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Mitigating personal protective equipment (PPE) supply chain disruptions in pandemics – a system dynamics approach

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Abstract

Purpose – The coronavirus disease (COVID-19) pandemic has emerged as an unprecedented health crisis worldwide and heavily disrupted the healthcare supply chain. This study focuses on analysing the different types of disruptions occurring in personal protective equipment (PPE) supply chains during the COVID-19 pandemic and on proposing mitigation strategies that are fit to the global scale and many interdependencies that are characteristic for this pandemic. The authors construct a conceptual system dynamics model (SD) based on the literature and adjusted with the use of empirical data (interviews) to capture the complexity of a global supply chain and identify leverage points (mitigation strategies).

Design/methodology/approach – This research follows a mix-methods approach. First, the authors developed a conceptual framework based on four types of disruptions that usually occur during health emergencies (direct effect, policy, supply chain strategy, and behaviourally induced disruptions). Second, the authors collected and analysed data from interviews with experts in the PPE supply chain. Based on the interviews data, the authors developed a conceptual system dynamics (SD) model that allows to capture the complex and dynamic interplay between the elements of the global supply chain system, by highlighting key feedback loops, delays, and the way the mitigation strategies can impact on them. From this analysis, the authors developed four propositions for supply chain risk management (SCRM) in global health emergencies and four recommendations for the policy and decision makers.

Findings – The SD model highlights that without a combination of mitigation measures, it is impossible to overcome all disruptions. As such, a co-ordinated effort across the different countries and sectors that experience the disruptions is needed. The SD model also shows that there are important feedback loops, by which initial disruptions create delays and shortages that propagate through the supply chain network. If the co-ordinated mitigation measures are not implemented early at the onset of the pandemic, these disruptions will be persistent, creating potential shortages of PPE and other critical equipment at the onset of a pandemic – when they are most urgently needed.

Originality/value – This research enriches the understanding of the disruptions of PPE supply chains on the systems level and proposes mitigation strategies based on empirical data and the existing literature.

Keywords COVID-19 pandemic, PPE supply chain, Supply chain disruptions, Public health supply chain, Behaviour, Policy, Conceptual system dynamics model (SD), Empirical study, Health emergencies and supply chain disruption

Paper type Research paper

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1. Introduction

The coronavirus disease (COVID-19) pandemic has emerged as an unprecedented global health crisis. As health authorities were scrambling to combat the disease, the very pandemic they are fighting has disrupted global supply chains (SC) and their access to personal protective equipment (PPE) and other critical items. The closure of production lines, lack of transportation capacity, and limited access to affected regions due to lockdowns led to PPE shortages (Livingston *et al.*, 2020). The COVID-19 pandemic has created both supply and demand uncertainties and capacity fluctuations, causing gaps and disruptions in global healthcare supply chains (Haleem *et al.*, 2020; Iyengar *et al.*, 2020).

The focus of this research is on analysing the different types of disruptions occurring in PPE supply chains during the COVID-19 pandemic, and on proposing mitigation strategies. We construct a conceptual system dynamics model (SD) based on the literature and adjusted with the use of empirical data (interviews), to better capture the complexity of a global supply chain and identify leverage points (mitigation strategies). We focus on PPE, because it represents a strategic product category whose supply chain was heavily affected by the pandemic. In terms of context, this study looks at the European public health systems where the decision of PPE procurement is centralised, and government driven.

Normally, health emergencies such as epidemics are events that overwhelm a health system and require external aid. Typically, the assumption is that external aid can be provided from other regions that have not been affected by the emergency. A pandemic is exceptional in that it impacts the whole world at the same time with unknown timing and up/downscaling (Handfield *et al.*, 2020; Park *et al.*, 2020; Schumacher *et al.*, 2021; Rozhkov *et al.*, 2022). As such, it becomes impossible to refer to unaffected regions for aid. This limits the possibilities to cross-utilise resources. Thus, COVID-19 is a unique global health emergency, an event that causes impact at multiple levels of the supply chain at the same time.

During the first wave of the COVID-19 pandemic (Mar. 2020–Sept.2020), the PPE market experienced a rapid surge of global demand which was further amplified by panic buying, speculative stockpiling, and their related bullwhip effects. Many countries faced shortages of face masks due to their exclusive production in China (Chopra, 2020). Wuhan in China not only was the epicentre of COVID-19 but also the largest manufacturer of nonwoven fabrics used in the production of PPE (Kuttner, 2022).

Because of the urgent need for PPE and the pressure to respond, governments and political decisions played an unprecedented role in the PPE supply chain. Governments imposed policies like lockdowns and quarantines (Schumacher *et al.*, 2021) as well as export bans on PPE supplies (Park *et al.*, 2020). While these measures promised to alleviate the pressure on the short-term, the supply chain disruptions caused by these measures in combination with behavioural phenomena like herding and panic buying led to delays and disruptions that cascaded through the PPE supply chain. Furthermore, policy recommendations for PPE use, and even the technical specifications for PPE have kept on changing during this pandemic, following the evolution of the COVID-19 pandemic, of different variants.

Extant literature of supply chain risks and disruptions follow a traditional risk management approach and categorises risks to product (PPE) manufacture, transportation, availability (e.g. Miller *et al.*, 2021) or supply, demand, and control risks (Van Hoek, 2020). But supply chain disruptions during the COVID-19 pandemic have demonstrated that risk models trying to isolate and manage only one aspect of a complex system always fall short, as they fail to address non-linear behaviour caused by feedback loops, potential delays, and lead to undesirable side effects. The complexity of the PPE supply chain system during the outbreak of pandemics needs to be further analysed using different methodologies. What is missing thus far is robust empirical evidence supervised by system analysis of the factors that drive PPE supply chain disruptions, their mitigation measures, and their interdependencies as they propagate in interlaced supply chains during epidemics and pandemics. This research aims to systematically analyse the phenomenon and seeks to answer the following research question:

(1) Which mitigation strategies can be used to overcome different causes of PPE supply chain disruptions and ensure the availability of the strategic goods during global health emergencies, while integrating the many interdependencies and feedback loops characteristic for pandemic supply chains?

We followed a mixed approach, combining qualitative data with SD methodology to answer this research question. First, based on the relevant literature published until 2021, we developed a conceptual framework of what causes disruptions during health emergencies (Kumar and Chandra, 2010; Nagurney, 2021; Ranney *et al.*, 2020; Evenett, 2020; Lee *et al.*, 1997; Patrinley *et al.*, 2020; Zheng *et al.*, 2011). This framework guided the collection of qualitative data from interviews with PPE supply chain experts in the first wave of the COVID-19 pandemic to identify mitigation strategies. Based on the findings from the interview study and existing literature, we constructed a conceptual SD model that highlights key mechanisms causing PPE supply chain disruptions (supply chain elements, feedback loops and delays) and how mitigation strategies can leverage them. We combined the insights derived from the interviews with the SD model to propose mitigation strategies to counter the PPE supply chain disruptions caused by the pandemic. Finally, we developed four propositions for SCRM in global health emergencies and made four recommendations for policy and decision makers involved in pandemic response.

The remainder of this article is organised as follows. Section two gives an overview of the literature on disruptions in supply chains and mitigation strategies during health emergencies and provides our conceptual framework. Section three explains the methodology and how we collected and analysed the qualitative data. Section four reports the results of our study both the qualitative as well the SD results. Section five includes recommendation for the supply chain management. The article concludes with section 6 that includes, conclusions, limitations, and avenues for further research.

2. The relevant literature and the conceptual framework

Research on health emergencies is situated at the intersection of two research streams: health (care) operations, and humanitarian supply chain management. Both fields have tackled questions of epidemic response. There is a common understanding that epidemics simultaneously disrupt supply and demand of medical supplies and health care provision overall. Epidemics do not disrupt critical infrastructures (Kumar and Chandra, 2010), though there may be cross-sectoral impacts between health and nutrition, or health and water and sanitation (Kachali *et al.*, 2018). At the same time, infectious disease outbreaks are also typical for the aftermath of other emergencies (Charnley *et al.*, 2021). Pandemics differ from those events in their (by definition) global scale. Some prior epidemics (e.g. avian flu, Zika, SARS, MERS) have had global repercussions, though often with an incident evolution across different geographies and rarely affecting the globe simultaneously. The sheer size, waves, and simultaneous impact of the COVID-19 pandemic makes it rather unique also from the perspective of the impact of related supply chain disruptions.

