high care facilities and 80% of the regular demand. The costs are 11,129,500 € resulting from operating 1,028 emergency water wells, 13 water treatment systems close to a water source and one water treatment system that has to be supplied by truck. The map shows that some of the mobile systems are placed in more central districts like Mitte, Friedrichshain, Charlottenburg, Tempelhof, and Steglitz (see Figure D.6). This

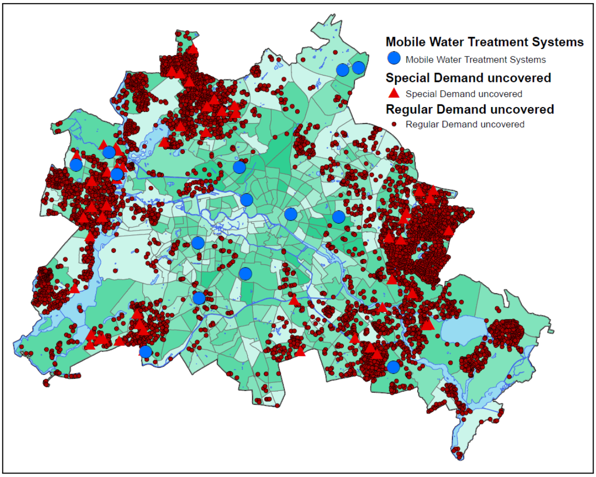

Figure D.6: Map of locations of mobile water treatment systems placed when prioritizing high care facilities.

emphasizes the prioritization of the special demand in this area, as high care facilities that were only partially supplied are now being fully supplied.

D.6. Discussion

This section discusses the generated results and highlights trade-offs between different objectives. The design and assumptions of the model are also critically reviewed.

D.6.1. Length of the Supply Route

The maximum length of the supply route impacts the total demand coverage (Figure D.7). In the diagram, the length of the supply route ranges between 500 meters and 2,000 meters (as suggested by Langenbach and Fischer (2008)). While shorter supply routes decrease the travel distance of a supplied person, longer maximal supply routes increase the total coverage.

The results show that a short maximum supply route leads to a considerably low coverage of 63%. The coverage increases by 12 percentage points when the maximal length allowed is set to 750 meters. Within the defined value range, the maximal total coverage is 88%.

As coverage is strongly influenced by the supply route, a short supply route reduces the chance that demand can be allocated to a facility within the defined maximum length of the supply route. However, we can also see that prolonging the supply route from 1,250 to 2,000 meters only gains 4% additional coverage. Thus, the decision maker has to determine a reasonable length for the supply routes.

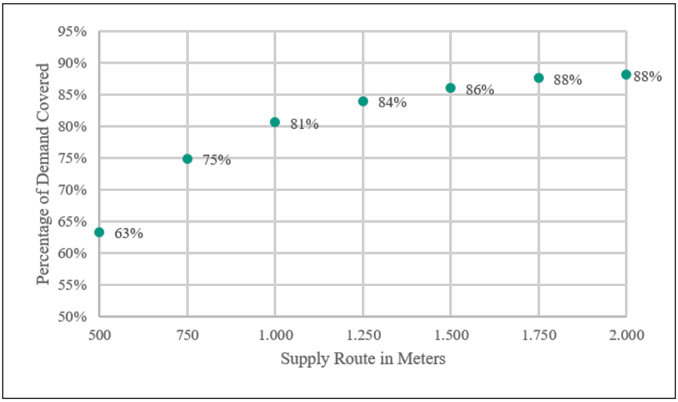

Figure D.7: Achievable coverage dependent on the maximum length of the supply route.

Within this paper, the distance is determined by the linear distance between two points and a tortuosity factor. Thus, the distance between supply and demand is only an approximation. Determining the distance based on a network length could increase the accuracy of the results.

D.6.2. Number of Water Treatment Systems to Ensure a Specific Coverage

To increase the supply, it is possible to purchase additional purification systems at additional cost. Therefore, we analyzed the number of necessary systems to provide predefined coverage with the help of a capacitated location set covering problem (CLSCP). The optimal and capacitated version of the prototypical LSCP is described by Church and Murray (2019). The introduced notation is extended by the parameter $perTotalCov$ introduced in Table D.2, which determines the percentage of the total water demand that must be covered.

The CLSCP is locating the minimum number of facilities needed so that the defined coverage can be reached (Church and Murray 2019). Thus, the objective function 19 minimizes the number of placed facilities. Compared to the prototypical formulation by Church and Murray (2019), total demand must not be fully covered in our case since total coverage only has to be higher than a predefined percentage described by constraint 20. Therefore, not every demand point must be covered within the service standard (21). The other constraints are equal to the constraints formulated for the CMCLP. Therefore, they are not further discussed.

$$
\begin{aligned}
\text{minimize} \quad & \sum_{i \in WT} x_j && (19)\\
\text{subject to} \quad & \sum_{i \in I} \sum_{j \in N_i} z_{ij} * a_i \geq perTotalCov * \sum_{i \in I} a_i, && (20)\\
& \sum_{j \in N_i} z_{ij} \leq 1, \qquad \forall i \in I, && (21)\\
& z_{ij} \geq y_{ij} * f, \forall i \in I, \forall j \in N_i, && (22)\\
& \sum_{i \in K_j} a_i * z_{ij} \leq c_j * x_j, \forall j \in J, && (23)\\
& \sum_{j \in J} s_{jw} \leq c_w, \qquad \forall w \in WS, && (24)\\
& \sum_{w \in W} s_{jw} \leq 1, \qquad \forall j \in J, && (25)\\
& s_{jw} \leq al_{jw}, \qquad \forall j \in J, \forall w \in WS, && (26)\\
& \sum_{w \in WS} s_{jw} \geq x_j, \qquad \forall j \in J, && (27)\\
& z_{ij} \leq x_j, \qquad \forall i \in I, \forall j \in N_i, && (28)\\
& y_{ij} \geq z_{ij}, \qquad \forall i \in I, \forall j \in J, && (29)\\
& y_{ij} \leq z_{ij} * M, \forall i \in I, \forall j \in J, && (30)\\
& x_j \in \{0, 1\}, \quad \forall j \in J, && (31)\\
& y_{ij} \in \{0, 1\}, \quad \forall i \in I, \forall j \in J, && (32)\\
& z_{ij} \geq 0, \qquad \forall j \in J. && (33)
\end{aligned}
$$

Since the introduced CLSCP determines the required number of water treatment systems to reach a predefined percentage of total coverage, the relationship between both is analyzed. The nonlinear trade-off curve shows that there is no feasible solution for full coverage while considering only the identified locations to place the mobile treatment systems (Figure D.8).

The maximal possible coverage is 99% with 116 required water treatment systems. The existing infrastructure of emergency water wells is covering 77% of the total demand. A high number of water treatment systems is needed to yield a significant increase in coverage.

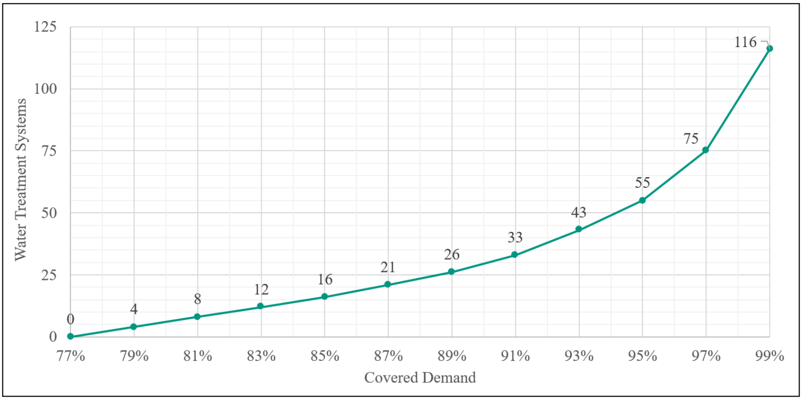

Figure D.8: Number of water treatment systems required to reach a targeted coverage.

