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CORE

sCience and human factOr for Resilient sociEty

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ABSTRACT

The impact of COVID-19 on the lives of people and businesses across the globe was devastating. While governments across the world had undertaken a slew of measures to control the spread of the COVID-19 virus within their geography, many of these measures had long unintended consequences. In many instances, people could not access necessities including food and healthcare systems. The restrictions imposed by the governments on the movement of people and goods across the world brought supply chains to a grinding halt and had cascading effects of supply chain disruptions across geographies. This study identifies cascading effects of supply chain disruptions on critical sectors, such as food, water, energy, and healthcare systems. Since these systems are closely integrated, and the impact of COVID-19 needs to be analysed at a much broader level, this study uses systems thinking approach to study the effect of supply chain disruptions on critical services. The study also develops a causal loop model to gain further insight into how supply chain disruptions caused by COVID-19 affected the coping capabilities of society and how critical services were affected. Further, the study also puts forth certain policy recommendations for both businesses and governments to prepare and protect against a similar situation in the future. This study is undertaken as a part of Work Package 4, task 4.3 under the CORE project funded by the European Union under grant agreement no. 101021746.

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LIST OF abbreviations

AMP	- Asset Management Period
CER	- Critical Entities Resilience
CFA	- Carry and Forwarding Agents
CORE	- sCience and human factOr for Resilient society
BCI	- Business Continuity Institute
EU	- European Union
GMB	- Group Model Building
HSE	- Health and Safety Executive
OFS	- Oil Field service
PPE	- Personal Protective Equipment
SCD	- Supply Chain Disruption
SCN	- Supply Chain Network
SKU	- Stock Keeping Unit
WASH	- Water, Sanitation and Hygiene

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INTRODUCTION

The recent trends and developments in the supply chains, such as the increase in the outsourcing of manufacturing and R&D to the suppliers, the reduction of supplier base to gain competitive advantage, and reduction in inventory and lead time buffers for improving the efficiency have created long lean and interconnected supply chains which are often very vulnerable to disruptions and can have potentially devastating ripple effects. Further, this integrated nature of supply chains indicates that it is not possible to manage disruptions and risks associated with these disruptions in a single stage. Often the mitigation strategies need to be developed and implemented in such a manner that they can mitigate risks across the supply chains. This has been the concern of the businesses for a very long time, and industry efforts to combat supply chain disruptions have either to adapt a traditional thinking or formulate company specific strategies. However, the recent COVID-19 induced supply chain disruptions indicate that our global supply chains are still very much vulnerable to disruptions and can potentially have long lasting impact on multiple global economies simultaneously.

Supply Chain Disruption (SCD) can be defined as an occurrence which has negative consequences for regular supply chain operations and, hence, causes some degree of confusion or disorder within the supply chain. At a broad level, SCDs are usually classified based on the reason of SCD, such as acts of nature (e.g., flooding, earthquake, hurricanes, and pandemics). While this cause-based classification would identify the underlying reason for these disruptions, it is often much more useful to further classify them based on various other factors. This has led to multiple types of classification for SCD. Ivanov et al., (2017) classified the SCD based on the level or echelon at which the disruption has occurred and classified them as production-based disruption, supply based disruption, and transportation disruptions. Chopra and Sodhi (2014) classified SCD based on the cause of disruption. They identified that supply chain disruptions can be caused due to disasters, delays in commerce systems, forecast, intellectual property, procurement, receivables, inventory and capacity. Similarly, other classifications for SCD based on frequency of occurrence (Tang et al., 2014), nature and their source of origin (Christopher et al., 2011), who they affect, from broad to specific (Dolgui and Ivanov, 2021) can also be found in literature. Table 1 below summarises the reasons for SCD, and the classifications based on them.

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Table 1: Classification of supply chain disruption from literature (Source: authors)

Reasons for disruptions	Types of SC disruptions
SC echelons/level of disruption (Ivanov et al. 2017)	• production • supply and • transportation disruptions
Reason that caused the disruption (Chopra and Sodhi 2014)	• disasters (e.g. natural disasters, terrorism, war, etc.) • delays (e.g. inflexibility of supply source), • systems (e.g. information infrastructure breakdown), • forecast (e.g. inaccurate forecast, bullwhip effect, etc.), • intellectual property (e.g. vertical integration), • procurement (e.g. exchange rate risk), • receivables (e.g. number of customers), • inventory (e.g. inventory holding cost, demand and supply uncertainty, etc.) and • capacity (e.g. cost of capacity)
Frequency of occurrence (Tang et al., 2014)	• supply risks, process disruptions • demand disruptions • intellectual property disruptions • behavioural disruptions • and political/ social disruptions
Nature and their source of origin (Christopher et al., 2011)	• process risk, • control risk, • demand risk, • supply risk and environmental risk
Based on who they affect, from broad to specific (Dolgui and Ivanov, 2021)	• external to the SC network and are termed environmental, • internal to the SC network but external to the focal firm, called network or industry risks • internal to the firm, called organizational disruptions, • problem-specific and • decision-maker specific

A-2019-study by the Business Continuity Institute (BCI) identified that some of the major reasons for SCD included unplanned telecommunication outage, an adverse weather, a cyber-attack and data breach, loss of talent/skill, disruptions in the transport network, and health and safety incidents. The report also suggested that changes in the laws and regulations and political change could be the future drivers of supply chain disruption across the world. However, post COVID-19 the major reasons for supply chain disruptions have significantly changed. Report by BCI in 2021 identified that human illness and health and

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safety incidents could be the major reasons of supply chain disruptions going forward. This significant change in the causes leading to the supply chain disruption has brought back the attention of both managers and politicians onto the importance of human capital in supply chains across the world.

The impact of supply chain disruptions has also been studied in detail in the supply chain literature. The main impacts of supply chain disruptions on businesses can be broadly classified into operational, marketing and financial impacts. Operational impacts may include, for example, a failure to meet the end customer demand as a result of a product unavailability, partially fulfilled orders, late deliveries, logistic challenges, the use of alternative transportation source for product deliveries, and higher administrative costs. Some of the marketing impacts due to the supply chain disruptions include an increase in the customer complaints, a damage on the brand reputation, the loss of customers, a breach of supplier contracts, penalties associated with breach of contracts, a failure to meet legal or regulatory requirements. Financial impacts include, for example, a loss of sales and revenue, a reduced market share, a production shutdown, and a reduction in the asset utilisation.