Supply chain disruptions during large scale health emergencies could occur because of the (1) *direct effect of an outbreak*, like sick workforce, leading to reduced production or retail capacity and thereby supply (Kumar and Chandra, 2010; Nagurney, 2021; Ranney *et al.*, 2020), as opposed to (2) *policy induced disruptions*, like export bans (Evenett, 2020), travel bans and quarantines, indirectly restricting cargo movement (Nuzzo *et al.*, 2014; Singh *et al.*, 2020). Disruptions could also occur because of (3) *pandemic-induced behaviours*, like bullwhipping, panic buying, hoarding, as well as speculative pricing and fraud (Lee *et al.*, 1997; Patrinley *et al.*, 2020; Zheng *et al.*, 2011). In addition, (4) *supply chain strategy-induced disruptions*, due to single sourcing or lack of risk management plans (Kumar and Chandra, 2010; Tang, 2006) exposing medical supply chains to severe disruptions if those suppliers are affected by an epidemic. Figure 1 presents the four types of disruptions identified by the existing literature and used as a guidance to collect empirical data as we describe in section 3.

Extant literature published until 2021 suggests various mitigation strategies to manage such supply chain disruptions, for example, the concepts of supply chain "agility", "flexibility", "responsiveness", and "resilience" are recommended by many studies to overcome disruptions (Ye *et al.*, 2022; Heckman *et al.*, 2015; Jüttner and Maklan, 2011; Gupta *et al.*, 2021; Kim *et al.*, 2015; Tang and Tomlin, 2008). The overall idea is to either own additional surge capacities or have access to them in different ways by building flexible, agile, and responsive supply chains (Flynn *et al.*, 2021; Finkenstadt and Handfield, 2021; Sodhi and Tang, 2021; Handfield *et al.*, 2020; Golan *et al.*, 2020; Ivanov, 2020a, b). Owning additional capacity aside, access to surge capacity often involves business in the form of additional suppliers, or even joint endeavours through public-private partnerships (Balcik *et al.*, 2010; Tomasini and Van Wassenhove, 2009). Access to joint surge capacities is based on supply chain visibility (Handfield *et al.*, 2020), both in terms of extant inventory but also scheduled arrivals (Tatham *et al.*, 2017). Pre-positioning relevant supplies at strategic locations to bridge initial surges in demand is recommended by many researchers and used in emergency response (Altay *et al.*, 2009; Comes *et al.*, 2020; Kovács and Spens, 2009; Tang, 2006; Toyasaki *et al.*, 2017). Strategic national stockpiles follow a similar logic (Handfield *et al.*, 2020; Kachali *et al.*, 2018).

A different approach to mitigation is to ensure the interoperability of items, identification of interdependencies, and the preparedness of joint modules (Saïah *et al.*, n.d.) or even kits (Vaillancourt, 2016). Kitting interdependent items to ensure all of them are available when needed, and to ensure the interoperability of the response across organisations is used in the humanitarian context and is considering as important element to ensure effective response in

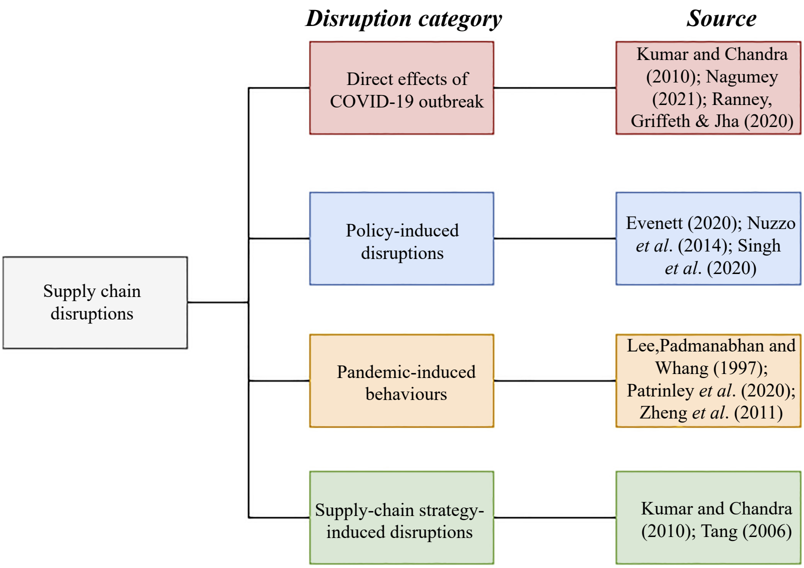

Figure 1.
Conceptual framework: different categories of supply chain disruptions and the corresponding source literature

disasters (Jahre and Fabbe-Costes, 2015; Vaillancourt, 2016; Kovács and Falagara Sigala, 2021).

Multiple sourcing strategies, both across multiple suppliers and multiple geographic regions, to overcome shortages from one site or supplier are also recommended as mitigation strategies to disruptions (Yang *et al.*, 2018; Berger and Zeng, 2006). Pre-qualifications of suppliers, and framework agreements for quicker scaling up to meet surge demand is used in the humanitarian context as a mitigation strategy to ensure the availability of items when is needed (Gossler *et al.*, 2019).

Recent literature also suggests further mitigation strategies to supply chain disruptions, including in pandemic response. For example, Handfield *et al.* (2020) looked at the pandemic response of the US to COVID-19 with the focus on common goods like PPE, hospital beds, and testing, and proposed flexibility, traceability and transparency, persistence, and responsiveness, globally independence, and equitability as key attributes to strengthen the national supply chain system. Furthermore, and again with the focus on the US, Finkenstadt and Handfield (2021) suggested visibility and velocity as the two key attributes that are required to enable critical decision-making accuracy. By increasing the visibility and velocity of the supply chain, it will increase the ability of local, state, and federal healthcare and public health decision-makers to respond to shifts in the US system. In contrast, our research focuses on more centralised public health systems, like the ones in Europe that depend on the global PPE supply chain.

Traditional SCRM categorises risks to product (PPE) manufacturing, transportation, and availability (e.g. Miller *et al.*, 2021) or supply, demand, and control risks (Van Hoek, 2020). But supply chain disruptions during the COVID-19 pandemic have demonstrated that risk management approaches that aim to isolate and manage only one aspect of the complex supply chain system fall short, as they fail to address non-linear behaviour caused by feedback loops, potential delays, and lead to undesirable side effects. As such, they fall into the category of systemic risk, which are characterised by complexity and interconnectedness, uncertainty, and dynamics, as well as ripple effects that go beyond the initial risk source (Renn, 2021). Yet, this systemic approach to risk management is largely absent in the supply chain literature. Delays from the detection of (first) infections, long lead times and quality control, further exacerbate these effects and mandate systems view on risk management. What is missing is robust empirical evidence and a system analysis of the factors that drive PPE supply chain disruptions, the mitigation measures, and the interdependencies as they propagate in interlaced supply chains during pandemics.

This article intends to make a headway in bridging this research gap by using conceptual SD models based on empirical data. The SD approach allows to capture the systemic interactions and establish causal relations between different factors and actors engaged in the increasing complexity of organisational objectives and outcomes. It is an effective modelling paradigm for obtaining insights into problems with dynamic complexity and policy resistance (Besiou *et al.*, 2011). Thus far, however, the literature on disruptions caused by global pandemics using systems dynamics modelling is limited (Ivanov, 2020a, b; Schumacher *et al.*, 2021; Mandal, 2017; Patel *et al.*, 2017).

To conclude, our study differs from previous ones on PPE supply chain disruptions in the following aspects. First, the first stream of literature related to COVID-19 is theoretical and similar to traditional supply chain disruption literature. In contrast, we empirically investigated the mitigation strategies and the action that the key stakeholders of PPE supply chains should take to overcome supply chain disruptions caused by the COVID-19 pandemic. Second, we combine empirical research with SD methodology to investigate interlinkages and feedback loops that occur in the PPE supply chain and propose mitigation strategies, which extends on the extant knowledge from studies that review primary and secondary data (such as Finkenstadt and Handfield, 2021). In addition, our research differs from recent studies on PPE supply chains both with respect the to its contextual focus being on European public health systems where supply chain decisions are more centralised, as well as in terms of extending the view beyond the typical manufacturing capacity focus on the PPE supply chain (as in Armani *et al.*, 2020; Gereffi, 2020) to incorporate also other aspects.