In the case study, only 14 systems are available increasing the coverage to 84%. The purchase and deployment of additional water treatment systems for the THW is therefore an option to increase the demand coverage. However, a small number of additional systems would only lead to a small increase of coverage. Moreover, the decision makers have to decide if an increase in coverage is worth the associated costs or if the money could be spend more efficient in other ways.

Reasons why full coverage cannot be achieved may result from data quality and data preparation. Moreover, it is possible that individual persons cannot be reached within the approved lengths for the supply route. This could include, for example, the inhabitants of the islands in Lake Tegel, as they are isolated.

Figure D.8 also indicates the importance of the existing emergency wells, which can be accessed easily. Eliminating the capacities of the wells results in a coverage of 7% deploying the currently available 14 water treatment systems. The highest possible coverage without wells is 99%. 1,596 mobile treatment systems with an average utilization rate of 7% are required.

This demonstrates the importance of the existing emergency water wells. Mobile water treatment systems are not suitable to reach full coverage by themselves and the existing network of emergency wells should be extended.

D.6.3. Relaxation of Constraints for the Prioritization of Special Demand

The objective attainment degree allows a deviation from the optimal solution to investigate the possible trade-off between coverage of special and regular demand. This degree defines the minimum value of the optimal solution that must be reached. The attainment degree of 100% yields an optimal coverage for the special demand of 91%. For this solution, the regular demand covered is 80% resulting in a total coverage of 81%. By lowering the attainment degree, it is possible to cover more regular demand points (Figure D.9).

We see that the total coverage varies little within the analysis. The optimal total coverage of 84% is reached with an attainment degree of 95%. With this attainment degree, 87% of the special demand and 83% of the regular demand is covered. The coverage of the regular demand is close to its possible maximum of 86%.

The results show that the impact of the special demand on the total coverage is smaller than the impact of the regular demand. This results from the lower total demand at high care facilities, which account for 10% of the total demand. The optimum coverage of the total demand decreases only slightly when high care facilities are prioritized. The decision maker has to decide if the prioritization is worth this difference.

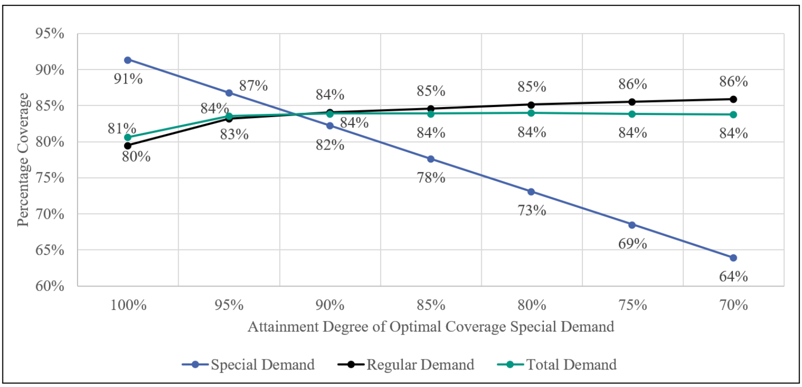

Figure D.9: Trade-off between coverage of high care facilities and coverage of regular residents.

D.6.4. Trade-off Between Coverage and Costs

In the following Subsection, we analyze the trade-off between coverage and costs. However, we want to point out that this does not hint that authorities would not try to supply as many people as possible. A reduction of cost could also mean that authorities make resources available for other measures that support the population as well. For example, authorities could increase the total supply to the population if a comparably small loss in coverage by the treatment systems saves enough money to purchase a truck full of bottled water. Even though it can be discussed that Berlin's authorities could count on more or less unlimited financial support of the state in such a severe disaster, this probably does not apply to some authorities in developing countries or Non-Governmental-Organizations (NGOs) working on a budget.

The trade-off curve between optimum coverage and flexible daily costs shows that a deviation from the optimal coverage enables potential cost savings (Figure D.10). The flexible daily costs associated with the optimal coverage are 128,800 € (14 mobile purification systems * 9,200 € per day).

The reduction of the attainment degree to 99% leads to cost savings of 9,200 € while 83% of the total demand is covered. Further reduction of the attainment degree leads to a linear decrease of the daily costs. This trend is interrupted between the attainment degree of 95% and 94% before continuing linearly after 94%. With the reduction of the attainment degree below 93% no water treatment systems are placed, and water is only provided with the existing emergency infrastructure.

In the linear parts of the trade-off curve, the decision maker has to decide whether cost savings of 18,400 € are worth it to lose 522,414 liters of water, which could supply more than 34,000 residents. The trade-off curve, therefore, provides the decision maker with a higher transparency regarding the consequences of his or her decision. Consequently, he or she can derive more efficient and well-informed decisions on the deployment of water treatment systems, and use the available budget as efficient as possible.

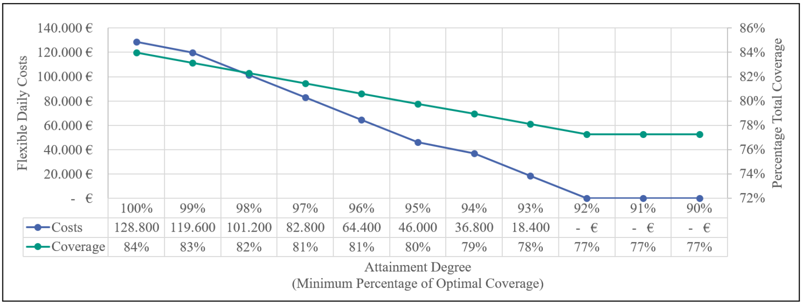

Figure D.10: Trade-off between cost and coverage displayed based on the attainment degree of the solution for optimal coverage.

D.7. Conclusion and Research Outlook

The design of an emergency water distribution system represents a difficult challenge for authorities. A variety of trade-offs has to be regarded for an efficient solution. To support public decision makers in this process, we developed a capacitated maximal covering location model based on georeferenced data that maximizes the water demand covered, followed by a cost minimization step.

We applied the approach to a case study in the city of Berlin, Germany. Therefore, we extended the model with a multi-objective approach to regard various trade-offs. For example, we showed that a prioritization of special demand suggests completely different locations for the mobile treatment systems. Moreover, we increased cost transparency by the investigation of the trade-off between cost and coverage. This enables the decision maker to know the effective price (or opportunity cost respectively) of additional water supply facilities in an emergency.

It can be concluded that the deployment of mobile water treatment systems extending existing infrastructure increases the covered water demand and the supply of suffering people significantly. Thereby, a high spatial density of existing emergency infrastructure is the basis for a high coverage within reasonable supply routes. In Berlin, this is demonstrated by a close network of wells within the city center, already covering 77% of the total demand. The deployment of additional 14 mobile water treatment systems increased the total demand covered by only seven percentage points to 84% of the total demand. Furthermore, a supply based on mobile water treatment systems alone resulted in a total coverage of 7%. Mobile systems are associated with additional costs, leading to the key trade-off between coverage and costs.

However, the case study did not regard uncertainties like the functionality of a well or the availability of treatment systems. Even though legal maintenance procedures both on water treatment systems and emergency wells are implemented, there is still a risk of water treatment system or well failure. Therefore, the effects of possible malfunction could be analyzed a priori with the help of a Monte Carlo Simulation or two-stage stochastic programming in a follow-up study or could be covered posteriori by another model run with respectively updated data. Moreover, it is reasonable to expect a significant time delay between the start of the crisis and the availability of all treatment systems. Therefore, a stochastic or dynamic extension of the model could provide valuable information.

Another extension could be to take the geographic distribution of stockpiled water into consideration and locate the adjusted demand. One example could be that people with larger apartments are more likely to store water at home than people with small apartments (Bell and Hilber 2006). Integrating the adjusted demand into the developed model consisting of wells and mobile water treatment systems might further increase the applicability to the real world. Furthermore, the adjusted demand might lead to higher coverage rates.