However, what has been lacking in the studies related to the SCDs is its impact on societal vulnerabilities. Societal vulnerability is generated by social, economic and political processes that influence or affect people in varying levels of differing intensities (Wisner et al., 2014). Societal vulnerability is a by-product of the social inequalities that exist. It can be defined as the susceptibility of social groups to the impact of hazards, as well as their resiliency, or the ability to adequately recover from them (Cutter and Merich, 2006). Wisner et al. (2006), identified that the indicators used to capture social vulnerabilities can be broadly categorised into demography-based indicators, social economic based indicators, access to public resources-based indicators, coping capability-based indicators and risk perception-based indicators. They also identified that access to public resources during a hazard or a crisis usually has a great impact on reducing the vulnerability of society. Previous studies have explored how lack of access to public health institutions and public infrastructure during crisis has led to social vulnerabilities. However, there are no studies evaluating the impact of supply chain disruptions on the ability of public resources to provide services during crisis. The recent COVID-19 pandemic has brought this aspect of vulnerability into the forefront of decision makers.

To summarise the preceding discussion, COVID-19 has shed light on the intricate relationship between societal vulnerability and supply chain disruptions. While the previous studies on supply chain disruptions have been primarily focusing on businesses, societal vulnerability has received almost no attention in the past. In

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the modern world, almost all products and services depend on the intricate supply chain network connecting buyers, sellers and consumers across the world. Any disruption can cause a severe societal impact and might even be detrimental to the lives of people as it was observed during the COVID-19 peaks. In this study, the impact of supply chain disruption on societal vulnerability will be evaluated in four critical sectors, i.e. food, water, energy, and health. This study aims to identify the major impact of COVID-19 caused supply chain disruption on these sectors and how it has affected societal vulnerability and thereby the coping capability of the society towards COVID-19.

This this study is being carried out as a part of the Work Package 4, task 4.3 of CORE project funded by the European Union under H2020 research and innovation program.

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LITERATURE REVIEW

The disruption of supply chains during the COVID-19 is a well-documented fact. The impact of these disruptions has been quite phenomenal and have spread across the national and international boundaries cascading across various sectors. This section of the report reviews the impact of supply chain disruption (SCD) on four sectors, i.e., food, energy, water, and health in EU. The effect of SCD is often manifested through its impact on the critical infrastructure (CI), and thus, the report also explores the impact of SCD on CI as well.

Impact on Food supply chain

Impact of the COVID-19 on food supply chains can be observed from three perspectives: food supply, food demand and food security. Food security is also related to these two features, so the security of the food is at risk. COVID-19 led to constraints in labour movement, limited food trade techniques, and monetary development across the food supply chains. It further causes disturbances in manufacturing, packaging, handling, and logistics (OECD, 2020a). Unlike other food related diseases like bird flu, E-Coli, foot-and-mouth disease and listeria, the impact of COVID-19 was not direct, where tons of food had to be destroyed to stop the diseases from spreading. Here, the food supply was affected due to challenges with harvesting, logistics, processing, go-to-market, and sourcing. On the other hand, food demand was affected by a fundamental change in the consumption patterns of people and procurement by companies triggered by the lockdown and restrictions imposed by the governments to prevent the spread of the COVID-19. This was manifested in, for example, changes in the shopping behaviour of customers and patterns of consumption, an increase in the non-store food shopping. Figure 1 shows the components of the food supply chain system and the various drivers.

Logistics and transport disruption

With the increase in the COVID-19 cases, the first response of many governments was to close their borders and restrict the movement of people and material. This, meanwhile, was steadily turning into a logistics nightmare. Where produce did get harvested, border controls and air freight restrictions made international transport of fresh goods extremely difficult and expensive. Within EU, these measures consisted of the reintroduction of border checks or closure of the borders with other Member States (with temporary suspension of the Schengen rules on free movement), and in strict confinement measures for parts of national territory (for instance, 'red zones 'where no access was allowed). These resulted in blockages to transport routes and long queues at border checks (especially problematic for fresh food), or quarantine measures preventing or limiting access

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to markets. Restrictions on goods transport in their turn affected international trade in agri-food products (Rossi, 2020).