3. Research design and methodology

This paper is part of a larger COVID-19 research project with the focus on the impact of the COVID-19 pandemic in the European context. As such, the project is embedded in a more centralised public health system. The overall objective of this research project is to improve the effectiveness and efficiency of the response to the COVID-19 outbreak from the perspectives of governance, epidemiological modelling, as well as supply chain management. The project includes a variety of end users, i.e. organisations that have responded to the COVID-19 pandemic in different capacities and that are part of the project consortium. They are healthcare providers and medical humanitarian organisations including those running clinics and hospitals, emergency medical teams, and medical aid deliveries around the world. These organisations were instrumental in the research and in identifying expert respondents. The project started in the first wave of COVID-19 in March 2020 with the focus on the European public health systems and how these were affected by supply chain disruptions.

This research follows a mixed methods approach. First, we analysed the literature on supply chain disruption and mitigation strategies in health emergencies, and we developed a conceptual framework of four types of disruptions that occur during pandemics and epidemics. Second, we conducted interviews with experts of PPE supply chains to validate and better understand our findings from the literature with respect to the disruptions and mitigation strategies. Third, we used the data and results from the interview study to identify causal relations and feedback mechanisms between key variables of the PPE supply chain system. From there, we developed a conceptual SD model that captures the identified mismatches between PPE supply and demand. The SD methodology is commonly used for the analysis of complex systems and designing policy interventions (Sterman, 2001). As such, SD has been proven useful to analyse strategic decisions aimed at mitigating the disruptions caused by pandemics (Olivares-Aguila and ElMaraghy, 2019). Our SD model complements the results from the empirical study in highlighting key feedback loops and the way specific mitigation strategies impact on them in the COVID-19 pandemic. Figure 2 presents the research process that we followed.

3.1 The interview study

The main reason for using an interview study was to capture not just the phenomenon of disruptions and mitigation strategies, but especially their underlying causes and interrelations as they occurred in a pandemic context with global effect. Since the phenomenon and the literature on supply chains in the pandemic context is limited, we took an exploratory approach to investigate how organisations responded to supply chain disruptions caused by the COVID-19 pandemic and how they enhanced their ability to avoid upcoming disruptions. Interview respondents were identified through a combination of snowball and criterion sampling, complemented by convenience sampling. First interviews were with project end users. These interviewees were also used to identify other relevant organisations and experts. Further experts were identified through the networks of project members. In addition, medical NGOs also contacted us directly to express their interest to contribute to the study.

In total, 80 organisations were contacted for this study, resulting in 38 interviews with experts during May–September 2020. Respondents came from different geographical areas

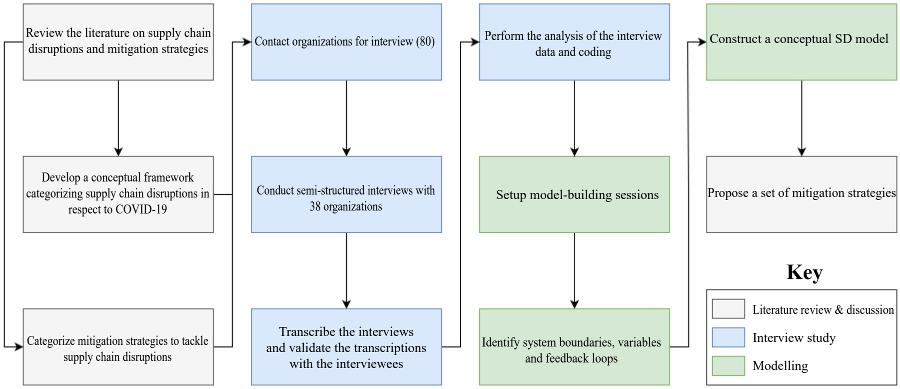

Figure 2.
Research process

(Europe, China, US and Canada) and included experts from non-governmental organisations (NGOs), health care providers, health professionals (medical doctors and nurses from hospitals), pharmaceutical professionals, decision-makers of ministries of health, medical item and equipment suppliers, and PPE manufacturers (see Table A1). To better understand the logistics challenges and the mitigation actions, we targeted roles related to the supply chain, procurement, and logistics within these organisations. We talked to logistics directors, procurement and supply chain managers, sourcing directors and emergency response managers. The mix of the different roles that we interviewed helped us to understand the supply chain disruptions that occurred along with the corresponding mitigation actions that different types of organisations used.

Prior to the interviews, a semi-structured interview guide was developed. Semi-structured interviews allow to capture emerging, new insights, as respondents can express their experiences and add insights that were not anticipated (Fawcett *et al.*, 2008). The interview questions are guided by the conceptual framework of supply chain disruptions (see Figure 1).

Due to travel restrictions and social distancing rules, all interviews were carried out online via MS Teams or Zoom. Interviewees were contacted via email to set up the calls and consented actively to their participation. Most of the interviews were held in English, except for two that were conducted in, and later translated from, Cantonese. Interviews lasted between 45–60 min each. They were recorded, and then transcribed using the automated transcription function of NVivo, a qualitative data software program that has also the ability to organise and code data (Dean and Sharp, 2006). Transcripts were manually cross-checked by the research team as well as the respondents.

Using NVivo, the data was coded with respect to the causes of PPE supply chain disruptions which are identified from the literature and mitigation strategies to overcome them. The coding paradigm of Corbin and Strauss (2015) was followed, which consists of open, axial, and selective coding, as it provides a thorough and structured approach for examining the phenomenon of interest while leaving room for upcoming new categories.

First, open coding was introduced based on the four types of disruptions identified by the literature. In NVivo, open codes were introduced as free nodes (direct effect of COVID-19, policy induced disruption, strategic induced and pandemic induced disruptions) and measurements taken or suggested to overcome those disruptions. Then, axial coding was used to identify themes and subcategories. During this process, we identified the effect of the disruptions on different areas. We continued with the selective coding as the final stage in the data analysis, resulting in selected core categories and sub-categories (capacity, regulations, strategic dimensions as well as on the behaviours). Table A2 shows the resultant nodes and their subcategories, what causes them (fourth type of disruptions identified from the conceptual framework and validated by our data), include representational quotes from the data and the mitigation strategies and the representative quotes.

The quality of the empirical study can be assessed by the dimensions of pre-understanding, credibility, transferability, dependability, conformability, integrity, and utilisation, as recommended by supply chain researchers for qualitative studies (Flint *et al.*, 2002; Halldórsson and Aastrup, 2003; Kaufmann and Denk, 2011). The researchers in the study have worked with medical supply chains before, shaping their pre-understanding. Regular discussions among project team members and with end users further contributed to the deeper understanding of medical supply chains in pandemics, the credibility of the analysis, especially with regards to emerging themes and their categorisation, and the integrity of interpretations. Integrity was further attested by the respondents who cross-checked their transcripts. Transferability was addressed by using respondents from various geographical areas and expert roles.

During interviews, respondents reflected on their expertise and previous experience. Knowledge was constructed together in the research team, increasing the conformability of the research. The utilisation of results was increased by the cross-checking of transcripts by respondents, but also by the organisation of a stakeholder workshop in October 2020 to which end users, respondents, and other stakeholders were invited, including a wider audience of experts in the same and similar roles of expertise. To ensure triangulation, we compared responses across respondents and with the existing literature and we had access to the reports of the organisations that are involved in the study related to their response to COVID-19.

3.2 System dynamics modeling

The results of the interviews data analysis informed the SD model. At its core, SD models complex dynamical systems and helps to understand them by building a causal theory of the interaction of their numerous parts represented in a causal loop diagram (Pruyt, 2013). It also allows taking into account non-linear relations between system elements, feedback loops and delays, which are critical for supply chain planning. While insights from the SD methodology and related concepts can generate managerial insights (Turner *et al.*, 2018), an alternative is to develop a conceptual model, which later can inform a simulation model (Zhao *et al.*, 2019). In this study we are focused on the second. Importantly, SD is not the only methodology to model complex systems. Other examples are complexity science (CS), with its core concept of a complex adaptive system (CAS) and discrete-event simulation (DEVS). CAS has a set of novel and potentially useful for supply chain concepts such as *resilience*, *self-organisation*, etc (Van Dam *et al.*, 2012). CAS is typically either a *network* or an *agent-based model* (Mittal and Risco-Martín, 2017). The individual elements of these models "grow" the overall behaviour of a system through a set of interactions at micro-level (Epstein, 1999).