In addition, most of the used data is publicly available. Therefore, the data (and cost data in particular) could be further validated by experts and adjusted to the way costs are invoiced or distributed in disaster management practice. Requests to validate the cost estimations led to the surprising situation that different organizations and authorities could not provide us with real data, but instead, reciprocally referred to each other. This hints towards a general cost-transparency problem, which could be addressed in future studies.

In spite of the aforementioned challenges, the approach has the potential to significantly increase the transparency of decisions for decision makers and therefore improve the efficiency of disaster relief management.

D.8. Acknowledgements

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E. On the Value of Accurate Demand Information in Public-Private Emergency Collaborations

Abstract[1]

In cases where the private sector struggles to cope with the impact of a disaster, authorities try to reduce the burden on the population and set up supply chains to distribute essential goods. Therefore, they estimate demand and location of the affected people and open points of distribution to supply goods from, e.g. public buildings or sports facilities. However, the location of these points of distribution depends heavily on accurate demand estimations. Combined with a high time pressure that prevents the collection of detailed data, inefficient decisions result. However, these decisions improve significantly if private actors share their market knowledge. Since this information is strictly confidential for companies and at the same time requires a lot of coordination effort from public actors to acquire, the quantification of the benefits of the collaboration is important for both sides. Moreover, the time at which the information is received and the way the information is utilized regarding different intervention intensities is supposed to be crucial. Therefore, we develop a framework to quantify the consequences of shared information for both actors and apply it to a case study for a tap water contamination in the city of Berlin. We highlight that both actors benefit from the collaboration

[1] This chapter includes the preprint of the article "On the Value of Accurate Demand Information in Public-Private Emergency Collaborations" by Miriam Klein, Marcus Wiens, Markus Lüttenberg, Frank Schultmann, and myself (Diehlmann, Klein, et al. 2020).

and that the time the information is received has a comparably low effect on the total supply. Moreover, we show that private actors can reduce the impact of market interventions on their processes significantly by actively collaborating with authorities.

E.1. Introduction and Motivation

While private actors manage the distribution of goods in peacetime, public authorities are responsible for guaranteeing sufficient supply to the population in times of crisis. Therefore, they need to establish new supply chains in a complex and uncertain environment (Holguín-Veras, Jaller, et al. 2012). However, critical decisions taken in disastrous situations are urgent, and information can therefore not be acquired in the level of detail that is required to understand the situation thoroughly (Gralla, Goentzel, and Fine 2016). The required information comprises both the supply side (production capacity, market quantities) as well as the demand side (location and demographic characteristics of people in need).

In contrast to private actors who manage to build a deeper understanding of the market every day, public actors usually only possess general market data about the firms' capacities or production quantities. For instance, German authorities conduct a survey that tracks the produced amounts of "fats, cereal, starch, feedstuffs, milk, and sugar industries" on a regular basis (Federal Office for Agriculture and Food Germany 2019). However, it remains unclear if and how this static and production focused data can prove itself valuable in disaster relief. Furthermore, the German government installed an interface where pharmacies can report bottlenecks in critical supplies (BfArM 2020). Even though this approach seems promising to reduce the response time to crises in the medical sector, a holistic approach to information acquisition seems more powerful.

To tackle this issue, the US Federal Emergency Management Agency is running a pilot study to test the value of near-real-time data in disaster relief, proactively by purchasing access to market data for 3.6 million USD for one year (Federaltimes 2019).

A less costly approach to receive information in crises could be by collaboration. The importance of collaboration in disaster logistics has been widely acknowledged and different aspects of collaboration have been discussed (see for instance Rodríguez-Espíndola, Albores, and Brewster (2018a) and Waugh Jr. and Streib (2006)). However, market information represents a pivotal asset to companies and have therefore been highlighted as one of the key challenges for effective collaboration (Nurmala, Leeuw, and Dullaert 2017). Therefore, it remains questionable if private actors are willing to share their knowledge. Consequently, public actors need to both understand the value of the information and the implications of their decision under the different levels of information accuracy. However, to the best of our knowledge, no approach exists that quantifies the value of possessing more accurate information in Public-Private Emergency Collaborations (PPECs). Therefore, we propose a framework to quantify this value of information and analyze how this value is affected by the point of time and the intensity of the state's intervention.

Our paper is structured as follows. First, we provide an overview of related literature in the next Chapter. Afterward, we present the framework and discuss the different components in Chapter E.3. Following, we highlight the power of the framework by applying it to a case study, in which German authorities need to open up *Points of Distribution* in the aftermath of a tap water system contamination. We conclude with a discussion of the strengths and weaknesses of our approach and highlight potential directions for further research.

E.2. Literature Review

This Section embeds our approach within the current body of literature. We focus on the following three aspects of disaster management: collaboration, facility location models, and information management.

E.2.1. Collaboration in Disasters

Various actors become active in the aftermath of a disaster. For example, Kovács and Spens (2007) name Government, Military, Logistics providers, Donors, Aid agencies, and other NGOs as key actors and highlight the importance of effective collaboration. Various factors might affect the coordination of these actors significantly (Balcik, Beamon, et al. 2010): the number and diversity of actors, donor expectations and funding structure, competition for funding and the effects of the media, unpredictability, resource scarcity/oversupply, and cost of coordination. Consequently, a variety of articles suggest approaches to mitigate some of these obstacles (Davis et al. 2013; Dubey et al. 2019; Heaslip, Sharif, and Althonayan 2012; Nagurney, Salarpour, and Daniele 2019; Rodon, Maria Serrano, and Giménez 2012; Rodríguez-Espíndola, Albores, and Brewster 2018b; Toyasaki et al. 2017).

Most of the studies discussed above involve some sort of collaboration that includes humanitarian organizations. On the other hand, the collaboration between public and private actors is especially critical for efficient disaster management (Cozzolino 2012). While private organizations are responsible for the distribution of goods in peacetime, public actors become responsible in times of crisis. Hence, efficient collaboration between these two actors can have a significant impact on efficient relief management.

A growing body of literature is actively discussing various aspects of these so-called Public-Private Emergency Collaborations ("PPECs"; Wiens et al. (2018)). For instance, Holguín-Veras, Pérez, et al. (2013) discuss different objectives of both actors and argue for extending cost-based objectives with a cost-proxy for human suffering. Since commercial actors are profit-driven, effective mechanisms are required to offer the chance to collaborate successfully (Carland, Goentzel, and Montibeller 2018). Furthermore, Gabler, Richey, and Stewart (2017) mention two additional barriers for PPECs: internalization and unidirectional communication. In the context of our study, unidirectional communication is especially important since it is supposed to inhibit the willingness to share information (Gabler, Richey, and Stewart 2017).

However, to the best of our knowledge, no study exists that quantitatively measures the effects of collaboration for both actors under combined operational and informational strategies.

E.2.2. Allocation and Facility Location Problems in Disasters

Researchers developed a variety of approaches to locate facilities in disasters or to allocate inventory or parts of the population to these facilities. For a recent and sophisticated review, see Sabbaghtorkan, Batta, and He (2020) who analyzed location, allocation, and location-allocation papers with a focus on the prepositioning of facilities and the allocation of inventory to these facilities in anticipation of a disaster.

Additional approaches focus on the disaster relief phase, which starts right after the impact of the disaster (Kovács and Spens 2007). Baharmand, Comes, and Lauras (2019) developed a bi-objective and multi-commodity location-allocation model that minimizes logistics cost and response time. Zhao et al. (2017) developed a model that minimizes opening cost and walking distance for beneficiaries dependent on the forecasted shelter demand. Görmez, Köksalan, and Salman (2011) identified shelter locations in response to an earthquake in Istanbul. None of these contributions explicitly consider strategies of information acquisition and information sharing.

Furthermore, it has to be mentioned that some covering models consider uncertainties in input values. For instance, Arana-Jiménez, Blanco, and Fernández (2020) dealt with knowledge uncertainties through fuzzy techniques, and Li, Ramshani, and Huang (2018) developed a stochastic cooperative maximum covering approach that analyzes the situation of NGOs utilizing free capacities of other NGOs' warehouses. Even though they regard different demand levels, they generalize the demand and do not regard different demand intensities for different regions simultaneously.