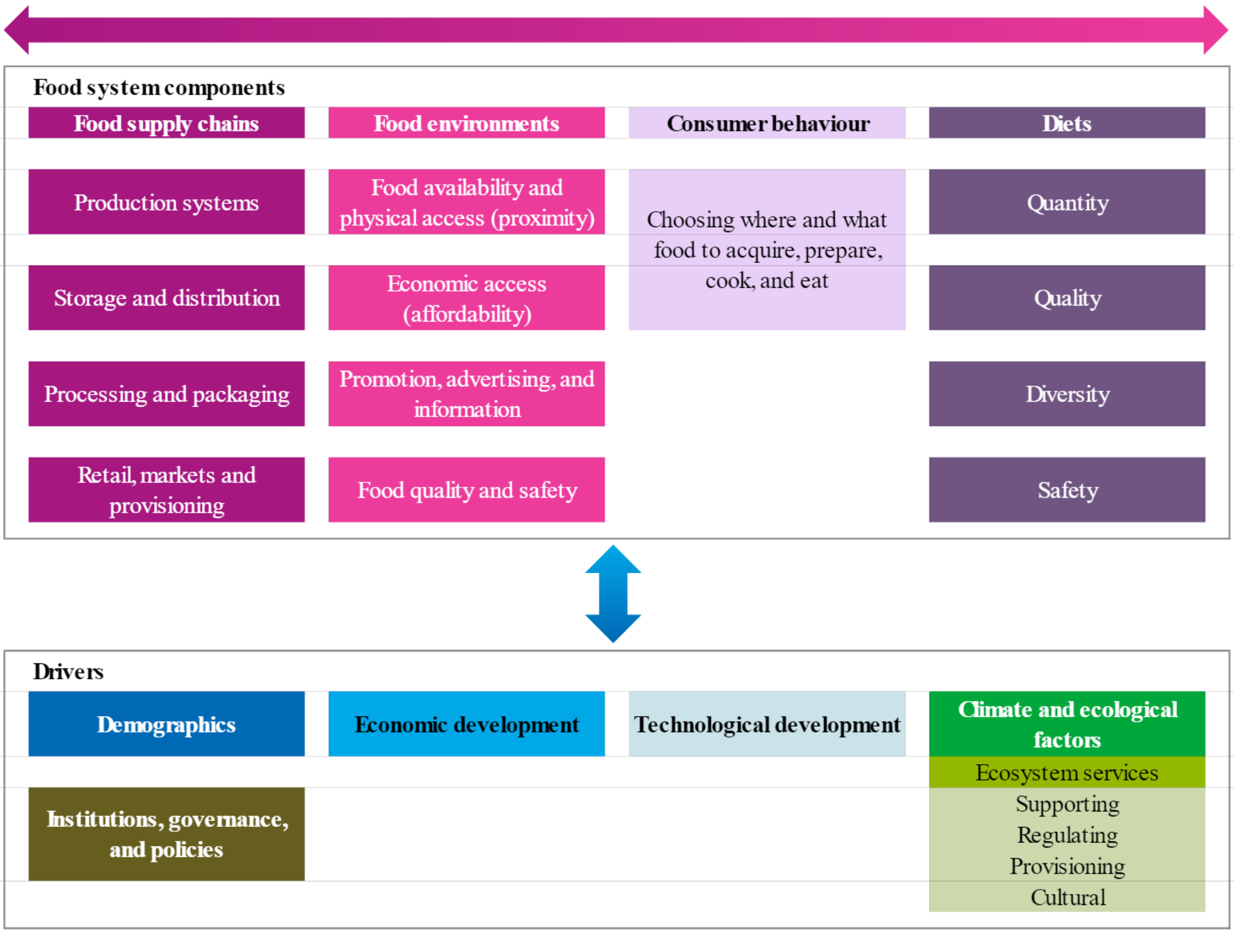

Figure 1: Food supply chain system components (Source: Resourcetrade.earth)

The impact of the logistics disruption varied considerably. Broadly speaking, the agriculture and food products use three main modes of transport, i.e., bulk shipping (ships and barges), containers (by boats and rails) and air freight. While bulk shipments did not see much of the disruptions, air freight was severely disrupted. During May 2020, the global air cargo dropped by 26% of lower than during the same period the year before. A significant amount of drop came with the record decline between the Latin America and Europe (as much as 80%). Disruptions to container and truck transport fell somewhere in-between. The number of container ships was at 8% below normal due to COVID-19 restrictions such as limitations on crew changes, additional screening, mandatory quarantines, and reduced demand In Europe. Truck traffic initially fell by more

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than 50% in Spain, 46% in France and 37% in Italy, although it has subsequently recovered. In mid-April 2020, the total distance driven by trucks in Europe was 24% below normal (Ulltveit-Moe and Heiland, 2020).

Labour shortages

The farm production was hit by bottlenecks on inputs, most notably the labour. Many farm sectors depend on the seasonal labour for harvesting. This includes fruits and vegetables which are more labour-intensive, while cereals and oilseeds typically require less labour. Limits on the mobility of people had reduced the availability of seasonal workers for planting and harvesting in the fruit and vegetable sector in many countries (Rossi, 2020). For instance, many farm operations that require significant amounts of labour (production of specialty crops, such as strawberries and lettuce), the most pressing pandemic-related challenge was the availability of workers (Fleix, et al, 2020). Furthermore, the COVID-19 led to disruptions in food processing industries, which were affected by rules on social distancing, by labour shortages due to sickness, and by lockdown measures. Many firms have also reported high rates of worker absences; for example, staff availability was reduced by up to 30% in French meat processing facilities in the regions of the country worst hit by the COVID-19. Meat processing is more sensitive than other types of food processing in part because of the labour-intensive nature of operations (OECD, 2020).

Food processing disruptions

Unfortunately, several countries partially instituted export restrictions on these. Kazakhstan, for instance, suspended exports of several cereal products, as well as oilseeds and vegetables. Vietnam temporarily ceased granting rice export certificates. These restrictions, even if temporary, created shortages across the globe (Glabuber, et al., 2020). This has caused increases in both retail and wholesale fuel price. The impact of fuel prices has cascaded to the rising freight costs on prices, particularly for producers and manufacturers that import products, like fertiliser and construction materials (OECD, 2020).

Changes in the consumer demand patterns

The COVID-19 had led to a drastic shift in consumer demand away from restaurants, food service and other types of "food away from home" towards food consumed at home, requiring significant changes in the way food supply chains operate. As the COVID-19 pandemic gathered pace, sales of food away from home (consumed in hotels, restaurants, catering, and cafés) collapsed. Restaurant reservations declined sharply in early March 2020 and fell to zero as lockdowns were enforced across Europe (OECD, 2020b). During the same time, the retail food demand soared to record heights. The demand for frozen and packaged foods almost doubled during the peak lockdown periods. This drastic

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shift in the consumer preference had adverse stress on the production and supply chain systems. In addition to logistical challenges, households' consumption patterns at home are different from those away from home. For instance, the packaging volumes, material and type for home and restaurant are different. This led to many food processing plants to change their stock keeping units (SKUs) rapidly. Some of the plants were not able to change it fast enough since it required separate tooling and set ups, causing temporary shortages across supermarkets (Laborde, et al., 2020).

Changes across supply chain

With the nationwide lockdown across various countries in Europe and other continents, the outbound orders suddenly stopped, even though inbound orders of food kept coming in from farmers, food-service producers, and processors. This led to logistical bottlenecks and storage-space shortages, and thus distributors tried to cancel incoming shipments of inventory from farmers. For those unaccustomed to supplying the retail channel, redirecting their sales added to the complexity of modifying their current supply chains, which further led to an increase in the cost of operations. On the other hand, grocery retailers faced additional challenges and had to undertake extraordinary activities to protect and serve their consumers. Those included constant and visible cleaning of stores, frequent loading of shelves to keep up with the demand, hazard-pay bonuses, and incentives to maintain employee numbers, and hiring of additional labour, with limited time for training. Challenges also included the cost of expanded hours of operation (since foot traffic is limited because of physical distancing), the cost of scaling up online-ordering and delivery systems, and the associated cost of handling consumer complaints for late and errant deliveries. That has created a lot of strain in the system, as there are multiple challenges associated with last-minute delivery, given the significant ramp-up in labour required with limited training time (Felix, et al., 2020).

Impact on energy supply chain

The increase in restrictions across the world as a response to the growing numbers of COVID-19 cases had a significant effect on the energy consumption. During this period, the distribution of energy usage shifted a great deal. For instance, the industrial energy usage reduced significantly while domestic energy consumption saw a marked increase. Due to a reduction in the energy consumption for transportation, industrial manufacturing and other economic activity, the oil prices fell to a record low. Some of the major impacts on the energy consumption patterns, and the reduction in overall energy consumption during pandemic period is discussed below.

