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

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ABSTRACT

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

1. Introduction and motivation

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

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

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

The focus of this paper is to describe and model the scope and

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

From a conceptional point of view, activities of actors after a disaster can be classified as in Fig. 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 Fig. 1). These operations can be significantly improved by a collaboration with private firms (PPEC). The importance of the private sector is underlined by Izumi and Shaw (2015), who point out that 70–85% of investments in emergency logistics are expected to come from the private sector.

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

Accounting for these phases, improved emergency management procedures within the private and the public sector can reduce the burden on the population significantly (Papadopoulos et al., 2017). Therefore, it prevents the worsening of the situation and that the disaster turns into a catastrophe. One way to achieve improvement is to establish sustainable collaboration mechanisms, since collaboration significantly improves efficiency and effectiveness of emergency response activities (Balcik et al., 2010; Kapucu et al., 2010). However, in spite of the prominent opinion stressing the importance of multiple actors in crisis management, most of the studies in the field of humanitarian supply chain management focus on a single actor (Behl and Dutta, 2018). In our view, sustainable and - from a welfare perspective - efficient crisis management research primarily requires in-depth research on the way private firms and public organizations

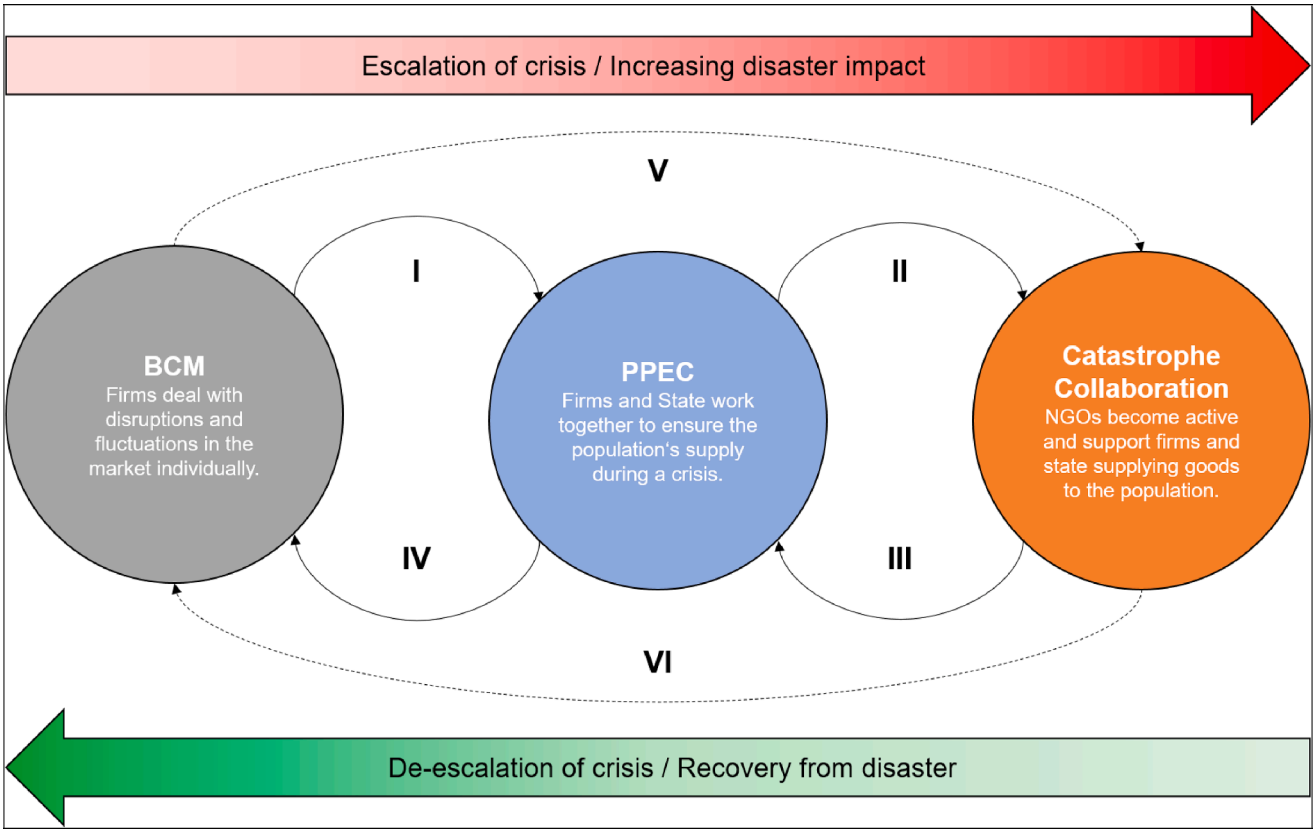

Fig. 1. Classification of phases or activities for different types of actors during a crisis.