However, to the best of our knowledge, no study exists in which different information levels and the implications of alternative decisions are compared.

E.2.3. Uncertain Information in Disaster

Disasters are characterized by a high degree of uncertainty. Therefore, a variety of studies exist that deal with different aspects of uncertainty, such as for example infrastructure status (Yagci Sokat, Dolinskaya, et al. 2018), travel time (Balcik and Yanıkoğlu 2020), staff availability and customer behavior (Schätter et al. 2019), or demand and supply (Bozorgi-Amiri, Jabalameli, and Mirzapour Al-e-Hashem 2013).

Our study builds upon literature regarding demand information and the exchange of information.

Even though humanitarian organizations are experts in disaster management and adapt their whole supply chain towards these uncertainties (see for instance van der Laan et al. (2016), who discuss the forecasting methods at Médecins Sans Frontières (MSF)), their supply chains are designed to be flexible towards a variety of potential disasters on a global level. Even though this increasingly leads to decentralized and more regional supply chain structures (Charles et al. 2016), the determination of concrete demand of the population after an unexpected disaster occurred still requires a significant amount of time. Therefore, humanitarian organizations use standardized guidelines like the Sphere-Handbook to define critical goods and their related demand per person in disaster settings (Sphere 2018) and determine the required amount of goods directly after the disaster stroke (for instance via a rapid needs assessments, which is supposed to take up to seven days (IFRC 2020)).

To speed up the time it takes to determine demand, some researchers tried to define criteria to quickly identify areas in which potentially vulnerable parts of the population live (Kapucu 2008; Kawashima, Morita, and Higuchi 2012; Sandholz 2019). For instance, Sandholz (2019) surveyed the population of the German city of Cologne and identified that the likelihood of a person to possess specific emergency goods like flashlight, matches, radio, and others increases with the duration a person lives in this apartment. In spite of the power of this information, a high dependency on the availability of such data results.

In contrast to public actors or relief organizations, commercial business-to-customer (B2C) business units are interacting directly with their customers on an everyday basis. Therefore, they are used to dealing with demand fluctuations in response to unexpected incidents in the context of their Business-Continuity-Management (BCM) and have therefore a good understanding of the population's potential reaction to the disaster (Schätter et al. 2019). Consequently, other actors in disaster relief would benefit from this information significantly.

Even though information exchange in disasters is widely understood as a crucial aspect of disaster management (Celik and Corbacioglu 2010), many impeding factors exist. Day, Junglas, and Silva (2009) conducted interviews with relief logisticians active during Hurricane Katrina and identified eight impediments on information flows: inaccessibility, incompatible formats, inadequate flow of information, low information priority, source information, storage, medium-activity misalignment, and unwillingness. Moreover, Altay and Labonte (2014) analyzed challenges for information flows (extracted from "27 evaluations, lessons learnt reports, and mission reports") from the

Active Learning Network for Accountability and Performance in Humanitarian Action. They highlighted that factors such as information quality and willingness to share information are especially important and argue that this could be improved by installing the Global Logistics Cluster as coordinator of the exchange of information. This could be combined with an approach from Sheu (2010) who developed an entropy-based fusion approach that generates information estimations based on multiple sources and their related belief strengths.

In spite of the possibilities to verify the quality of the information and to ensure that the information reaches the right decision maker faster, it remains questionable if private actors are willing to share their information with the whole cluster rather than in an exclusive and bilateral public-private setting. Moreover, sharing information is not necessarily every actor's objective. For instance, after the Haiti earthquake 2010, "some organisations simply did not feel the need to coordinate or share information, especially those with their own unrestricted funding." (Altay and Labonte 2014).

Furthermore, the consequences of information exchange can be crucial for both actors - especially for private actors that are, in the long run, dependent on monetizing their knowledge. Before private actors agree on exchanging information, they therefore need to understand the consequences. At the same time, public actors need to understand the value of the information in case they consider purchasing or seizing critical information. However, to the best of our knowledge, no approach exists that quantifies the value of the information and puts it in perspective with the consequences of sharing the information for both actors. In the next Section, we describe the framework we developed to fill this gap.

E.3. Model Framework

E.3.1. Problem Statement

We take the perspective of public authorities, which aim to supply the population of a city or an urban district with essential goods (e.g. water) during a crisis. Therefore, they need to decide which Points of Distribution (PoDs) they should open to supply goods to the population. However, they do not possess detailed information about the distribution of the total demand within the area. This demand depends on the goods people stockpiled at home. On the other hand, private actors possess this knowledge since they interact with their customers every day, e.g. by analysing Point of Sales data, and can therefore extract information regarding the purchasing behavior and goods people store at home. An example could be a district in which many diabetic people live, resulting in an increased number of diabetic-friendly products in stores.

Before authorities start to contact private actors and ask them to share the information, they need to determine the value of the information to decide for measures to take (extreme measures such as seizure can only be considered in case obtaining the information makes an extremely significant difference).

E.3.2. Framework to Quantify the Value of Information

The following framework describes the problem mentioned above and an approach to quantify the value of the information (see Figure E.1). Three steps are required to determine the value of information.

First, we analyze the Scenario, in which the decision-maker possesses no accurate demand information. Therefore, the demand of the population is assumed to be equally distributed ("ED"-Scenario; grey boxes in Figure E.1 and aggregated to Demand Points (DPs)). In the next step, we allocate these DPs to supermarkets, so that the utilization of the capacities of the supermarket is as high as possible. Moreover, a maximum walking distance is regarded. If the crisis is severe, the state - or in extreme cases NGOs - becomes active and open up PoDs to support the population that is not supplied by the supermarkets (Wiens et al. 2018). These PoDs can, for instance, be public buildings, churches, or stadiums (DHS 2006; PAHO 2009; U.S. Department of Agriculture 2017).

Second, we analyze the outcome, if the authorities had more accurate information with the same procedure as mentioned above. The chosen PoDs differ significantly from the opened PoDs selected with more accurate information (see "I"-Scenario; green boxes in Figure E.1).

Third, the quantification of the value of information follows. This requires an additional Scenario, the "Combined Outcome" or CO-Scenario (see "CO"-Scenario; blue box in Figure E.1). The CO results from the combination of

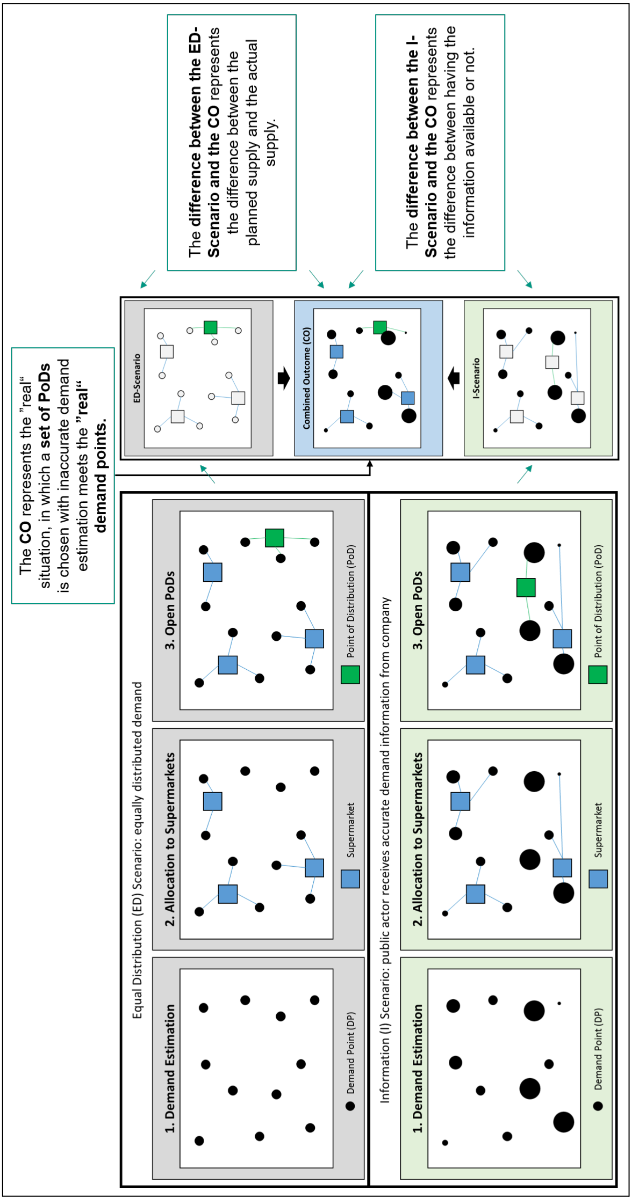

Figure E.1: Overview of the framework.