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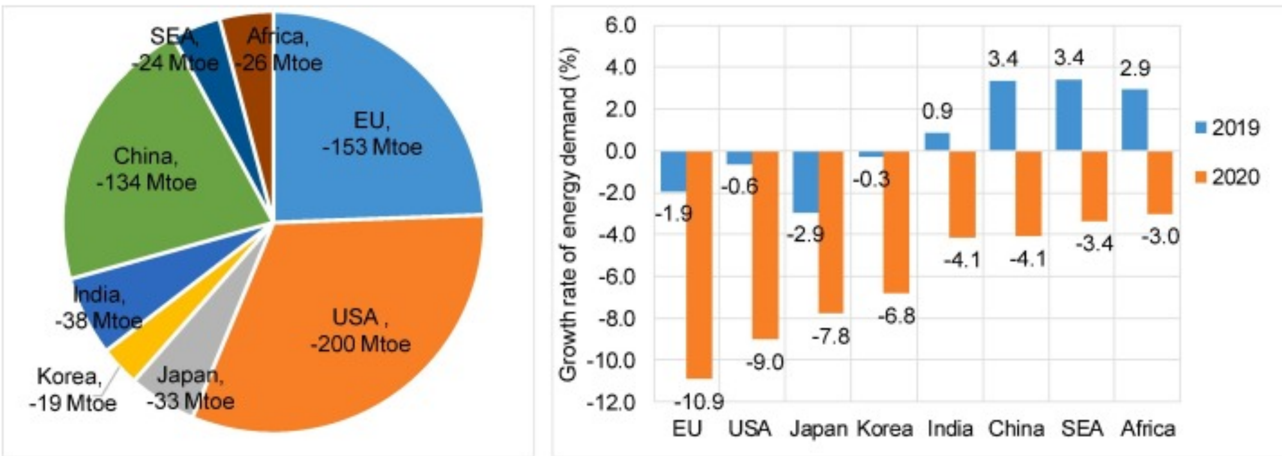
Impact on energy generation and consumption in small grids

Many counties noted the sudden reduction in energy consumption in the commercial and industrial sectors (Figure 2). In the UK, the energy consumption dropped to as 20% of the normal usage during the weekend as during the week (Wilson et al., 2020). The sudden reduction in the consumption of electricity lead to a significant deviation in the voltages due to the capacitive elements in the transmission line which generate reactive power. This abnormally low consumption of electricity can affect the management and control of the generation units and may lead to high fluctuations in the voltage and frequency of the electric current. These fluctuations can in turn result in affecting the resilience and reliability of the entire system (Carmon et al., 2020). Some of the major concerns during these times included the need to shutting down the power generation units. Since the electricity consumption is exceptionally low, the system operator must shut-down conventional power plants that are normally operated, until consumption goes back to normal. However, several large power plans when once shut down for a few days cannot be fully re-activated in a brief time. This means that in case of a contingency, such as a failure in a generation unit or an unexpected load deviation, backup units with a short start-up time are used, which are usually more expensive and polluting options. Furthermore, there may be delays in the synchronization of these units to the grid, making it difficult for the system operator to supply for demand during peak requirements (Carmon et al., 2020).



(a) (b)

Figure 2: Energy demand development.
(a) The projected drops of energy demand by regions in the entire year of 2020, (b) The year-on-year growth rates of energy demand in 2019 and 2020 (projected). Note:

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Mtoe = Mt of oil equivalent; Korea = South Korea; SEA = South (Source: Jiang et al., 2021)

COVID-19 led bankruptcies of energy companies

The most visible impact of COVID-19 was the energy market collapse. The price of the brent crude fell from US$69 a barrel (6 January 2020) to under US$23 (30-31 March 2020), before partially recovering to around US$32 (13 April 2020) because of deep production cuts by OPEC+ countries (Duffy and Disis, 2020). Cross-border travel limitations, supply insufficiencies, quarantines and Capex reductions had pronounced effect on the European energy service market, which is heavily dependent on its international workforce and efficient flow of goods and services between nations. A vast majority of the European Oil Field service (OFS), in Norway and the UK, lost purchases, worth around $4.5 billion, within the segments of MMO (Maintenance, Modifications, and operations), drilling rigs and well services. It was estimated 1,000 small- and mid-sized suppliers in the UK and Norway could become insolvent (Bajic, 2020).

Impact on renewable energy

Sharp economic downturn caused by the pandemic had significant impact on the renewable energy. With reduced financing and funding from the governments on the market incentives, the renewable energy investment has raised serious concerns among developers. On the other hand, there was a steady increase in the proportion of the renewable energy usage during the pandemic as shown in figure 3(a). However, in figure 3(b) the percentual growth of the renewable energy sources has decreased in 2020 compared to 2019. Therefore, the increase in the percentage of energy used from renewable energy source is not coming directly from the actual increase of renewables, but due to total decrease in the energy consumption due to pandemic induced lockdown.

Furthermore, the sudden halt of manufacturing process across the world has led to major disruptions in the global renewable energy supply chain (Ivanov and Dolgui, 2021). In Germany, one of the leading renewable energy producers in the world, the decreasing overall level of energy demand has negatively affected the pricing schemes for renewable energy production and carbon trading. Supply chain disruptions and halting of non-essential manufacturing activities have caused significant delays in the deployment of renewable energy projects. China, the leading supplier of solar PVs experienced a widespread shutdown of its factories due to the COVID-19 outbreak. Besides supply chain delays, grid integration of new renewable energy projects was postponed due to the delay of non-critical operations by the Distribution System Operators (Energy Community and "Energy, 2020). Furthermore, power companies have turned to

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adapt their operations in response to the fallouts from the pandemic by putting aside new investment projects, tightening budgets, and cutting unnecessary spending, reassessing project implementation and investment priority that collectively resulted in major impacts on the global renewable energy production in the near term (Hoang, et al., 2021).