deal with emergencies together. While collaboration increases the efficiency of the logistical operations, incentives and a surplus for all involved partners are critical as well. Consequently, a comprehensive account on collaboration in emergency logistics operations requires a profound understanding of both, the operational logistics perspective on the one hand and the incentive-oriented game-theoretic perspective on the other.

However, in comparison to research on humanitarian-business partnerships (Fikar et al., 2016; Nurmala et al., 2018; Tomasini and Van Wassenhove, 2009), the body of literature on PPECs remains scarce (Chen et al., 2013; Gabler et al., 2017; Stewart et al., 2009; Swanson and Smith, 2013; Wang et al., 2016; Wiens et al., 2018). Moreover, to the best of our knowledge, only two publications exist that explicitly consider logistical and game-theoretical approaches in the disaster context simultaneously (Nagurney et al., 2016; Nagurney et al., 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.

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).

2.1. Public–private partnerships in general

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

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

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

2.2. PPEC barriers, requirements and potential benefits

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

However, several real-life examples highlight that the public sector struggles to collaborate with the private sector efficiently. One case is Hurricane Katrina, in which the successful emergency response of retailers, including Walmart, diametrically opposed the insufficient performance of government agencies (Horwitz, 2009; Sobel and Leeson, 2006). Exemplary was the private sector's fast delivery of necessary goods like food and clothes to the places where they were needed, while the trucks under control of the governmental organization FEMA experienced a lot of difficulties organizing and distributing essential supplies (Horwitz, 2009). Another well-discussed case is the earthquake and tsunami hitting Japan in 2011, where the government excluded private companies from the impact zone and attempted to create entirely new supply networks. As a result, millions of people with a real need for food could not reach commercial organizations, while those

outside the disaster area started hoarding (Palin, 2017). This raises the question why such collaborations between public and private actors did not succeed in the way they were supposed to. We argue that there is a significant potential for collaboration but that this potential is more difficult to identify and "extract" compared to other forms of collaboration.

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

In economics, the agency theory (Milgrom and Roberts, 1992; Townsend, 1982), contract theory (Salanié, 1997) and the theory of relational contracts (Gintis, 2000; Macaulay, 1963; Macleod, 2006) form the methodological framework for the analysis of collaboration between actors with, at least partially, conflicting objectives. In addition to the theoretical foundation, behavioral experimental economics contributed enormously to this field of research over the last decades. Collaborative agreements can significantly reduce transaction cost but have to cope with agency-specific risks based on asymmetries of power and information, such as exploitation, hold-up problems, or moral hazard (Fudenberg and Tirole, 1991). Key factors for a stable and efficient collaboration are (among many others) open (Jüttner, 2005) and credible communication (Farrel and Rabin, 1996) about the partners' objectives and intentions (Falk and Fischbacherk, 2006), transparent and fair allocation of risks and benefits (Fehr and Gächter, 2000) as well as the future perspective of an enduring relationship (Fudenberg and Maskin, 1986). The possibility of a longer-term relationship allows the partners to stabilize their relationship on the basis of reciprocity and parallel expectations. From a game-theoretical point of view, relational contracts are self-enforcing contracts, since no external body (such as a court) is required to enforce the contractual interests, but the contract is fulfilled by mutual agreement and in the best self-interest. The range of application of these established concepts is broad and includes labor markets, project management, R&D collaboration and also public–private partnerships (Bing et al., 2005; Desrieux et al., 2013).

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

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

Additional advantages can result from an optimized division of tasks and improved coordination of logistics operations (see also Section 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.

2.3. Already established PPECs

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

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

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

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 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.

3.1. The role of public actors in emergency logistics

In this paper, we define "public actors" as all types of institutions and organizations under the control of public authorities on a federal and/or provincial level. This includes - inter alia - public disaster management institutions (for instance the US FEMA or the German THW), the military, police forces and firefighters (as long as they are not privatized),

and all types of ministries directly or indirectly involved in the relief process (legal, environmental, financial etc.).