PoDs chosen with theoretical, inaccurate demand information and the "real-world" DPs. It therefore represents the outcome of the plan in reality. Hence, the difference between CO and ED quantifies the planning error, while the difference between I and CO represents the value of the information.

In the following Subsections, we provide a brief overview of the main components of the framework, while the case study discussed in Chapter E.4 highlights the power of the approach in practice. Moreover, potential extensions of the framework, e.g. regarding different time of interventions or different intervention intensities are discussed in Chapter E.5.

E.3.3. Definition of Demand Points

DPs consist of two components - the location and the demand of a required good (or a combination of goods) at time t.

- The location of the DPs depends on the level of aggregation. While the highest level of detail results from a per capita analysis, aggregations on a house, block, or district level might be more feasible in terms of computation power and available data.
- The demand for a good depends on various factors such as the disaster context, individual preferences, or the physical constitution of the population. While certain minimum standards in disaster situations exist (see for instance Sphere (2018)), an assessment of the needs of the population is central.

E.3.4. Allocation of DPs to Supermarkets

The concrete formulation of the allocation model depends on the context of the disaster and many realizations are possible. An example of objective functions could be the minimization of PoDs required to offer a target service level (Charles et al. 2016), the minimization of total cost (Lin et al. 2012), or a multi-objective approach (Baharmand, Comes, and Lauras 2019). Dependent on the quality of the available data and the specific context of the model, specifications such as customers' supermarket chain preferences could also be included.

E.3.5. Facility Location Model

Similar to the allocation model mentioned above, the Facility Location Model (FLM) needs to be tailored to the disaster context. Since public actors are not profit-driven, the objective functions could for instance entail the minimization of the total walking distance between DPs and a number of PoDs (Görmez, Köksalan, and Salman 2011), the maximization of supply to the population (Balcik and Beamon 2008), or the minimization of social costs (Loree and Aros-Vera 2018). Furthermore, aspects such as differences in the suitability of a building to become a PoD, or specific types of buildings could be considered (PAHO 2009).

E.4. Case Study: Tap Water Contamination in Berlin

The case study was inspired by the water contamination from the city of Heidelberg, Germany, where the drinking water was contaminated on February 7th, 2019, for a couple of hours (Heidelberg24 2019).

We assume that the tap water system in the city of Berlin is contaminated. Even though it is still usable to flush, wash clothes, or to shower, it is not drinkable anymore. Moreover, it is known that the tap water will be drinkable again after one day, reducing the level of panic within the population. Due to the crisis, the demand for bottled waters increases significantly and companies try to cope with the sudden increase. To reduce complexity, we only focus on drinking water. Indirectly induced demands for products such as food or soap will not be regarded.

Public authorities realize that the supermarkets are not able to supply enough water to the population. Therefore, they decide to open PoDs. Due to a contract with a logistics service provider, transportation of water to these facilities is secured and does not need to be regarded in the model. Furthermore, we assume that only public schools are considered as locations for PoDs and that these schools are all equally suitable as a PoD.

E.4.1. Definition of Demand Points

As mentioned above, two key characteristics define DPs: the location and the demand.

E.4.1.1. Location of DPs

An aggregation level of an "on a house basis" offers a high resolution. Data acquired from the city of Berlin (Berlin 2019a)[2] is the basis for the location of the 387, 083 buildings. However, not all of these buildings are inhabited. Since the city of Berlin provides information on the population density on a "per block" base (Berlin 2019b), we only select the buildings that lie within one of those defined blocks, reducing the numbers of buildings in the scope of our analysis to 372, 629 (see also Figure E.2). Following, the inhabitants per block are evenly distributed over the buildings that are located within this block. The number of people per house results. The way the demand for each house is determined will be described in Subsection E.4.1.2 below. However, due to the extremely high computational effort that comes with the allocation of 372, 629 buildings, the sum of the demand of the houses within one block is aggregated back on a block base to reduce computational complexity. A total of 14, 759 DPs results.

E.4.1.2. Demand Estimation

According to the Sphere handbook, 15 liters of water per person and day are sufficient for short periods of time (Sphere 2018). Moreover, the authors of the handbook consider 2.5 – 3 liters of water per day as an adequate amount for "drinking and food" (Sphere 2018). Therefore, we regard demand of 3 liters per day and person.

We define the two different scenarios for the demand based on the respective actor: While private actors can predict the demand due to their experience with demand fluctuations (*accurate information*), public actors cannot estimate the demand as accurately, especially under high time pressure. Therefore, they can only relate on immediately available data (e.g. census data; *inaccurate*

[2] Data licence Germany – attribution – Version 2.0

information) or wait until the situation becomes more clear (for example, Comes, van de Walle, and van Wassenhove (2020) states that the Philippine army was unaware of the concrete impact of Typhoon Haiyan until it was covered by international media).

Since private actors' success depends heavily on their market knowledge, this information is not publicly available, and we need to determine an approximation for our case study with the help of proxy data. Even though this data is free to access, the data analysis and manipulation process is extremely time consuming and cannot be done efficiently by authorities right after the disaster occurred.

We base our estimation on the assumption that, due to the short time of the crisis, only the part of the population, which did not store bottled water at home, requires water. Following, the demand per person we regard in the case study results from the required amount of water (3 liters) reduced by the stockpiled amount.[3]

According to a recent study by Sandholz (2019), where the authors conducted a representative survey of the stockpiling of 1,109 households in a major German city, 66.8% of the population stockpiles water for more than five days. Therefore, the stockpiling amount of 33.2 % of the population is 0.

In the case of inaccurate information, we assume that authorities only know the number of people living at each DP and the average amount of water stockpiled per person. Consequently, the demand for each person is reduced by 66.8% for the ED-Scenario, while the demand in the I-Scenario is 0 liters for 66.8% and 3 liters for 33.2% of the population.

Regarding the approximation for the accurate demand information, we regard three indicators for the number of goods stockpiled at home: the available space in the apartment (Bell and Hilber 2006), the financial or social status of the person (Havranek, Irsova, and Vlach 2017), or the distance to the closest supermarkets (Jiao, Vernez Moudon, and Drewnowski 2016). Even though we acknowledge that multiple additional indicators influence the stockpiling, we only regard these three characteristics for each house for the sake of simplicity. After all, the objective of this study is not to provide an improved

[3] Even though a person that stockpiles a limited amount of water could still try to buy additional water, we do not regard this "exceeding" demand further.

estimation of stockpiling behavior but to show how information sharing can improve decisions.

To determine the stockpiling, we rank the DPs in terms of these indicators and sum up the individual ranks to attain a merged rank.[4] Finally, the best ranked 66.8% of the population is regarded with a demand of 0 liters. Furthermore, the demand for each DP (each block) results from the aggregation of each building within this block.

Size of the apartment

We use the population density per block as a proxy for the size of the apartment (see also Figure E.2). Each building receives the density value of the block it is located in.