The second methodology - DEVS, is more conventional (Mansharamani, 1997). DEVS models a system through interaction between *entities* (e.g. trucks) in a series of *events* (e.g. load-unload) where they change their *state* (e.g. empty-full). One helpful way of distinguishing these three modelling methodologies is how they look at the system of interest. SD assumes that a system can be modelled "top-down" - a modeller has enough information to capture its mechanisms from the "bird's eye view". Such an approach is useful for models on a large scale: national economy, population growth and so on. On the contrary, CAS operates "bottom-up" - a modeller does not try to model a particular system's behaviour. Instead, they look for an emergent phenomenon generated by those interactions by defining a simple set of interactions. CAS is often used for small and mid-scale models: virus spread, segregation in a city (Tisue and Wilensky, 2004). DEVS takes a mid-standpoint instead. A modeller has to have a bit of "top" and "bottom" knowledge about the system of interest.

All three modelling methodologies can potentially bring insight into a complex system. Our rationale to choose SD is threefold: (a) the scale of a system - a global supply chain, the information derived from the interviewees, (b) delays, focusing on key actors such as suppliers, customs, etc., and finally, (c) the availability of data - at the time when the study was conducted there was a lack of reliable data about the impact of the pandemic on the key elements of the global supply chain.

In supply chain management, SD has been used for modelling supply chain uncertainty under different conditions including aspects of interest to our study, such as capacity planning (Cheng *et al.*, 2008), behavioural patterns and the related bullwhip effect (Langroodi and Amiri, 2016; Özbayrak *et al.*, 2007), but also humanitarian supply chains (Besiou *et al.*, 2011), medical supply chains (Attridge and Preker, 2000; Mirchandani, 2020), and even to demonstrate the repercussions of a workforce being sick in an epidemic and its impact downstream the supply chain (Kumar and Chandra, 2010).

In this article, we used the results from the qualitative study to construct a conceptual SD model in the form of a causal loop diagram (CLD). The purpose of this model is threefold: (1) connect the main elements of the PPE supply chain into a system, (2) explain the potential causes of disruptions with feedback loops and delays, and (3) propose a set of interventions with mitigation strategies to understand systemic supply chain risk. Our approach for developing the model is as follows. We use existing models on supply chain disruptions as a base, and interview data to guide the further work. Based on the empirical data from the COVID-19 pandemic, we then adjust and adapt the model to this case. To do so, we follow the stepwise approach proposed by Pruyt (2013), where we start by identifying the main problems formulated by the interviewees and end by formulating a dynamic hypothesis explaining how disruptions are generated by the model structure, and how the identified strategies can contribute to mitigate these disruptions. More specifically, we started by mapping the "elements" of the system - the global supply chain of PPE, from the interviewees' perspective: stock of *PPE items*, *PPE items in production*.

The SD methodology allows us to incorporate not only "physical" elements of the system (e.g. *stock of PPE items*) mentioned by the interviewees but also other, more "conceptual" (e.g. *panic buying*). Next, we connect those elements with casual relations - how does one element affect another and is this link positive or negative? For example, how *panic buying* affects the number of *items in production*. The effect of one element on another can be nonlinear and with a delay: an increase in *customs clearance time* may result in fewer items in stock. If an interviewee indicated a delay, we added it to the causal loop diagram. The identified elements and casual relations create feedback loops: several connected elements looped on themselves. In case of a conflict of opinion, one interviewee says that the causal link is negative while the other thinks it is positive; we contacted both of them to resolve it. Overall, we intend to create a more comprehensive description of the system. Finally, we search for potential ways to manage the system's behaviour through a set of mitigation strategies proposed by each interviewee. We specifically focus on the mitigation strategies that are special to the pandemic to estimate their potential effects.

4. Results

We first present the empirical results from the interview study and then we present the SD models: the PPE supply chain disruptions model and the model where we introduce mitigation strategies for PPE supply chain disruptions.

4.1 Empirical results

Our empirical results showed that all four types of disruptions identified from the literature had an impact on the different aspects of the PPE supply chain (see the coding scheme and representative quotes from the interviews in Table A2).

The pandemic itself had a *direct effect* on the organisations involved in the PPE supply chain through sudden surges (and later fluctuations) in demand, at the same time as PPE producing companies experienced capacity constraints in their production due to their own workforce being sick, or due to lockdowns.

Policy-induced disruptions such as travel bans and export bans had strong negative effects on the transportation, import and export of PPE. The dominant *supply chain strategies* of single sourcing and lean health care led to further disruptions. Most PPE producers came from China, and when these companies experienced the direct effects of the pandemic (especially sick workforce), the lack of alternative suppliers, and alternative regions whence to procure PPE resulted in a lack of PPE altogether; not being able to meet the global surge in demand. SCRM literature often notes the dangers of single sourcing; what is novel here is the accentuation of not just a single supplier failing, but sourcing from one single region.

Pandemic-induced behaviours further exacerbated disruptions in the PPE supply chain. Surges in demand not only led to surges in prices but also to gaming with those through withholding supplies from the market until prices would rise. At the same time, governments outbid one another for the same PPE, and their panic buying resulted in a lose-lose situation for all. Sadly, this situation gave rise to fraudulent behaviour as well, with fake companies, counterfeit products, and even cargo theft.

Apart from unearthing all these disruptions, our interviews also discovered which *mitigation strategies* were used to counter them. In the past, typical mitigation strategies to counter supply chain disruptions in epidemics had included pre-positioning (Altay *et al.*, 2009; Comes *et al.*, 2020; Kovács and Spens, 2009; Tang, 2006; Toyasaki *et al.*, 2017), kitting (Jahre and Fabbe-Costes, 2015; Vaillancourt, 2016), multiple sourcing (Yang *et al.*, 2018; Berger and Zeng, 2006) and pre-qualifying (alternative) suppliers (Kumar and Chandra, 2010; Tang, 2006).

We found evidence of all of these mitigation strategies (see Table A3), but also some new nuances to them, and some further ones that were used in the pandemic. In the area of *pre-positioning*, health care systems that had some PPE inventory fared better in the first wave of the COVID-19 pandemic and bought themselves the necessary breathing time to search for alternative suppliers. Pre-positioning is a common mitigation strategy employed by humanitarian organisations globally, as well as disaster management organisations in their respective countries and is proved to work effectively (Toyasaki *et al.*, 2017).

Kitting proved very useful for emergency health care. While typically health care systems work with pull supply chains and stock items individually, in an emergency, it is important to have all items at hand that are needed in a specific operation. However, PPE kits for different roles differ, and this differentiation was highlighted in the interviews. Kitting itself is a method of standardising what is in a package. Standardisation was even more highlighted due to a current lack of *global PPE standards* and technical specifications. Sizes, quality requirements, and other technical specifications differ for PPE in e.g. South-East Asia vs. North America vs. Europe. Interestingly, it is the same PPE producers that produce PPE for all these regions in separate lots, later exporting these lots to different environments. A lack of global PPE standards reduced the possibility for using PPE from one geographical region in another, and created further quality control (and compliance) issues around the world if the PPE was delivered did not match the national requirements. Our results indicate that the standardisation of PPE technical specifications would facilitate the response to COVID-19 from production to transpiration to quality compliance.

In the case of face masks, for example, the standardisation of technical specifications does not extend to performance standards like filtration levels alone, but also to labelling, certifications, and quality management systems in manufacturing. Importantly, we refer to the quality requirements on PPE products, e.g. in terms of their required filtering efficiency. There are different ways to employ such a mitigation strategy: either by agreeing on one product technical specifications standard that is globally acknowledged, or by harmonising existing standards and recognising corresponding ones as equals across different countries.

Multiple sourcing and *pre-qualifying alternative suppliers* are also recommended as mitigation strategies to the disruptions by our data. Single sourcing can be seen as the root cause for many supply side disruptions also in the COVID-19 pandemic. Many organisations were left without medical supplies, because they relied on just one supplier and had to find last minute alternatives. *Multiple sourcing* with flexible supply bases enables companies to shift production among suppliers promptly (Yang *et al.*, 2018). As our data shows, organisations in the PPE supply chain are now re-considering their sourcing strategies. This is not only to find alternative suppliers, but also specifically for geographical diversification of the supply chain, to ensure that PPE is produced also in different countries (i.e. not only in China), and even on different continents.