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

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

The delivery of goods for a large amount of people requires a variety of resources (e.g. trucks, people). However, purchasing and maintaining resources is extremely costly - especially if the resources are only needed in extraordinary times. Consequently, public actors only have a comparably low number of resources at their direct disposal. Without a PPEC, public actors therefore need to hire logistics companies (for instance in the US via the Disaster Response Registry (US Small Business Administration, 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 et al., 2018; Wang et al., 2016) or access to logistical competences (Qiao et al., 2010; Tomasini and Van Wassenhove, 2009). During the COVID-19 outbreak, the German state clearly acknowledged the important role of private supply in crisis response by supporting firms as much as possible. For example, authorities loosened restrictions on truck driving hours and trucks with essential supplies were allowed to drive on Sundays (BMVI, 2020), shop hours for grocery stores were extended to Sundays (RL, 2020), and even an exemption from the strict COVID-rules on immigration was made for harvest workers from Eastern Europe (BReg, 2020).

At the same time, public actors provide special capabilities for a PPEC (see for instance Kovács and Tatham (2009)). First, public actors have specialized equipment and competences at their disposal. For instance, the German THW owns multiple mobile water purification plants (THW, 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 et al., 2018; Pettit et al., 2010).

3.2. The role of private actors in emergency logistics

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

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

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

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

In the following, we present real-life examples of the private sector facing a crisis. One example is the contamination of tap water in the city of Heidelberg, Germany, on February 7th, 2019 (Heidelberg24, 2019). The duration of the event was uncertain in the beginning. Hence, people started to hoard bottled water and buy large amounts from retail stores, which in turn had to be refilled as soon as possible (Heidelberg24, 2019). A sudden increase of demand affects different stages in the supply chain, which can cascade along the supply chain (Kildow, 2011; Snyder et al., 2016). In Fig. 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

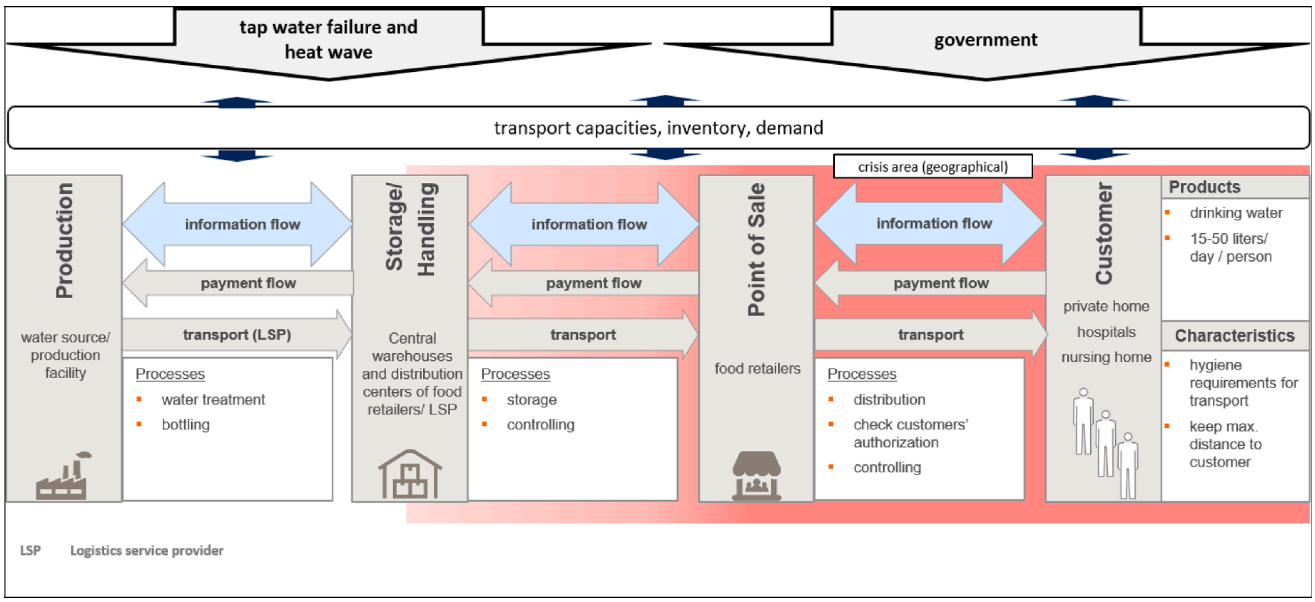

Fig. 2. Exemplary visualization of commercial water supply chains in case of tap water failure (based on Dani and Deep (2010)).

affected area (Horwitz, 2009). Not only in this case, supply speed compared to governmental response is seen as a core strength of private actors in crisis response (Nurmala et al., 2018). This goes along with findings from Dani and Deep (2010), who found that supply chain collaboration can help move goods faster and more efficiently during crisis.