Figure E.2: Extract from map of Berlin with the population density highlighted on a per block basis [in ppl per hectar] (Berlin 2019b)

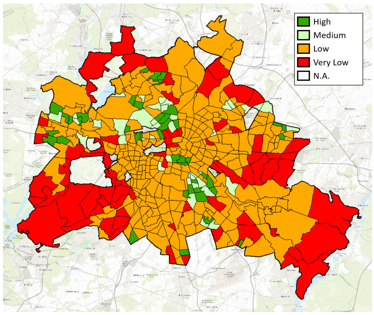

Figure E.3: Map of Berlin with 447 PRs and their social status index (Berlin 2019c).

Financial situation

We estimate the financial situation with the help of the local "Status Index" (SI), which is based on the current and long term unemployment rates, the child poverty rate, and the "proportion of not-unemployed recipients of transfer payments" (SSW 2019a). The SI is defined on the level of the so-called

[4] In case of equal values, each of the related buildings receives the highest value.

"Planungsräume" (PRs, see also Figure E.3) - 447 geographically defined areas dividing Berlin into segments of similar social and demographic characteristics (SSW 2019b).[5] Consequently, we allocate the SI of the related PR to each building.

Distance to supermarkets
The average distance between each building and the five closest supermarkets was calculated with ArcGIS Desktop 10.6.1. and represents the distance to the supermarkets. Afterward, the buildings were ranked accordingly.

Determination of stockpiled amount
As mentioned above, the individual ranks for each building were summed up to determine an overall ranking. We combine these overall ranks with stockpiling data obtained from Sandholz (2019) to determine the demand per DP. The allocation of DPs to supermarkets follows.

E.4.2. Supermarket Allocation

The model for allocating the DPs to supermarkets is a maximum covering model (Farahani et al. 2012). With the binary decision variable x_{ij} (indicating if $DP\ i$ is allocated to supermarket j), a demand of b_i per DP, a supply of a_j per supermarket, a distance d_{ij} between DP_i and supermarket j, and a maximum walking distance of r, we define the model as follows:

[5] Since January 1st, 2019, the city of Berlin slightly changed the structure and now defines 448 PRs. As the statistical data available refers to 447 PRs, we will keep using the "old" classification of the PRs without the minor adaptions.

$$\max \quad \sum_{i \in I} \sum_{j \in J} x_{ij} * b_i \tag{E.1}$$

$$s.t. \quad \sum_{i \in I} x_{ij} * b_i \leq a_j \qquad \forall j \in J \tag{E.2}$$

$$x_{ij} * d_{ij} \leq r \qquad \forall i \in I, \quad \forall j \in J \tag{E.3}$$

$$\sum_{j \in J} x_{ij} \leq 1 \qquad \forall i \in I \tag{E.4}$$

$$x_{ij} \in \{0; 1\} \qquad \forall i \in I, \quad \forall j \in J \tag{E.5}$$

While Eq.(E.1) defines the objective to maximize the allocated amount of water from all supermarkets j to all DPs i, Eq.(E.2) ensures that the capacity limit of each supermarket is not exceeded. To compute our calculations, we use supermarket data obtained from the Berlin Senate Department for Urban Development and Housing (BSDUP 2016). Since this data only contained GIS coded data about 1062 supermarket locations and the corresponding size of the sales area, we needed to determine the capacity per supermarket by approximation: we broke down the amount of bottled water sold in Germany per year (VDM 2019) on a per-day and capita base and multiplied it with Berlin's population to calculate the daily sales of bottled water in Berlin (in our case: 1.77 million liters per day). Following, we divided this number by the total sales area to determine the water capacity per m^2 of sales area (in our case: 1.63 liters per m^2). The capacity per supermarket follows by the multiplication with the size of the corresponding sales area.

Eq.(E.3) ensures that a DP is only assigned to a supermarket ($x_{ij} = 1$) if the geodesic distance between DP and supermarket is within walking distance of the DP. In the context of our case study, we follow the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety and define the maximum walking distance as 1,000 meters (BMUB 2014). Moreover, Eq.(E.4) ensures that no DP is allocated to more than one supermarket to reduce the complexity to collect the goods for the population. Finally, Eq.(E.5) defines x_{ij} as a binary variable.

E.4.3. Location Selection for PoDs

The remaining demand after the allocation to the supermarkets is considered as the input-demand for the PoD location selection. We assume that the authorities are only able to open a limited amount of schools as PoDs and that each of these PoDs has a capacity of 60,000 liters per day (roughly five trucks with a load of 12 tons). This capacity would furthermore be in line with the recommendations of the World Food Programme, who recommend limiting the number of people per distribution site to 20,000 (WFP 2002). Regarding potential schools to open, we use data received from the Berlin Senate Department for Education, Youth and Sport (BSDEYS 2019) that included GIS data for all public schools in Berlin. After data editing and preparation, the pool of potential PoD locations included 631 schools.

The following model decides, which of the schools k should be opened as PoD ($y_k = 1$), and which DP is allocated to which school ($x_{ik} = 1$) if a total number of L schools can be opened ($L \leq |K|$):

$$\max \quad \sum_{i \in I} \sum_{k \in K} x_{ik} * b_i \tag{E.6}$$

$$s.t. \quad \sum_{i \in I} x_{ik} * b_i \leq a_k \qquad \forall k \in K \tag{E.7}$$

$$x_{ik} * d_{ik} \leq r \qquad \forall i \in I, \quad \forall k \in K \tag{E.8}$$

$$\sum_{k \in K} x_{ik} \leq 1 \qquad \forall i \in I \tag{E.9}$$

$$x_{ik} \leq y_k \qquad \forall i \in I, \quad \forall k \in K \tag{E.10}$$

$$\sum_{k \in K} y_k \leq L \tag{E.11}$$

$$x_{ik}, y_k \in \{0; 1\} \qquad \forall i \in I, \quad \forall k \in K \tag{E.12}$$

Note that, even though I refers to the same set of DPs, the demand of the DPs of the second model differs (whenever a DP x was allocated to a supermarket within the supermarket allocation model, the demand of this DP x in the school allocation model is 0). Eq.(E.6-E.9) are equivalent to the supermarket allocation model mentioned above, with the objective of maximizing the allocation to the population. Eq.(E.10) ensures that an allocation is only possible, if a school k is open. Eq.(E.11) accounts for the maximum number of schools to open (L), while Eq.(E.12) defines y_k and x_{ik} as a binary variable.

E.5. Results

E.5.1. Demand Points

The calculation of ranks and the allocation of demand to the DPs was conducted using Microsoft Excel (16.0.4849.100 64-bit) and ESRI ArcGIS Desktop 10.6.1. A total demand for 3,720,554 liters results. Since the information about potentially vulnerable blocks is very sensitive, we avoid highlighting the assessment on a per-block base and aggregate the demand for each DP on the level of the PR (see Figure E.4 and E.5).

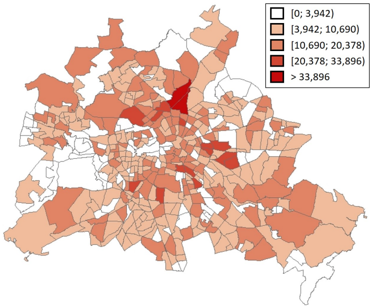

Figure E.4: Visualization of the demand per PR assuming evenly distributed stockpiling estimation [in l per PR].

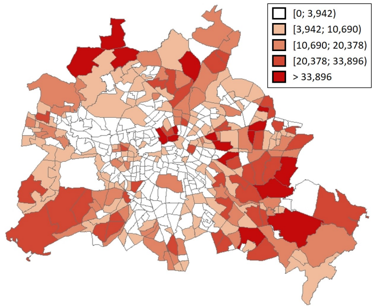

Figure E.5: Visualization of the demand per PR highlighting the accurate demand stockpiling estimation [in l per PR].

Therefore, accurate information helps to identify potentially critical regions since the demand in different regions of Berlin varies stronger than in the case of equal distribution. Following, it is possible to prioritize regions more efficiently.