An additional, procurement-related mitigation strategy is that of *joint procurement*. While little of this was evident in the PPE supply chain prior to the COVID-19 pandemic, organisations did eventually come together either nationally, or across similar interests. We consider joint procurement special to the pandemic since it motivated countries like the EU member states as well as organisations like the International Federation of the Red Cross and Red Crescent Societies (IFRC) to engage in joint procurement of essential products to fight the pandemics. IFRC in Geneva, according to one of our interviewees, consolidated orders of PPEs for the whole membership to make sure that the products will arrive at the needed quality and quantity). Later, joint procurement played a bigger role in for COVID-19 vaccines. Overall, joint procurement increases the buyer's negotiation power, especially under uncertainty (Xianglinga and Ping, 2018). Joint procurement, as well as joint pre-positioning, even as virtual stock, increases the flexibility of the use of items across organisations and regions.

Furthermore, *production changeover* was used across many countries and companies to support pandemic response. As global PPE supply did not meet global demand during the first wave of the COVID-19 pandemic, increasing global supply became the prime issue. Thereby started a race to set up extra PPE production facilities. As highlighted by our interviewees, there is a need to be able to produce a percentage of critical items locally to ensure that they are available in time of emergency. Reshoring and domestic production became a political mantra in many countries. Thus, governments supported domestic production not only through direct financial support and risk sharing of such investments, but also by fast-tracking regulations and certification processes (Sodhi and Tang, 2021).

Production changeover was used across several industries, e.g. the car industry switching to the production of respiratory ventilators, distilleries to manufacture sanitizers, and within PPE, the fashion, garment and textile industries switching to face masks. For example, in the United States of America, in March 2020, the government invoked the Defense Production Act (DPA) which gives the president the authority to compel the private sector to work with the government to provide essential material goods needed for national defence. Different companies made contracts to produce respiratory ventilators. But since there is no mechanism to drive domestic demand towards those producers once cheaper global options become available, there is the risk of losing resources of this investment.

Air transportation was itself disproportionately hit by the pandemic, especially due to policy-induced disruptions (travel bans). However, many medical items including PPE are frequently transported as belly cargo of passenger planes. Applying production changeover principles, airlines converted passenger planes to cargo planes to be able to support pandemic response. The Project Airbridge in the US is an example of successful production changeover that funded flights to shorten the amount of time it takes for US medical supply distributors to bring PPE and other critical medical supplies into the U.S. during the COVID-19 pandemic response.

In summary, our results highlight both different types of supply chain disruptions and also mitigation strategies for the PPE supply chain. Many of these mitigation strategies can be applied to other types of disruptions, and disasters, as well. However, some of them are either emergency health care-specific (such as kitting), and others are specific to a pandemic situation. Such is the accentuation of a need to standardise or at least harmonise PPE across the globe, and to apply production changeover also to transportation.

Most importantly, however, none of these mitigation strategies can be seen in isolation but they are highly interlinked with one another. Disruptions create incident evolutions and cascades, and mitigation strategies may either stop, or change those. Our findings clearly show that no single mitigation measure will be sufficient to address the different types of supply chain challenges encountered. Rather, we argue that a coordinated intervention across the different options is needed. In the following section, we will analyse the interdependencies of the different types of SC disruptions to identify feedback loops and identify the impact of the mitigation measures in the dynamic SC system.

4.2 A system dynamics model of PPE supply chain disruptions

We further analyse the data and the literature to understand the links between the various causes of PPE supply chain disruptions and propose a SD model that captures these causal mechanisms during the first wave of the COVID-19 pandemic. As PPE is primarily produced in China and then exported to the rest of the world (ROW), the modelling is done from the perspective of a Chinese-ROW PPE supply chain. In essence, the model focuses on the supply chain from final manufacturing and assembly (here of medical respiratory face masks in China) to use in health care centres in the rest of the world, with air transportation as common for PPE. Figure 3 depicts the key elements of the PPE supply chain. While a supply chain may have more elements and is more complex, we have focused on those highlighted by our respondents: from the PPE producer to PPE delivery to their users - hospitals. To be more comprehensive, we also highlight two other nodes critical to the global supply chain of PPE but left out of the scope of the study: raw materials and disposal.

The first model presents the baseline performance of the global supply chain system during the first wave of the COVID-19 pandemic in the rest of the world (with data from Apr–Sep 2020) is in Figure 4. It consists of 19 elements: system's variables or stocks (plain text), connected into a system with causal links, four main feedback loops (italic in bold): *COVID-19 outbreak*, *Lack of items*, *Lack of transportation capacity* and *Global supply chain disruption,* and four policies imposed by different actors (text in a rectangle). Altogether, the model's structure generated the undesirable behaviour that led to a lack of PPE in the country of the outbreak aka "customer country" (ROW).

The outbreak itself, i.e. the *COVID-19 outbreak* feedback loop, is at the core of the model (see Figure 4). It is a *negative* (balancing) explaining the rise in the PPE demand given the rise in infections. Given a low initial number of PPE in stock and without a policy to tackle the virus spread (e.g. a lockdown), this feedback loop will seek to maximise the country's infections until it reaches a goal equal to a certain percentage of the population. With an

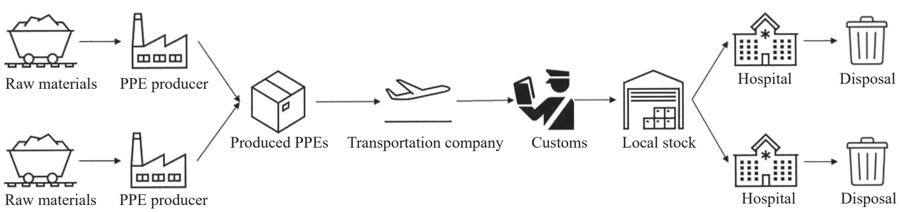

Figure 3. A schematic representation of the PPE supply chain

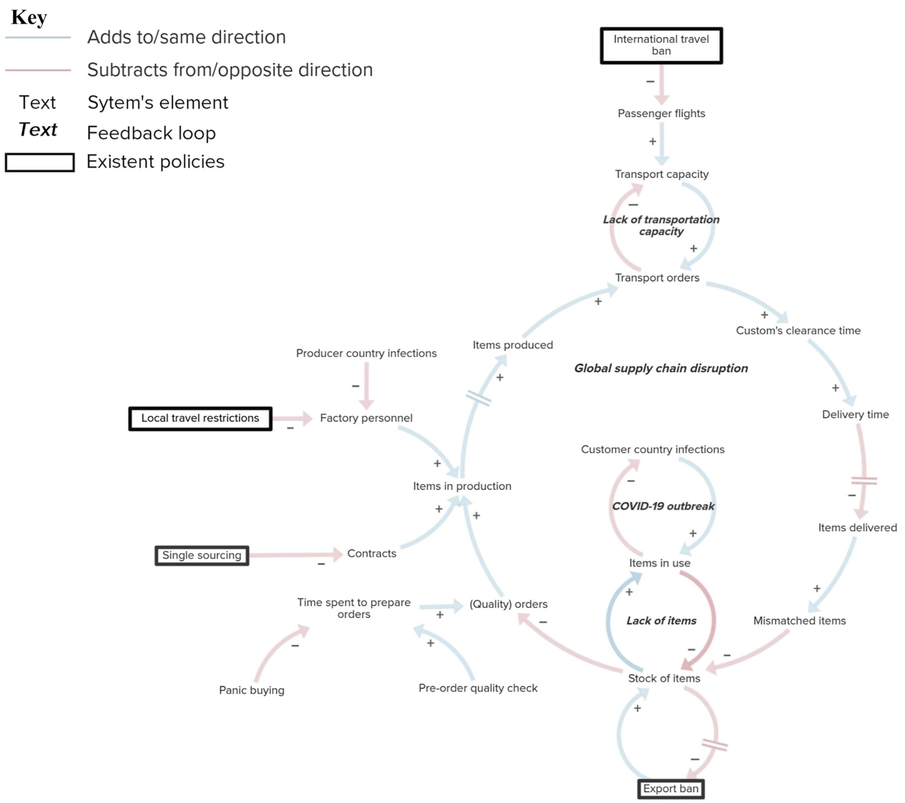

Figure 4.
Causal loop diagram representing PPE supply chain disruptions during the first wave of the COVID-19 pandemic in spring 2020

increase in *Items in use,* the *Stock of items* decreases, and it initiates the order placement represented with *(Quality) orders* stock. On the other hand, *Stock of items* is influenced by a key policy that was employed by various countries in the COVID-19 pandemic: an *export ban*. Such policies were implemented to counteract the quick depletion of the extant stock and provided a temporary effect.