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

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

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

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.

4.1. Collaboration in logistics

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

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

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

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

Another threat to the sustainability of a collaboration is the evolution

of the relative bargaining power of the participating companies over the lifetime of the collaboration (Cruijssen et al., 2007).

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

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

4.2. Collaboration in emergency logistics

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

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

4.2.1. Strategy and motivation

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

Multi-objective nature of logistic models

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

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

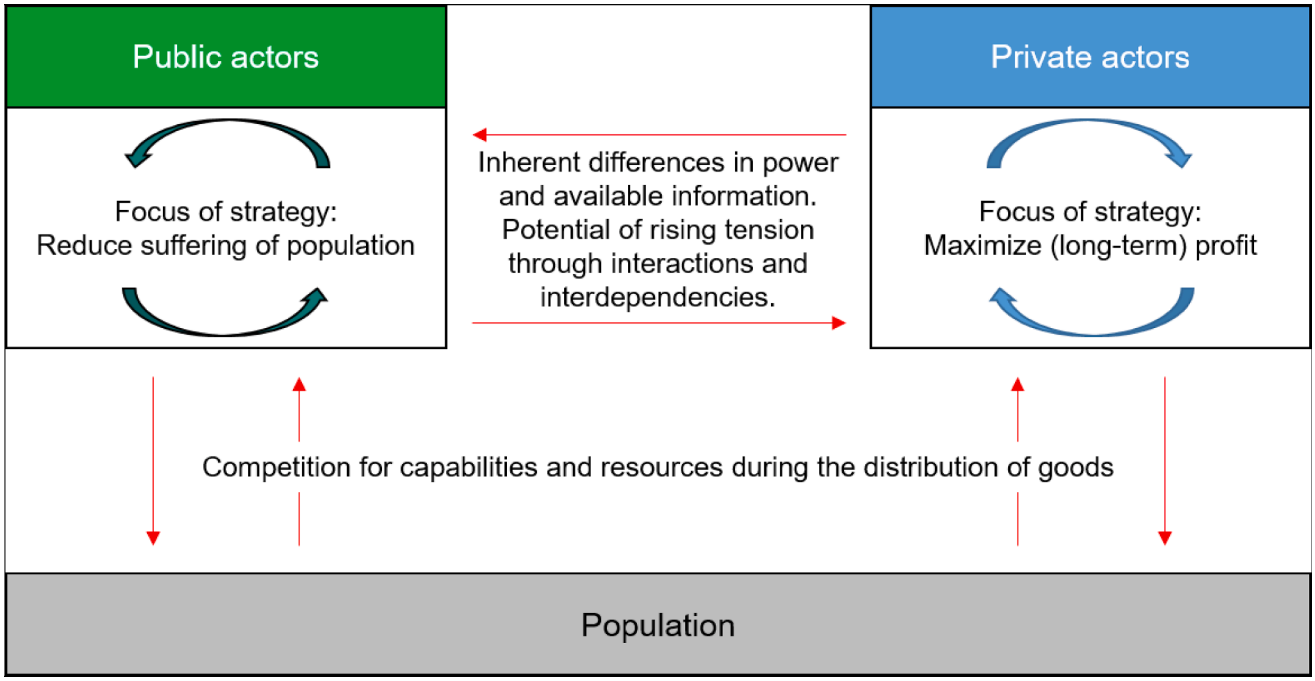

Fig. 3. Interdependencies in Public–Private Emergency Logistics.