E.5.2. Allocation to Supermarkets

The model to allocate DPs to supermarkets was implemented in GAMS and solved using the CPLEX Solver (on an Intel Xeon CPU E7-4850, 2.00 GHz, 256 GB RAM). It took approximately 45 minutes to solve the problem with a relative MIP-gap of 0.5%, resulting in a total supply from the supermarkets of 1,734,812 liters and capacity utilization of 98%. Consequently, the exceeding demand results in 1,985,742 liters.

E.5.3. Location Selection for PoDs

Regarding the number of PoDs to open, we distinguish between two cases - 10 schools and 33 schools. Thirty-three schools were chosen since this number ensures that the capacity of supermarkets and schools matches the demand. On the other hand, the significant operational effort required to open 33 PoDs cannot be neglected. Therefore, we also regard 10 PoDs as a more feasible number of schools to open. This number is further supported by the blackout in Berlin Koepenick in February 2019, in which five schools were opened (RBB 2019). Since Koepenick only represents a small part of Berlin, a safety cushion of 100% was chosen.

The PoD location model was implemented in GAMS and solved using the CPLEX Solver (on an Intel Xeon CPU E7-4850, 2.00 GHz, 256 GB RAM). It took on average 9 minutes to solve the problem with a relative MIP-gap of 0.5%, resulting in a total supply of 416,321 liters from 10 schools and 947,518 from 33 schools. Therefore, public authorities are able to estimate that opening ten schools lead to a total supply of 2,151,133 liters of water (equivalent to 58% of the total demand of the population), while 2,682,330 liters could be distributed with 33 schools (equivalent to 72% of the total demand). Therefore, it can be followed that 28% of the capacities are unused due to the distance restriction if 33 schools are considered.

E.5.4. Quantification of the Planning Error

As discussed in Chapter E.3, the planning error results from the difference of the CO- and the ED-Scenario. Furthermore, the CO is determined by an additional run of the location selection model with the additional restriction:

$$y_j = 1 \qquad \forall\ j\ \in\ \{\text{Locations selected in ED-Scenario}\} \tag{E.13}$$

It follows that the results planned do not reflect potential outcomes since the chosen locations only lead to a supply of 120,586 liters from 10 schools and

396,843 liters from 33 schools. Consequently, authorities would overestimate the outcome of their intervention by up to 71%. This can have severe consequences. If, for instance, a mayor of a city planned to supply goods for 10,000 people, aid would, in fact, only reach less than 3,000 people. This effect is furthermore underlined by the fact that only 23 of 33 open schools actually distribute goods, while 10 are left with all of their goods and nobody around to pick them up.

E.5.5. Quantification of the Value of Information

The value of information results from the comparison of the I-Scenario and the CO-Scenario described in Section E.5.4 above. If the state possessed all information before making its decision, the supply to the population would result in 496,608 liters from 10 schools and 1,092,457 liters from 33 schools. Therefore, public actors benefit significantly from the exchange of information, leading to an increase in supplies of up to 412%.

Figures E.6 - E.8 furthermore highlight the results, presenting the 33 locations chosen for the ED-, the CO-, and the I-Scenario. It follows that authorities would rather open schools in the center of Berlin, even though schools more towards the outskirts of the city are better if the real demand is considered.

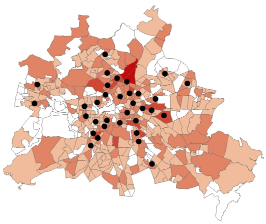

Figure E.6: 33 schools opened in the ED-Scenario.

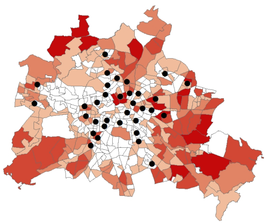

Figure E.7: 33 schools opened in the CO-Scenario.

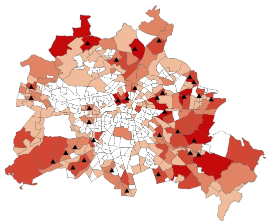

Figure E.8: 33 schools opened in the I-Scenario.

E.6. Discussion and Further Analysis

The presented framework allows for a precise determination of the planning error and the value of information. Therefore, it provides crucial insights for decision-makers in disaster management. They can, for example, use the planning error from this study as an outcome estimation indicator in cases of high uncertainty. Furthermore, it highlights the impact of an increase in information accuracy and provides an understanding of how much the quality of disaster relief can be improved by higher information quality. However, it remains questionable if private actors are willing to share information.

Moreover, the exchange of information is challenging, even if a company is willing to collaborate. For example, agreeing on appropriate data-types, interfaces for the data-exchange, or update-cycles can - together with the time it takes to find a partner to collaborate - take a long time. Therefore, relief can significantly speed up if public and private actors agree on the specific collaboration parameters before the crisis. Moreover, PoDs chosen in the model can be regarded as designated disaster sites in disasters, reducing the communicational and planning effort in the direct aftermath of the disaster drastically (similar to Dekle et al. (2005) who identified designated relief sites in the US).

To gain a better understanding of the importance of time, we compare the decision in the case study above with an alternative, accelerated decision where schools open up at the same time as the supermarkets. Therefore, beneficiaries have more opportunities to receive goods while supermarkets might sell less.

E.6.1. A Comparison of Different Times to Start the Intervention

While market interference was implicitly excluded due to the dime lag between the start of the crisis and the start of public actors' intervention, it is also possible to analyze the consequences of an earlier intervention of public actors. Earlier intervention in this context refers to opening the PoDs at the same time as the supermarkets open (see Table E.1). Hence, parts of the population that were expected to go to supermarkets in the Scenario above could go to schools. Therefore, earlier intervention leads to market interference.

This Subscenario "B" is calculated similarly to the CO-Scenario described in Section E.5.4: after the selection of PoDs to open, an additional run of the supermarket allocation model follows, in which the opened PoDs are included as additional distribution points.

Subscenario B leads to an increase in total supply (see Table E.2). While total deliveries increase in each Scenario analyzed, the overall effects are rather small, ranging from a 2% increase in the I-Scenario for 10 schools up to an increase of 12% in the ED-Scenario for 33 schools.

Name of Subscenario	**A** **Benchmark w/o market interference**	**B** **Simultaneous w/ limited market interference**	**C** **Simultaneous w/ market interference**
Relevant demand for public actors	Unmet demand after the population is allocated to supermarkets.	Expected unmet demand after supermarkets ran out of goods.	Total demand of the population.
Time information is shared and public actors become active	After supermarkets are out of capacity.	At the beginning of the crisis.	At the beginning of the crisis.
Narrative description / Interpretation of strategy	Public actors wait until supermarkets run out of capacity before they receive the information and can start to supply goods to people without water.	Public actors estimate the demand that will be left when the supermarkets run out of goods and choose the best locations to fulfill this demand. Each person can either go to one of the supermarkets or one of the PoDs that are open.	Public actors choose PoDs so that the total demand can be supplied best. There, PoDs are in direct competition to supermarkets for the demand that could have been met without public intervention.

Table E.1: Overview of the different Subscenarios.

The implications of public interventions on private supply chains cannot be neglected and should be considered carefully before intervening. In Subscenario B, public actors implicitly tried to reduce the impact of their interventions by only focusing on the demand that cannot be supplied for by the market. However, public actors could also try a more holistic approach and consider the total demand. Hence, the impact on supermarkets is expected to be more significant. In the following Subsection, we analyze this Subscenario C.

E.6.2. A Comparison of Different Intervention Intensities

In the context of this case study, we define the difference in intervention intensity by the demand regarded in the public actors' optimization model (see also Table E.1). In the case of a less severe intervention (Subscenario B), authorities only consider the demand that would not be fulfilled by the supermarkets if the supermarkets were to distribute goods by themselves. In the case of a stronger market intervention (Subscenario C), public authorities consider the total demand of the population. Consequently, Subscenario C can be interpreted as the population's favorite Subscenario since the best possible supply results, in which the allocation to supermarkets and the facility decision for schools occurs at the same time.