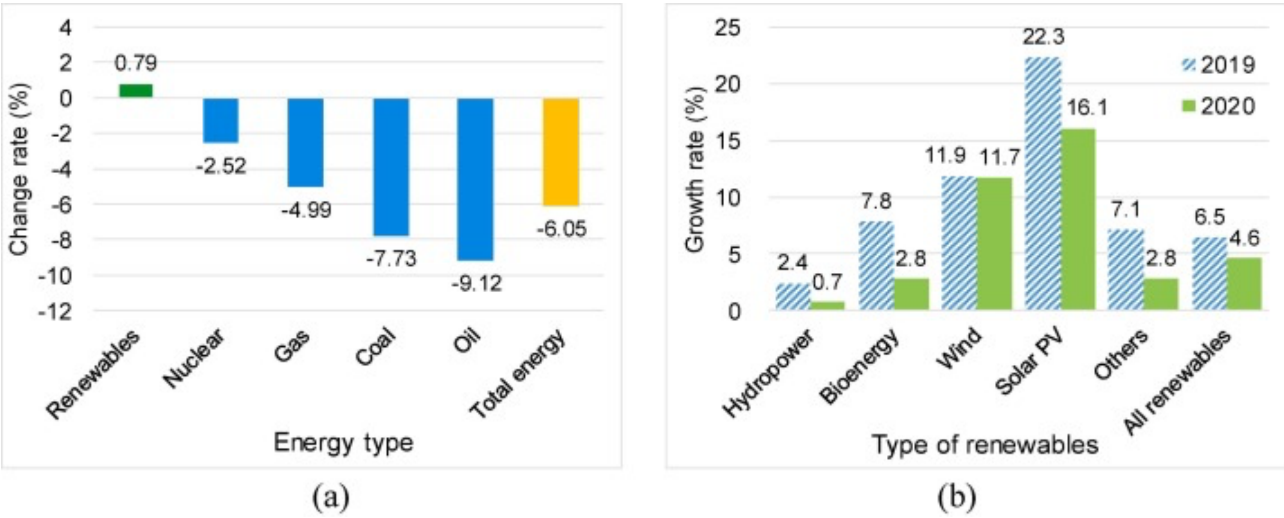

Figure 3: The projected change rates of energy types across 2019-2020 (a) primary energy demand in 2020 compared to 2019 and (b) growth rates of renewable electricity generation in 2020 and 2019 (Source: Jiang et al., 2021)

Supply chain disruption in energy sector

The global lockdown and ensuing supply chain disruptions had tremendous impact on the energy supply chain, especially the renewables supply chain. The renewable energy sources can be primarily classified into solar power, wind energy, hydro energy, and others. However, solar energy industry was the worst affected due to the supply chain disruptions. China is known to be the largest solar PV manufacturing country in the world and accounts for almost 80% of the solar cells and modules imported. The pandemic had brought production to a halt leading to lower consumption of power manufactured by solar PV (Kanda and Kivimaa, 2020). As a result of these disruptions in the supply and lockout of crucial workers, 2020 saw a major decrease in solar energy supplements.

Furthermore, plummeting oil prices had expanded the scope of cheap oil-based energy generation that impeded renewable energy development. The shift to low-carbon production and renewable energy was to be halted temporarily around the world. Meanwhile, Bloomberg NEF study estimates that solar power will decline as policymakers concerned with battling the impact of COVID on their economies than to build new plants and agree on renewable energy growth

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goals (Manzanedo and Manning 2020). Green energy ventures are also facing instability as a direct result of COVID-19 even after the global pandemic. Wind producers GE, Vestas, and Siemens Gaemsa are preparing to close their factory. For solar, a shortage of construction components such as inverters and modules were ushing up costs by as much as 15 percent in some markets (Priya et al., 2021). Payment defaults are also causing ripple effects on the entire renewable energy market. A shortage of working capital was expected to fund short-term routine operating liabilities within two to three months if the condition continues (Priya et al., 2021).

Impact on critical infrastructure

European Union defines critical infrastructure as follows: “An asset, system or part thereof located in Member States which is essential for the maintenance of vital societal functions, health, safety, security, economic or social well-being of people, and the disruption or destruction of which would have a significant impact in a Member State as a result of the failure to maintain those functions” (European Union, 2008). This understanding of critical infrastructure in terms of assets means that the protection is only limited to facilities or objects, without taking into consideration their dependencies or interdependencies. Moreover, because of such an understating of critical infrastructure, crisis planning and preparing processes did not include such complexities as indirect consequences (Carvalhaes et al., 2020). For instance, the system that has been the most heavily affected with high pressure is the health system. The dependence of the healthcare system on other systems, such as transport, created shortages of many goods and equipment, such as ventilators and PPE which were intended for frontline health care workers. This required critical health infrastructure operators to be more flexible, to be able to adjust to the current situation and to look in advance for different suppliers or back-up systems (Tomalska, 2022).

Supply chain disruptions on critical infrastructure

Because of lockdown and including disruption in supply chains, the availability of workers for (critical) infrastructure projects (construction) and operations, delays and cancellations, demand shocks, as well as interruptions to investment processes and procurement. Infrastructure projects relying on single-source supply chains were the worst affected. The COVID-19 has served to highlight the critical nature of many infrastructure systems and services, both for maintaining economic and social activity and enabling responses to unexpected threats and challenges – but also being a potential source of vulnerability (OECD, 2021). The COVID-19 shed light on the need to consider where infrastructure can play a role in support of healthcare value chains, for example, through a more efficient trade and transportation infrastructure to support delivery of essential goods.

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World Bank has noted that in the medium term, a lasting downward trend in revenues, adverse impacts on access to financing for projects, and potentially continued disruption of construction schedules of projects should be anticipated (Diop, 2020). On the one hand, a downturn in infrastructure balance sheets, creation, and maintenance does not bode well given the sector's role in getting people to jobs, goods to market, electricity to hospitals, and digital access to students. On the other hand, we know from previous experience in other crises that many governments will use infrastructure spending to stimulate their economies, so there may be a ray of hope for the sector that allows it to continue to improve quality of life for people across the globe. However, with respect to supply-chain delays, the construction industry which is heavily reliant on manufacturers in China, faced delays and cancelations. Furthermore, projects were also disrupted due to the non-availability of laborers due to lockdown measures. Countries like the Philippines, India, and Colombia enforced enhanced community quarantines, resulting in labour shortages at construction sites. Other reasons included delayed or cancelled tender processes, lower demand projections, and government budget funds reallocation to tackle COVID-19 containment. Overall, the supply chain disruption caused by the COVID-19 affected the maintenance and construction of critical infrastructure across the world. Figure 4 summarises the main reasons for delays or cancellations of critical infrastructure projects (Diop, 2020).