Time horizon of decision making

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

4.2.2. Interaction between actors

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

Power differences

Both public and private actors' involvement is determined by the power they possess in times of disaster. The public sector is only entitled to intervene if the situation provides the legal prerequisites for an intervention. If this is the case, public authorities can have far-reaching rights which give them access to several resources (e.g. goods, transport capacities, production facilities) (Daniels and Trebilcock, 2006; Wood, 2008). Private sector involvement in emergency logistics is voluntary if not being forced through governmental seizure. However, motivated to implement CSR and BCM strategies, companies still possess their operational freedom in decision-making. Hence, they can determine their level of involvement in emergency logistics (Johnson and Abe, 2015). Moreover, power differences within commercial supply chains are crucial. For example, firms can have strong negotiation positions with their suppliers (Spence and Bourlakis, 2009), which can also affect the abilities to respond quickly in crises.

Information sharing

Research has shown that a lack of information sharing among commercial supply chain members results in increased inventory costs, longer lead times and decreased customer service (Simatupang and Sridharan, 2002). Since logistics is responsible for 80% of relief operations (Van Wassenhove, 2006), coordination of information flows has a critical influence on relief chain performance (Balcik et al., 2010). As opposed to a commercial supply chain environment, however, the sources of information can be limited or even unidentifiable in the aftermath of an emergency (Sheu, 2007) and the information themselves incomplete (Yagci Sokat et al., 2018). For this reason, the UN Joint Logistics Center has been formally established in 2002 with the aim of collecting and disseminating critical information and setting up information-sharing tools (Kaatrud et al., 2003).

Trust and partner selection

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

Identification and division of costs

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

4.2.3. Capabilities and resources

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

Capabilities

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

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

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

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

It can be concluded that modeling commercial logistics capabilities

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

Resources

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

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

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

5. A basic game-theoretic PPEC-approach

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

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

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

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

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

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

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

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

5.1. The model

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

Many measures are conceivable for such joint planning. These

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

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

5.1.1. Basic structure

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

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

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

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

$$L\left(x^N, x^C\right) = \varepsilon\left[\mu\left|D - x^N - x^C\right| + \overline{B}^C\right] + B^N, \quad x^N \geqslant 0, \quad x^C \geqslant 0 \tag{1}$$

The term $\left|D - x^N - x^C\right|$ 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 $\mu \geqslant 1$ takes into consideration that the losses, which result out of uncovered need in the population (deprivation) have a different unit than all other cost components, which are expressed in monetary units. By increasing μ, the state can give more weight to the distribution of goods compared to budget concerns; for $\mu \to \infty$ it gives absolute priority to people's needs and completely ignores budget restrictions. The terms $\overline{B}^C$ 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 $\overline{B}^C$. 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 $\overline{B}^C$ will certainly be a larger budget than $B^N (\overline{B}^C > B^N)$, 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:

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

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

The normal-times budget is spent for the procurement of emergency stock under regular (market) conditions and for investment in collaboration (budget Eq. (2)). The crisis-budget (budget Eq. (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 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.

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

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

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

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 $\theta_S\, \theta_F$.

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

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):