Pandemic-induced behaviours (*panic buying*) significantly impacted how orders were placed. They lead to a perceived rush in procuring the surge capacity needed in the outbreak area. Another affected critical aspect is order's "quality". A quality order in the model represents the one that fits the needs of the healthcare centre, takes all necessary steps of quality compliance, and complies with standards and regulations. Interviewees highlighted that they had spent less time on the *Pre-order quality check*, which often led to a decrease in order quality. In the case of face masks alone, that would extend to any batch delivered to, e.g. EU countries complying with FFP standards and their required levels for use in health care (with FFP3 for intensive care units, surgical masks in health care otherwise). Other PPE included gloves, eye protection, hazmat suits and powered air-purifying respirators. Notably, the requirements of what was supposed to be used were changed several times during the first wave of the COVID-19 pandemic.

The supply side was affected by the pandemic due to both the direct effects of the outbreak, and due to policy-related disruptions. Sick or infected *Factory personnel* could not participate in the manufacturing process anymore. In addition, workers could not get back to factories after the Chinese New Year due to *Local travel restrictions* (lockdowns) imposed by the government. Since factories were often operating at maximum capacity due to the number of orders received, further orders were adhered to with a delay. Such delays propagated throughout the supply chain, with customers receiving orders later than anticipated.

Further, we highlight the supply chain strategy-related disruptions. Especially the number of signed *Contracts* with PPE manufacturers is a matter of single vs multiple sourcing. They impact both on the quantities produced as well as the potential to add surge capacity elsewhere, if personnel at the single source supplier is sick, for example.

Produced items still need to be delivered to their destination, however. A surge in deliveries leads to an increase in *transportation orders*. The bottleneck here is modelled in the *lack of transportation capacity* feedback loop, with remaining *transportation capacity* decreasing with further orders, but also being affected by *international travel bans* and their related decrease in the number of *passenger flights*. The latter is significant since medical items including PPE are often transported in those.

Further steps remain before the PPE is delivered. Here, *customs clearance time* increases with the surge in deliveries, negatively impacting on overall *delivery times*. Any bullwhip effect, and any mistakes induced by panic buying will play out as critical delays and potentially *mismatched items* in the overall *global supply chain disruption* feedback loop.

Overall, the model represents a system's perspective at representing global PPE supply chain disruptions. First, the direct impact of the pandemic limits production capacity. Workforce that has fallen sick cannot participate in the production process anymore and forces the country to impose the lockdown, which in turn will make it impossible for other workers to get back to factories. The single-sourcing strategy further increases dependence on specific suppliers. The thereby reduced capacity with limited potential to rapidly extend production meets an increased demand as countries and people prepare themselves for the pandemic. In combination with pandemic-induced behaviour (e.g, panic buying), this creates a sustained demand shock with limited capacity. The increased pressure on customs combined with low-quality orders further delays delivery of critical medical goods. This leads us to Proposition 1:

P1. The direct impacts of the pandemic lead to reduced production and transportation capacity that coincides with peak demands, leading to amplifying feedback loops and sustained delays.

Further, we observe that transport is affected by both: the pandemic and subsequent policies to respond to it. Here, we find that the policies that are designed to protect people or countries on the short-term from the virus create bottlenecks on the longer-term further down in the supply chain, for instance via the combination of travel and export bans. The final complication is caused by the mismatch between ordered and delivered items, driven by the occurring delays, rushed orders and the lack of common global PPE standards.

P2. Short-term public health policies that are designed to prevent epidemics spread and protect local markets hamper the free exchange of goods and mobility of people, thereby exacerbating supply chain bottlenecks and delays in global and interconnected supply chains.

4.3 Analysing the effects of mitigation strategies for PPE supply chain disruptions

In this section, we present the mitigation strategies that were highlighted as specific to the pandemic and estimate their effects on PPE supply chain disruptions: introducing *global standards* for PPE, *joint PPE procurement,* and using production changeover to *convert passenger* planes *to cargo flights.* In addition, we added *multiple sourcing*. These mitigation strategies are noted in blue in Figure 5. Below, we present the causal mechanisms between the

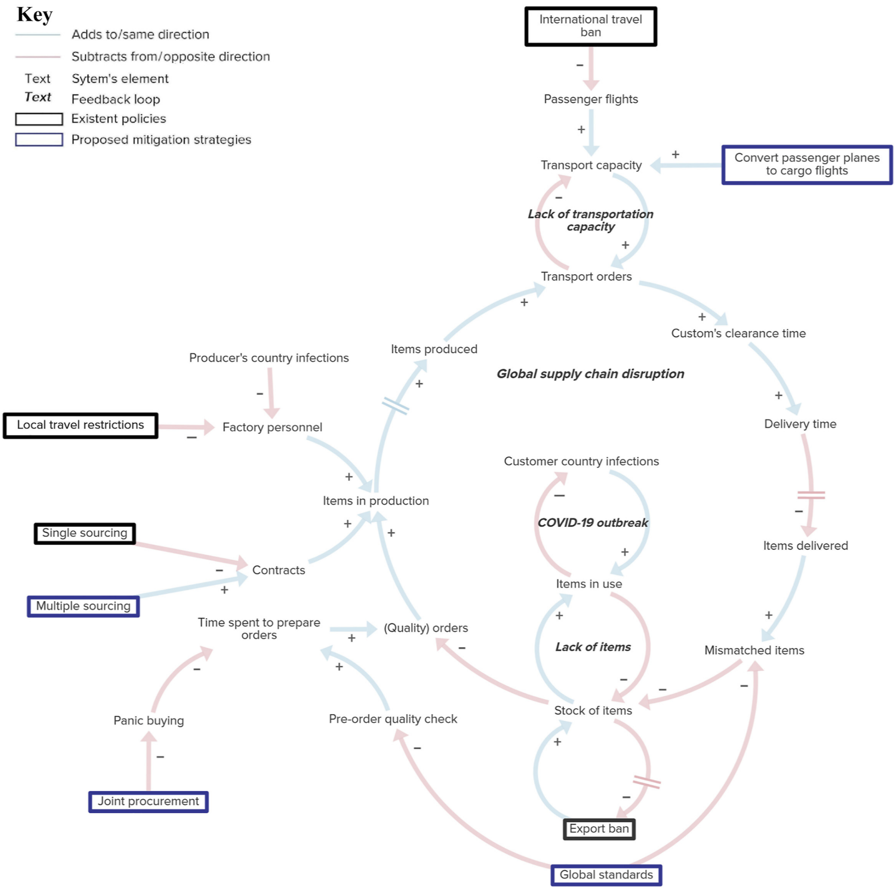

Figure 5.
Causal loop diagram with a set of proposed mitigation strategies and their potential impact

selected measures and how they reduce disruptions, before developing propositions on mitigation strategies.

4.3.1 Standardisation of PPE technical specifications. An increase in the level of standardised parts for products increases production flexibility and helps in having interchangeable product assemblies (Serdarasan, 2013). The mitigation strategy of *global standards* (i.e. PPE product standards, technical specifications, certifications and labelling) reduces the need for additional pre-order quality checks, and indirectly the time to fill in quality orders. It simultaneously reduces potential mismatches between demand and supply.

4.3.2 Production changeover. Production changeover was used across several industries as a means to respond to the pandemic demand. The principles of production changeover were not limited to manufacturing as mentioned in section 4.1, but interestingly, also applied in transportation. Attempts were made to add transportation capacity with repatriation flights, military aircraft and passenger planes converted to cargo on a temporary basis (Spanish Red Cross, 2020). Production changeover in transportation, i.e. converting passenger planes to *cargo flights* increases transportation capacity and reduces delays between order placements, production, and delivery.

Joint procurement reduces pandemic-induced behaviours such as panic buying but also speculative pricing, and price wars. It further reduces the time spent on procurement, and related transaction costs. *Multiple sourcing*, on the other hand, has some of the opposite effects in terms of time spent on procurement overall, but increases the potential for surge capacity, as well as reduces the time spent on finding such resources during pandemic response.