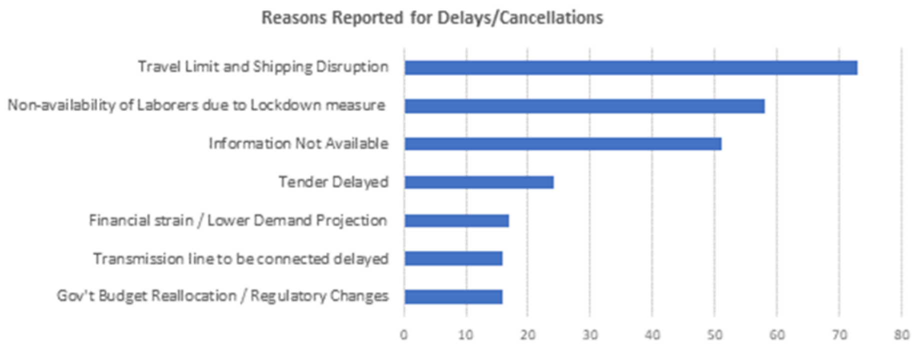

Figure 4: Reasons for delays or cancellations of critical infrastructure projects (Source: Diop, 2020)

Impact on water systems

Prior to COVID-19, the water industry across the globe was impacted by five major trends. These included:

a) global warming lead increase in extreme floods and droughts challenging the resilience of water and sanitation systems,

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b) increasing number of people living in areas facing water stress (currently two billion), which increases water supply vulnerabilities,
c) rapid urbanization, which strains existing water resources and ecosystems,
d) the emergence of megacities, which adds the challenge of extending water and sanitation services to about one billion people living in informal settlements not served by water grids,
e) aging infrastructure, which has increased pressure to accelerate investments in more advanced markets, following decades of underinvestment (Butler et al., 2020).

COVID-19 has shown the importance of the water industry for public health in the wake of a pandemic and has shed light on the importance of identifying water systems as a critical entity for the public health. However, the COVID-19 has also shed light on the vulnerabilities in the current water industry. Along with the pre-existing challenges, some of the major impacts of the COVID-19 on water services are summarized below.

Shift in consumption patterns

With the nationwide lockdowns, there was a marked increase in the household consumption of water and a significant decrease in the non-household or industrial consumption. With the increase in the household consumption, the per capita consumption increased and thereby increasing the cost of water production. This was caused by the increase in household demand more than offset the reduction in non-household demand (Ong and Nielsen, 2020). For instance, in the UK, all water companies experienced a significant decrease in non-household consumption and an increase in non-household voids. While the data issued by the companies revealed that it is difficult to differentiate between temporarily vacant flats from businesses that are permanently closed, there was a clear increase in non-household voids for most companies. However, revenue from metered household customers had increased because of an increased demand. Revenues from unmetered households remained unchanged in the short run. As a result, companies with comparatively more metered customers saw a greater increase in household revenue in the short-term (Ong and Nielsen, 2020).

Water sector operations and engineering projects

The Health and Safety Executive (HSE) in the UK advised business including water sector to prioritize becoming "COVID-secure" by adapting to current guidance and implementing measures to control the risk of COVID-19 to protect workers and others. These steps included carrying out COVID-19 risk assessments adhering to HSE guidance, enhancing cleaning, hand washing, and hygiene procedures, taking all reasonable steps to help people work from home, etc. To

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comply with these mandates, water companies have had to adapt various measures, including regulatory inspections, limited site visits, phone calls (remote working), and collection of visual evidence (photos and video footage), etc. (Frontier, 2020; HSE, 2020).

The pandemic further disrupted the water sector's demand and growth projections, with an increase in the demand for domestic water as business demand decreased. Hence there was a need for readjustment for the rest of the Asset Management Period (AMP) to reprioritize projects supported by Ofwat (England and Wales agency that Promotes competition, sets price limits, ensures that water companies can finance and carry out their functions, promotes economy and efficiency). It was also anticipated that 20–30% of operational staff might not have been available during the pandemic peak period (Horton and Laikin, 2020).

New projects in water sector

With the increase in the number of people in urban settings and aging infrastructure, the need for capital investments both in terms of maintenance and upgrading the water systems across the world has been the need of the hour pre-pandemic. However, the cost structures and lack of funding sources in the post-pandemic environment has put halt on the new capital expenditures for both maintenance and modernization of the water system. For instance, water industry is labour intensive with high energy utilisation and constant demand for chemicals and other consumables. These account for the bulk of Operating expenses (Opex) for water utilities. Capital expenses (Capex) comprise mostly networks and treatment facilities. Water utilities' operations are typically funded by customer receipts (comprising water tariffs and one-off connection charges), grants, and taxes. Tariffs are often set to achieve socio-political objectives at levels that are insufficient to recover operating costs. Therefore, the water utilities require support from other sources, usually the government budget (Butler, et al., 2020).

The outbreak of COVID-19 slowed down investments in the water sector worldwide. It also increased the importance of operational reliability due to the cost of disruption. These operational needs derived from shifts in demand patterns, supply disruptions, and the various emergency measures employed by governments to cope with the pandemic. Many large users of water have downscaled or reduced activities resulting in declining industrial demand. A decline in demand from large industrial and commercial users due to lockdowns and travel restrictions significantly reduced revenues to water utilities. Specific measures adopted included (a) deferments on or exemptions from utility bill

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payments for vulnerable groups, (b) moratoriums on cutting off the water supply, and (c) suspensions of meter reading and invoicing (Butler, et al., 2020).

Water, Sanitation and Hygiene (WASH) and COVID-19

The water supply and sanitation services must be considered within a larger framework of integrated water management water quality, ecosystem health and governance and are crucial for public health and human development (Gaddis et al., 2019). Mukhtarov et al., (2022) argued that the COVID-19 and water management will have long term mutual impact on each other. The direct impact includes prioritizing WASH at the expense of other crucial challenges, such as climate change adaptation, land use patterns, ecosystem health and energy. Furthermore, lesser public funds will be made available for water infrastructure and management and the danger of oversized influence of private financial capital in the water sector might cause lower quality of water related infrastructure. On the other hand, the long-term indirect impact will be securitisation of WASH that may lead to day-to-day and fragmented management. With a private financial take-over of water infrastructure and services, the attention to techno-fixes with a relative neglect of social and political aspects of water management and governance may be affected in long term and might as well take a back seat in long run.