From a mathematical perspective, we implemented this Subscenario as an extended location selection model with $M = \mathrm{I} \cup \mathrm{J}$. Furthermore, we set $y_m = 1 \, \forall \, m \in \mathrm{I}$. Consequently, the constraint that controls the number of opened PoD (Eq. (E.11)) is adapted to include the 1,062 additionally opened PoDs:

$$\sum_{m \in M} y_m \leq L + 1,062 \tag{E.14}$$

Subscenario C leads to a better supply to the population than the baseline (A) and the less severe intervention (B, see Table E.2).[6]

However, the proportion of the supply that is taken care of by the private sector remarkably deviates from the intuitively expected outcome since supermarkets lose, on average, a higher share of sales in the case of weak intervention than in the case of strong intervention. A reason for this is the increased flexibility of public actors regarding potential beneficiaries and the implicit division of the population between the two actors that results from the holistic optimization approach. Consequently, supermarkets have an incentive to collaborate closely with public actors in case they expect any kind of intervention. However, it is not possible to eliminate crowding-out effects if public and private actors are active at the same time.

[6] It has to be mentioned that due to the increased complexity of the problem, we had to increase the allowed relative MIP-gap to 3%.

#Schools	10			33		
Distribution Strategy	**A**	**B**	**C**	**A**	**B**	**C**
Equally Distributed Scenario						
Total Deliveries to Population	2,151,133	2,289,701	2,303,329	2,682,330	2,991,653	3,071,427
Utilization of Total Capacities	0.91	0.97	0.97	0.71	0.80	0.82
Proportion of Total Demand supplied	0.58	0.62	0.62	0.72	0.80	0.83
Deliveries from Supermarket	1.734,812	1,733,508	1,714,781	1,734,812	1,541,330	1,679,129
Utilization of Supermarket Capacities	0.73	0.98	0.97	0.73	0.87	0.95
Deliveries from Schools	416,321	556,192	588,548	947,518	1,450,323	1,392,297
Utilization of School Capacities	0.69	0.93	0.98	0.48	0.73	0.70
Combined Outcome Scenario						
Total Deliveries to Population	1,562,120	1,584,712	1,593,988	1,838,377	1,904,606	1,884,325
Utilization of Total Capacities	0.66	0.67	0.67	0.49	0.51	0.50
Proportion of Total Demand supplied	0.42	0.43	0.43	0.49	0.51	0.51
Deliveries from Supermarket	1,441,534	1,408,424	1,369,340	1,441,534	1,256,422	1,279,380
Utilization of Supermarket Capacities	0.81	0.79	0.77	0.81	0.71	0.72
Deliveries from Schools	120,586	176,289	224,648	396,843	648,184	604,945
Utilization of School Capacities	0.20	0.29	0.37	0.20	0.17	0.31
Information Scenario						
Total Deliveries to Population	1,938,142	1,977,576	1,982,790	2,533,991	2,705,482	2,709,825
Utilization of Total Capacities	0.82	0.83	0.84	0.68	0.72	0.72
Proportion of Total Demand supplied	0.52	0.53	0.53	0.68	0.73	0.73
Deliveries from Supermarket	1,441,534	1,397,066	1,408,249	1,441,534	1,290,523	1,361,218
Utilization of Supermarket Capacities	0.81	0.79	0.79	0.81	0.73	0.77
Deliveries from Schools	496,608	580,510	574,541	1,092,457	1,414,959	1,348,607
Utilization of School Capacities	0.83	0.97	0.96	0.55	0.71	0.68

Table E.2: Overview of the results of the different Subscenarios.

E.6.3. Effects of Different Subscenarios on Supermarket Chains

Since it is not possible to eliminate crowding-out effects, we further analyze the consequences of the different intervention strategies on supermarket chains. Therefore, we aggregate the supply from the individual supermarkets on a "per-corporate-group" level. In line with Kaufda (2019), we consider the following groups: Aldi, Edeka, Metro, Norma, Rewe, Schwarz, and "others".

Figure E.9 highlights the distribution per chain in the different Subscenarios.[7] For example, group 7 is highly affected by Subscenario B_CO_33, while the sales of group 3 change significantly less due to the intervention. Consequently, crowding-out affects different chains with different intensities. Therefore, public actors need to be very careful to make sure that they do not "pick winners" and have significant long term consequences on the competition in the market.

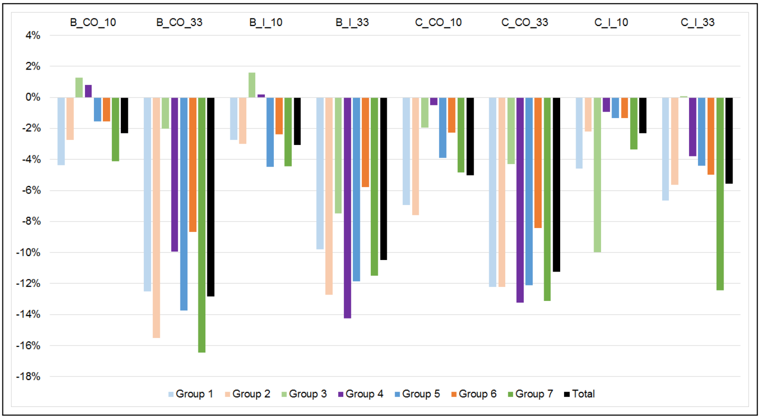

Figure E.9: Overview of the lost sales per group compared to no intervention (A).

7 Due to reasons of confidentiality, we do not link the names of the groups to the data and generalize them as group 1-7.

E.7. Conclusion

Public actors strategies strongly depend on accurate demand information during crisis intervention. Within the realm of our case study, inaccurate information can result in planning errors of up to 71%. At the same time, the impact of the intervention can increase by up to 412%, if decision-makers receive accurate information. Moreover, the earlier public actors become active also has a positive effect, even though this effect is comparably small. Furthermore, we were able to show that severe market intervention results in better exploitation of supermarkets than a less severe market intervention. Consequently, private actors should seek for collaboration in cases they are afraid that public actors would become active individually otherwise.

However, additional research is necessary to gain a deeper understanding of the crisis mechanisms. First, we did not consider the legal implications of the different Scenarios. We were able to show that the effects of the interventions on supermarket groups differ significantly. Since authorities are not allowed to pick "winners", it remains critical if addition in total supply justifies different decisions.

Moreover, we did not consider crisis dynamics. The objective of this article was to quantify the value of a current level of information in contrast to an alternative set of information. Therefore, we did not consider dynamic effects, even though additional information might change the assessment (for an overview of humanitarian logistics models that include real-time data, see, for example, Yagci Sokat, Zhou, et al. (2016)). Therefore, the approach could, for instance, be combined with dynamic optimization approaches such as the work from Paterson et al. (2019), who developed a work-in-progress approach for updating stochastic models of human-centric processes in disaster management through unstructured data streams and encoded information.

Furthermore, we treated every DP equally. Even though this is reasonable within an analysis of system capacities, a prioritization of vulnerable parts of the population could help to make the results more applicable for practice.

Closely connected is the definition of the next steps if authorities were to implement ways to receive information in crises. This could include defining DPs together, to agree on the format of the data sent (e.g. as an Excel, or as GEO-Coded files), or to discuss the way authorities can process the data.

Despite the challenges discussed above, the framework proved to quantify the value of information in disasters efficiently. Therefore, it can establish itself as a powerful tool to improve disaster resilience.

E.8. Acknowledgements

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The delivery of essential goods to beneficiaries in the aftermath of a disaster is one of the main objectives of relief logistics. The present work aims to improve relief logistics by improving the location selection of warehouses, distribution centers, and points of distribution. Four general recommendations for authorities are derived: First, it is essential to collect information before the start of the disaster. Second, training exercises with companies will help to ensure that planned collaboration processes can be implemented in practice. Third, adjustments to the German disaster management system can strengthen the country's resilience. Fourth, initiating public debates on strategies to prioritize parts of the population might increase the acceptance of the related decision. Consequently, the present work offers the potential to significantly improve the distribution of goods in the aftermath of future disasters and, thereby, increase disaster resilience.

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