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

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

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

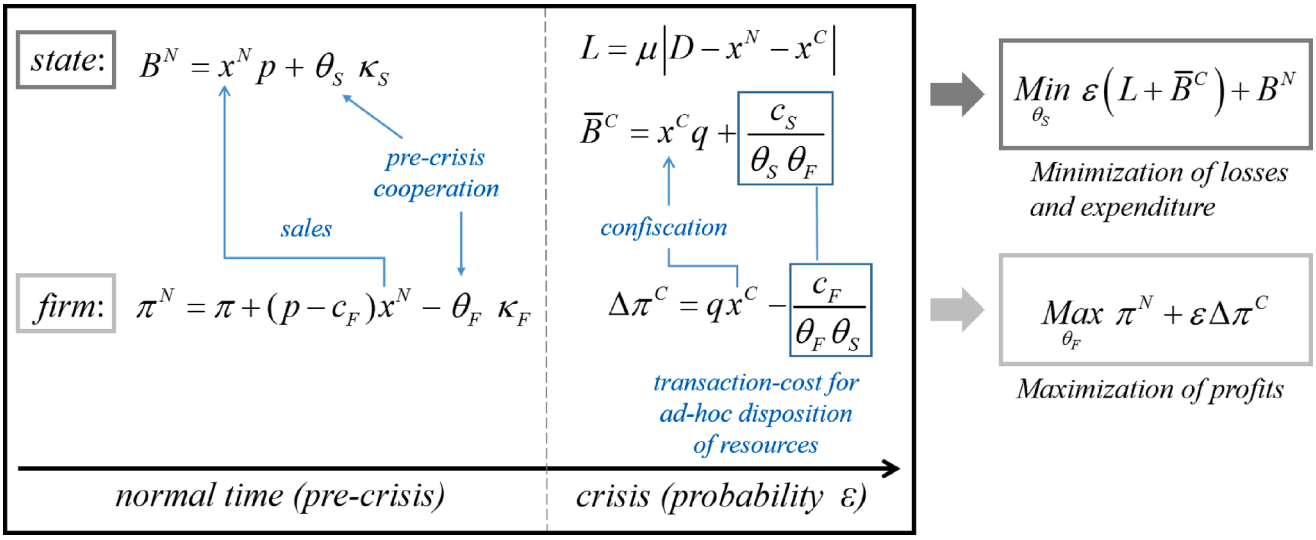

Fig. 4. Overview on model components.

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).

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

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

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

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

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:

$$\theta_S \geqslant \sqrt{\frac{\kappa_F}{(\varepsilon(c_F + c_S))}} \frac{c_S}{\kappa_S} \tag{10}$$

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

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 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 Fig. 5 illustrates this effect: The integration of the reputation term increases the reaction curve of the company and leads to higher collaboration rates of the firm. However, as collaboration rates are (imperfect) substitutes, the state will slightly reduce its level of collaboration and can use the saved resources to increase the emergency stock x^N.

Just as in the case of CSR, reputation does not automatically increase, but actions must be credible from the customer's point of view. Since reputation is a long-term mechanism, the company must be able to provide the externally visible resources and competence on a long-run basis. However, if customers have the impression that a company pretends to play a supportive role in humanitarian operations for tactical

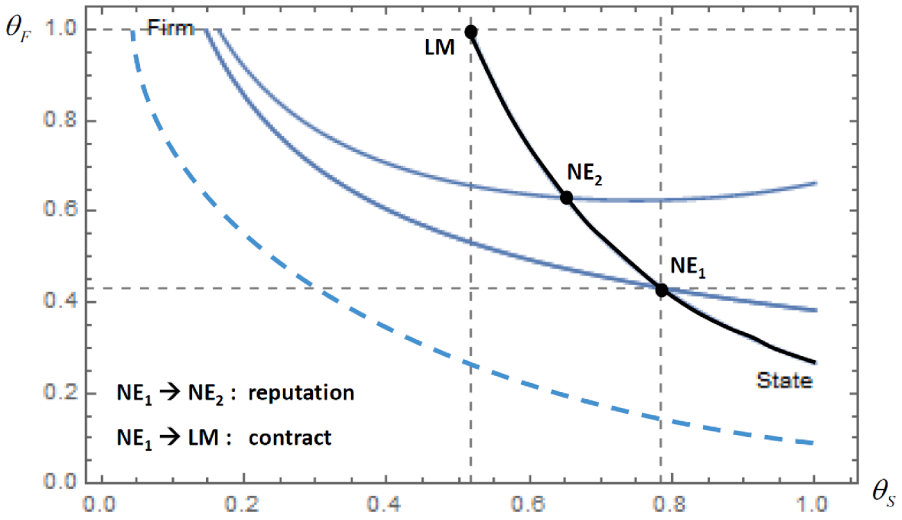

Fig. 5. Best-response functions.

reasons only, this critical perception can backfire and seriously damage the firm's reputation (Stewart et al., 2009; Donia et al., 2017). In the area of crisis management, a particularly high level of sensitivity on the part of the public can be expected, as human lives are at stake here.

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 $\theta_S^{LM}, \theta_F^{LM} = 1$ can be found at point LM in Fig. 4. However, a higher level of collaboration reduces the firm's profit (otherwise a PPEC would also be feasible in absence of any additional incentive). To motivate the company to participate, the state has to guarantee an outcome equal to the individually optimal position $\pi^*\ (\theta_S^*, \theta_F^*)$ to the firm. To achieve this, the state must compensate the company in monetary terms, say by a monetary transfer t. One aspect that favors the use of mechanism design in the context of a PPEC is the fact that the party to be compensated (the company) is also primarily interested in monetary payments. In order to seek an agreement with the company that comes as close as possible to the preferred target level $\theta_F = 1$, the state solves the minimization problem (11):

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

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

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

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

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

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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