Impact on healthcare operations

The healthcare operations were the most hit by the supply chain disruptions due to COVID-19. COVID-19 affected the health care operations both on supply and demand side. On one side, when the health care infrastructure had to grapple with the kind of demand which had never been seen before, the supply chain challenges made is both difficult to find the equipment and medicines required to handle the steep increase in the patient numbers. The main challenges in healthcare operations due to supply chain disruptions are listed below.

Legacy challenges in procurement

Usually in healthcare procurement process, the procurement is centralised, and procuring agencies serve a network of hospital. For instance, the procurement of medical supplies in Italy has traditionally been prioritised through contact competition to avoid skirts and improve profitability (Maheen, et al., 2016). Often these procurement agencies are Carry and Forwarding Agents (CFA) in the supply chain without owning their stockpiles (Swanson, 2020). These purchases often depend on foreign manufacturing and international supply chains that provide critical inputs in the form of both raw material and finished products for the medical suppliers (Vecchi, et al., 2020). Another major criticism against the public procurement in the health care sector is that it prioritizes cost and compliance over innovation (Patrucco et al., 2016). The result was that formal and

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informal public procurement institution that failed to give adequate attention to address long-term risks arising from supply chain disruptions, business continuity concerns, or product integration—which could better buffer the public sector to surges in demand.

Vecchi, et al., (2020) explored the issues with the Italian health care procurement process and how it had affected the effectiveness of health care service provided during the pandemic. They identified that in Italy, the regional authorities were primarily responsible for the procurement of the medical supplies. The law states that at Regional Level - Regions have direct responsibility for government implementation and expenditure to achieve the country's health goals. The Regions have exclusive competence in the regulation and organization of services and activities intended for the protection of health and of the funding criteria of local health authorities and hospitals (also about management control and the assessment of the quality of health services in compliance with the general principles established by the laws of the State). While, at Central Level - the State has the responsibility to ensure that all citizens have the right to health through a strong system of guarantees, and essential levels of assistance. During the pre-COVID times, the regional authorities worked to centralize the decision making and other critical functions to reduce costs. While in theory this sounded great, a lot of effort was spent in reducing expenditure, and fighting corruption. When COVID-19 hit Italy, these agencies were not equipped to manage the rapid increase in the demand for medical supplies. In the immediate aftermath of the COVID-19 crisis, agencies conflicted with one another in the acquisition of medical supplies, demonstrating a severe lack of coordination and a great deal of competition that both hindered the success of acquisition and drove up the prices for scarce goods. Due to a lack of expertise in dealing with public health emergencies and the conflicting roles between the national and regional authorities, the latter acted independently and took initiative in purchasing critical goods and services within existing governance frameworks established before the outbreak or developing innovative approaches. However, this lead to increased competition for the already scarce critical items in the market. Without national coordination, regional procurement authorities activated an informal network to launch joint tenders, share market information, and exchange good practices.

An international rush for supplies produced in global manufacturing hubs, a lack of national production after years of spending cuts, and decades of pressure on procurement authorities to seek cheaper products precipitated the severe medical supply shortage. Finally, Italian manufacturers of luxury brands and other domestic manufacturers in the textile industry started to convert their production lines to accommodate the needed health care supplies, as the

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regulatory and authorization processes were exceedingly lengthy. In some cases, procurement officials decided to proceed anyway and circumvent the regulatory requirements. In other cases, officials waited them out. Some of the most innovative regional procuring authorities played more of a strategic role in contracting. (Vecchi et al., 2020).

Lack of inventory visibility across supply chain

During the peak of COVID-19, there were shortages of medical equipment, especially the personal protective equipment (PPE). While it is safe to say that nobody could have anticipated such a sharp increase in the demand for PPE across the globe, which lead to severe shortages across, the lack of supply chain visibility might have also contributed to the issue. Finkenstadt and Handfield (2021) identified that PE shortages were pervasive in every region of the world, including South America, Europe, the Middle East, and Asia. Several characteristics of the PPE supply chain were the root cause of these shortages.

- First, no country was prepared for the closing of international boarders during COVID-19, which immediately shut down international shipments. Since more than 80% of PPE is produced in China, this caused significant shortfalls globally.
- A second reason is that there are few international standards when it comes to critical healthcare supplies, like PPE, and ventilators. Different government agencies were responsible for setting such standards, and there is often lead to disagreement even within Europe.
- Third, to track supplies globally is difficult and prevents transparency in sharing inventory levels across global healthcare agencies.

Another main reason for the shortage was the huge amount of inaccessible stock in the pipeline which was affected by the level of visibility to inventory and to shortages in PPE. This led to a huge disparity between the level of available stock viewed from the vantage of the government vs. the vantage point of healthcare workers. Finkenstadt and Handfield (2021) represented this in figure 5 where they classified the inaccessible stock into a ghost stock, a safety stock, a blocked stock, and an invisible stock. The ghost stock is a stock of items that is claimed to be available for use, but such claims are either mistaken, exaggerated or false for political motivations. Members of the government at all levels have an incentive to provide the most optimistic position during a time of crisis. The safety stock is the stock that certain hospitals and medical systems were hoarding for "just-in-case" scenarios. The blocked stock is the stock that is supposed to be shipped but was blocked as it was needed in the country. The Invisible stock was "created" because of elevated levels of reactionary planning, and interventionist strategies (e.g., universities stepping in to rapidly produce face masks using 3D printing)

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seeking to fill the gap for whatever category of material was in short supply on any given day.