Our model highlights that without a combination of mitigation measures, it is impossible to overcome the disruptions. While in the supply chain literature, the different mitigation measures are often discussed as isolated options that have a greater or smaller impact on a disruption, our model clearly shows that a combination or a bundle of measures is required to manage the complex supply chain risk, leading to the following proposition:

P3. In interconnected supply chains, there are complex interactions between mitigation measures, public health policies, and supply chain disruptions.

Such interactions between measures or policy instruments are increasingly becoming prominent in other fields, such as climate adaptation (Lambin *et al.*, 2014), but are not yet sufficiently considered in SCRM. The presence of such interactions implies that because of the global and cross-sectoral nature of pandemic crises, the planning and implementation requires a coordinated effort across different countries and sectors.

The many difficulties with coordination at the onset of the pandemic in Europe, highlight the challenges for setting up such coordination mechanisms at the onset of a disaster. The SD model also shows that there are important feedback loops, by which initial disruptions create delays and shortages that propagate through the supply chain network. While much of the literature argues for an adaptive approach to disaster management, by which decisions are adjusted to new information, we clearly show that if (co-ordinated) mitigation measures are not implemented early at the onset of the pandemic, these disruptions will be persistent, creating potential shortages of PPE and other critical equipment at the onset of a pandemic – when they are most urgently needed. Therefore, we propose:

P4. The response to pandemic supply chain disruptions shows path-dependencies, by which early decisions can create persistent disruptions, hampering conventional adaptive management approaches.

This proposition is in line with earlier work that confirms that decision-makers in pandemics tend to avoid revising initial decisions (Paulus *et al.*, 2022). However, the delays and feedback loops that we found in this study on PPE introduce further inertia of the physical flows. This likely amplifies the rigidity of the system. Therefore, early coordinated action is crucial following the precautionary principle to prevent persistent and lasting delays.

5. Recommendations for supply chain management

While there are many recommendations that have been made to mitigate supply chain risks, a pandemic is special in threatening the full supply network at the same time. Reflecting the specific challenges of a global health crisis, we identified strategies that are specific to the pandemics, or had nuances that are not conventionally considered. These findings are translated here into four concrete recommendations for supply chain management.

First, global standards for PPE are needed. While regional standards e.g. for face masks have been in place, only global standards of PPE will facilitate the required world-wide ramp up of production, pre-positioning, collaborative procurement, as well as it will decrease the impact of the disruptions occurring by behaviours and capacity constraints. Global standards even reduce potentially fraudulent behaviours such as fake certifications and make it easier to spot counterfeit products. Therefore, our recommendation to policy and decision makers is:

R1. Global PPE technical specification should be adopted to minimise delays and provide efficient and effective response to global health emergencies.

A second pandemic specific mitigation strategy is production changeover, applied not only to manufacturing but also to transportation. Turning passenger airplanes to cargo planes was an effective way of reducing bottlenecks and thereby disruptions in the global PPE supply chain. However, other options can also be explored, including the use of unmanned aerial vehicles that reduce contagion in a pandemic, even though this approach requires the right legislation and regulation in place (Kunovjanek and Wankmüller, 2021). Therefore, our recommendation to policy and decision makers is:

R2. To reduce delays between order placements, production, and delivery and increase capacity during pandemics, production changeover both in manufacturing and transportation should be adopted.

Joint procurement is also considered as a mitigation strategy to the disruptions occurring either from policy or the pandemic itself. Countries and health care organisations should jointly procure PPE during pandemics to ensure better prices and quality and avoid the price wars and speculations that we have observed in Covid-19. Therefore, our recommendation to policy and decision makers is:

R3. Joint procurement should be considered as a strategy to reduce pandemic-induced behaviours such as panic buying, speculative pricing, and price wars. It also reduces the time spent on procurement, and related transaction costs and furthermore improves the response to the pandemic.

In the literature, response diversity has been discussed as an important strategy to improve resilience of complex systems by ensuring a broad range of reactions to a changing environment or crisis (Elmqvist *et al.*, 2003). Translated to supply chains, multiple sourcing is an excellent way to increase response diversity as it ensures that health systems have access to the capacity of different suppliers and increases the availability of items when needed. Here, we refer to multiple sourcing not only in terms of suppliers or contracts, but also in terms of geographical regions. Therefore, our recommendation to policy and decision makers is:

R4. Multiple sourcing in terms of suppliers and geographically diversified areas should be considered to increase response diversity, the potential for surge capacity and to reduce delays during a pandemic.

6. Conclusions

A global pandemic is different from many other supply chain risks, as the entire supply network may face disruptions concurrently or sequentially. Therefore, the aim of this paper is to identify PPE supply chain disruptions and appropriate mitigation strategies to respond to a global health emergency while integrating the many interdependencies of globalised supply chains. To achieve our aim, we draw on literature in health (care) operations, humanitarian operations and SCRM to develop a conceptual framework of four types of disruption occurred during health emergencies (direct effect of the pandemic, policy induced disruption, supply chain strategy induced disruptions as well as behavioural induced disruptions).

Following a mixed methods approach, interview data collected from different actors in the supply chain network was then used to establish the causal mechanisms between various elements in the supply chain, resulting in an SD model. In addition, the unique mitigation strategies that could be used to alleviate PPE supply chain disruptions were then introduced in the model, and the interactions of disruptions and mitigation measures were studied.

While none of these mitigation strategies alone reduce the direct effect of the pandemic on surge demand, especially their combination can alleviate some of the disruptions, and their effects in PPE supply chains. From this analysis, we developed four propositions for SCRM in global health emergencies. These propositions can and should be tested in other cases and contexts. In addition, we provide four recommendations for policy and decision makers to be considered for the development of relevant policies.

Many strategies can be beneficial during a major disruption such as a pandemic, but they also bring challenges that are often not yet well-understood. The pre-positioning strategy, for example, is challenging in terms of items and their expiration dates as well as who pre-positioned the items: governments, hospitals, or firms. As recommended by Handfield *et al.* (2020) and Finkenstadt and Handfield (2021), the US Strategic National Stockpile (SNS) faced an expiration of stockpiles and proposed an update for the inventory management systems of SNS. More research is needed on the different global systems of stockpiles and how they manage their pre-positioned inventories, or how they can collaborate in this respect.

A joint procurement mitigation strategy comes with challenges with respect to the equitability in accessing stocks as well as co-ordination challenges. Thus, further research is needed to explore the equilibrium of joint procurement during pandemics. The implementation of global standards as a mitigation strategy relies on the collaboration and coordination between government and policy makers as well as manufacturers. Future research should investigate the economies of scale and assess the cost efficiency of this strategy. In addition, to build additional capacity in the PPE supply chain comes with fiscal and redundancy implications as well as quality compliance and usability and further research is needed to shed light on these implications. Implementing these strategies is costly, but they can safeguard the supply chain in times of global disruptions and can bring benefits in the long term.

As with any research, this study has limitations. We followed a qualitative approach to explore the pandemic phenomenon, which of course, could not be generalised and used in all contexts. One limitation of our study is that the empirical data were collected during the first wave of COVID-19, which capture the challenges during the outbreak but not the post-COVID-19 actions and behaviours. For example, our data do not cover the domestic investments in onshoring PPE supply chains that are used in the US or other countries. This should be further explored, to assess the impact of the return on investment and on the incentive for domestic producers to take domestic demand risks in the future.

We propose a conceptual SD model as a first step towards a better understanding of how the global supply chain of PPE was disrupted, and the interplay of the different mitigation options. While there is evidence of how the proposed mitigation strategies impact the system of interest, we cannot precisely quantify it yet. One of the next steps is to convert it into a simulation model given the newly available data at hand. Such a model requires a wide variety of data which were missing during the first wave of the pandemic: the number of items in stock, sick and healthy personnel, etc. This model can then also quantify the effectiveness and efficiency of those mitigation strategies for different scenarios and specify the interactions of disruptions and measures.

The proposed mitigation strategies contribute both scientifically, to the literature on PPE supply chain disruptions, as well as practically, to the work of health care organisations, governmental and non-governmental decision-makers, and to their suppliers, including logistics service providers. They can be used as a guide for the practitioners to develop preparedness and response mechanisms for the next epidemics or pandemics.

The case study on PPE for COVID-19 highlighted the interplay of different disruptions and mitigation strategies over time. The four propositions we formulated on disruptions and mitigation strategies stress the need to further develop SCRM literature to embrace a systemic risk perspective, and to focus on an evaluation of a mix of mitigation measures over and beyond individual measures designed for only a (small) part of the supply chain. However, a deeper theoretical and empirical understanding is needed of these phenomena for different contexts and types of disruptions. Here, further empirical work and case studies are needed to contextualise and further validate the propositions formulated in this paper.

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Appendix

Pseudonym	Type of organisation	Country
PL1NGOMED	Medical Provider-NGO	Poland
IT1NGOSC	Medical Provider-NGO	Italy
CN1NGSC	Medical Provider-NGO	China
US1NGOLOG	Medical Provider-NGO	USA
FI4NGOSC	Medical Provider-NGO	Finland
FI1GOVLOG	Supply Agency-Governmental	Finland
FI3GOVLOG	Supply Agency-Governmental	Finland
FI2PSSC	Pharmaceutical-Private	Finland
HK1PSDIR	PPE manufacturer	Hong Kong
PL2PSDIR	Supplier	Poland
FI5NGOLOG	Medical Provider-NGO	Finland
FI8GOVDIR	Ministry of Social Affairs and Health	Finland
FI9GOVMED	Hospital	Finland
FI6GOVRES	Ministry of the Interior	Finland
CA2PSDIR	PPE manufacturer	Canada
FI7GOVSC	Medicines Agency	Finland
FI10NGOSC	Medical Provider-NGO	Finland
IT3NGOLOG	Medical Provider-NGO	Italy
HK2PSDIR	PPE manufacturer	Hong Kong
CA3NGOLOG	Medical Provider-NGO	Canada
CA4NGOLOG	Medical Provider-NGO	Canada
FI11PSLOG	Logistics Provider	Finland
FI12GOVMED	Hospital	Finland
FI13GOVMED	Hospital	Finland
FI14GOVMED	Hospital	Finland
FI15GOVMED	Hospital	Finland
FI16GOVMED	Hospital	Finland
FI17GOVMED	Hospital	Finland
FI18GOVMED	Hospital	Finland
FI19GOVMED	Hospital	Finland
FI20GOVMED	Hospital	Finland
IT4GOVMED	Medical Provider-NGO	Italy
IT5GOVMED	Medical Provider-NGO	Italy
IT6GOVMED	Medical Provider-NGO	Italy
SE1GOVMED	Hospital	Sweden
SE2GOVMED	Hospital	Sweden
SE3GOVMED	Hospital	Sweden
SE4GOVMED	Hospital	Sweden

Table A1.
List of respondents

Sources of PPE supply chain disruptions Node	Description	Representative quote(s)
Capacity	*Direct effects of the pandemic itself*	
Demand	Surge in demand	*"The demand outstripped supply instantaneously and nobody was able to actually source material" (US1NGOLOG)* *"On the PPE the challenges were, of course, that everybody at that time were looking for the same PPE" (FI1GOVLOG)*
Workforce	Sick workforce, Need for surge labour	*"The biggest issue for them is the lack of manpower" (FI2PSSC)*
Production	Reduced production capacity	*"Production was interrupted due to a lockdown policy due to COVID-19 outbreak. The supply of raw material was limited due to country-level lockdown policy" (HK1PSDIR)*
Regulation	*Policy-induced disruption*	
Transportation	Reduced transportation capacity	*"It's also the global transport, which is extremely difficult at the moment. There's a very limited number of flights. There's a very limited number of airports that are open" (FI4NGOSC)*
Export bans	Pandemic policy-related export regulations and export bans of raw materials, medical items, and PPE	*"So have a restriction or bands of exportation of the PPEs or the medical devices, the middle of the March, we could not import PPEs or medical devices from Europe anymore" (*CN1NGSC*)*
Standards	Lack of harmonised standards and regulations; Regulatory uncertainty about required technical specifications	*"People were ordering products that were not meeting the specifications of what they needed" (IT1NGOSC)* *"The first challenge we had was to determine what were the standards of PPEs. You cannot buy just any mask or any gloves or any face shields, right. So we had to follow the WHO and recommendation from Health Canada to ensure we were buying the proper equipment" (CA3NGOLOG)*
Quality	PPE not meeting quality expectations and technical specifications; Lack of quality compliance	*"And there were concerns about the quality of the masks and especially in the eyes of the rest of the world that were starting to receive masks and reject them for quality issues" (CA2PSDIR)*
Customs	Capacity constraints at customs/regulatory entities Unclear/changing drug lists, and medical regulations for import	*"Customs clearance time increased dramatically instead of two to three days; it was more like four to seven days" (US1NGOLOG).*
SC Strategies	*Supply chain strategy-induced disruptions*	
Single sourcing	Single sourcing Lack of alternative suppliers	*"We will have to have more suppliers to mitigate the risk of having problems with one" (PL1NGOMED)*
Risk management	Lack of supply chain risk management (Lean health care supply chains without risk plans)	*"We did not have a risk plan in place for such a large-scale emergency" (FI3GOVLOG)*

(*continued*)

Table A2. Coding scheme of PPE supply chain disruptions

Sources of PPE supply chain disruptions Node	Description	Representative quote(s)
Behaviour	*Pandemic-induced behaviours*	
Pricing	Surge in prices due to surge in demand Withholding items from the market until prices rise	*"The price of the PPEs, it is one of the big obstacles. To find a reasonable price in this market has been very difficult" (FI3GOVLOG)*
Panic buying	Purchasing items in anticipation of their scarcity	*"Governments have been buying and stockpiling PPE" (FI4NGOSC)*
Fraud	Fake companies set up Counterfeit products Cargo theft	*"We had problems in terms of people creating fake businesses, trying to sell products that did not exit" (US1NGOLOG)* *". . . in some it was quite dangerous because there were cases in which the PPEs were stolen" (IT4GOVMED)*

Table A2.

Mitigation strategies Node	Description	Representative quote(s)
Pre-positioning	Inventory pre-positioning at strategic locations Share medical supplies between countries	*"We should have for three to six months PPEs" (FI3GOVLOG). "I think what could work is a pan-European network of all organisations. So, we know who is having, what number of PPEs, for example, and having the possibility to move freely between the organisations and countries" (PL1NGOMED)*
Kitting	Kitting/packaging interdependent items	*"It was very crucial to understand which were the right PPEs to give to the volunteers. . .as you can understand, if you drive the ambulance you need some PPEs, and if you are a volunteer inside the ambulance you need different PPEs, so there was some confusion about that" (IT4GOVMED)*
Global standards	Harmonisation of PPE standards and technical specifications around the world	*"An important thing, it would be the creation of a list of real useful providers of the materials and a list of valid certifications for that kind of material, we can use during emergencies. So, we would have been really helped if that existed before the emergency" (IT1NGOSC)*
Pre-qualified suppliers	Pool of vetted suppliers regardless beyond the ones with frequent transactions Framework agreements with suppliers	*"We definitely are looking to vet more suppliers . . . approving a new supplier, it's not something that you can do quickly, it usually takes half a year the process"(FI2PSSC). "Framework agreements definitely are one way of going. But I think this kind of faith in the fact that just because we would have a framework agreement that they would be owned is dangerous and we would still have to consider alternative measures" (FI4NGOSC)*

(*continued*)

Table A3.
Coding scheme of mitigation strategies

Mitigation strategies Node	Description	Representative quote(s)
Multiple sourcing	Multiple sourcing across suppliers, or across different geographical regions	*"Adopt multi-sourcing and find reputable suppliers to build long-term business relationships" (HK2PSDIR)* *"The need to diversify geographically to the base of a certain supplies is important" (FI4NGOSC)*
Joint procurement	Several organisations procuring together	*"We consolidate ordering as much as possible and really bring the whole membership together and try to make sure that we're trying to utilise consolidated supply chains" (FI4NGOSC)*
Production changeover	Adding surge capacity by changing existing production lines and facilities to the production of PPE (including reshoring)	*"Government would find businesses that were willing to change their production and they would support them financially" (CA2PSDIR)*
	In transportation: adding surge capacity by changing vehicles from passenger to freight transportation	*"We'll have to make the domestic domestic produce, PPEs, have to be also in the future at least in EU countries. Then we have to have the logistical chains in place, but we also have to make it more diverse"(FI2PSSC). "We used our national airlines that normally flew to China and back . . . we used planes to fly cargos only because they did not fly people" (FI1GOVLOG)*

Table A3.

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