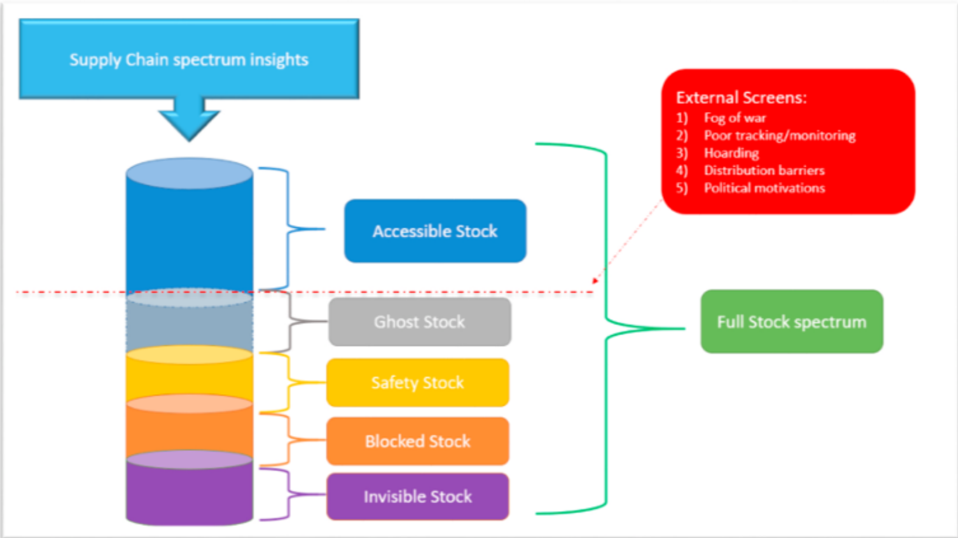

Figure 5: Supply chain spectrum of PPE during COVID-19
Source: Finkenstadt and Handfield (2021)

Supply chain disruptions

While the governments and the private sector across the world had disaster plans and stockpiles of PPE in place, the pandemic exposed shortcomings in these plans. COVID-19 was different because of the uncertainty and the scale of disruption which affected the entire world. The lockdown across the world severely affected the movement of goods across the world. The health care supply chain was also not immune to these disruptions. A variety of factors affected the health care supply chains and was a catalyst to the breakdown of health care services across the world. These include:

- forming chokepoints in ports that slowed down the deliveries of critical supplies,
- lack of enough workers to produce and transport products because workers were out sick or were not showing up to work,
- export bans put in place by countries where protective garments, medical equipment, and pharmaceuticals were manufactured, which limited supply to importing countries,
- panic buying of and stock piling of critical supplies leading to the shortage of products in areas that truly needed them,

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- lack of overall resiliency in the health care supply chain due to companies pursuing cost-focused strategies at the expense of creating redundancy in the supply chain and,
- excessive dependency on the few manufacturers of essential products (Mahmoodi et al., 2021).

Another issue which affected the health care supply chain included shortages in the raw materials used in the manufacture of medical equipment contributing to further shortages. For instance, supply shortages in aluminium, computer chips, paper pulp, and other materials created a ripple effect on health care providers, hospitals, and other health care systems. COVID-19 placed an undue amount of pressure on medical device manufacturers. There was a high demand from hospitals, clinics, and other healthcare sources but the manufacturers of supplies couldn't produce the numbers needed to protect medical workers. This led to the following effects on health care systems. First, difficulties in finding supplies were significant: all hospitals and health care systems reported challenges in getting vital supplies and the shortages lead to price increases. Second, there was a lack of sufficient number of vendors for medical supplies. Health care providers faced shortages from their regular suppliers and as a result, they used other vendors to get the medical and pharmaceutical items required to care for their patients. Third, shortage of raw materials used in medical supplies across the globe, and the companies and manufacturers were dealt a blow because raw materials were increasingly hard to procure: (Sisti, 2022).

The shortage of materials also was the severe bottlenecks in the health care supply chains. Although there were also other significant issues, component suppliers were the main bottlenecks. There was a shortage of raw materials for manufacturing, including critical semiconductor chips used in medical equipment, such as MRI machines, blood sugar monitors, and pacemakers. Additionally, these pieces normally cost a few dollars but during the peak of shortages, they commanded a price upward of $50 because there simply were not enough of them. Along with a battle for raw materials, transportation was another major blockage. Many of the chemical inputs for drugs used in the U.S. are manufactured in China and India, but shipping and transport issues made it difficult for them to reach their intended destinations (Anonymous, 2022).

Structural issues in health care systems

Health care systems across the world consist of a combination of public and private health care providers. Depending on the public and private healthcare provision mix, many organizations perform healthcare procurement, including procurement offices, regional and national government healthcare departments, hospitals, general medical practices, and private sector group purchasing

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representing insurance-based healthcare providers (Scala and Linsday, 2021). Stringent purchasing regulations exist nationally and internationally in trading blocs, such as the EU. Furthermore, a significant part of the healthcare budget (about 40%) of hospitals is spent on the medical consumables, medical supplies, and equipment. With increasing healthcare costs across the world, the governments have tried to reduce healthcare expenses through centralized and unified procurement practices with an objective of making the procurement process more efficient (European Commission, 2021).

The private and public entities in the healthcare supply chain have vastly different capabilities to respond to emergencies. In different countries, an extensive reliance on the medical distributors, a poor inventory visibility across the supply chains, and a reliance on foreign countries for the critical medical supplies make the national healthcare services dependent on several external factors for its smooth operation. While commercial supply chains and humanitarian supply chains have evaluated the risk of supply disruptions under emergencies, such as epidemics, wars, disasters, and the climate catastrophe, the literature in health care supply chains seldom discusses the risk of health care services being affected due to supply chain disruptions (Haraland et al., 2021). These emergencies often cause an unprecedented surge in demand for critical medical supplies which require an appropriate inventory and a logistic infrastructure to ensure that shortages can be avoided (Leite et al., 2021). Previous emergencies, such as the outbreak of SARS and Ebola, have indicated how critical it is for the health care supply chains to be prepared for rapid spikes in demand (Dasaklis et al., 2012). Some countries used this opportunity to identify the healthcare "system weaknesses". For example, in 2016, the UK government organized the "Exercise Cygnus", a flu outbreak simulation involving 950 officials to evaluate the readiness of the UK for an epidemic outbreak. The simulation concluded that the UK was clearly not prepared to face an event of such magnitude, with a lack of central coordination and an intra-state rivalry being the main reasons for failing to satisfy the peak demand for hospital and social care (Haraland et al., 2021).

The COVID-19 pandemic revealed the weaknesses in the health care procurement system, leading to an increase in buyer competition and supplier exploitation (Rakovska and Velinova, 2018). This resulted in the hijacking of crucial medical supplies, a rise in international counterfeiting and subpar products, price manipulation, and corruption (Patrucco and Kähkönen, 2021). Furthermore, the many different actors involved, inefficiencies in legacy systems, and difficulties in forming collaborations made it difficult to manage healthcare supply chains as a coordinated supply chain. Typically, supply chain strategies are implemented by

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individual actors, such as hospitals, rather than being approached as a unified system. (Dai et al., 2020.)

During the COVID-19 pandemic, both public authorities and private healthcare providers struggled to obtain essential supplies as international borders were closed and communities went into lockdown (Kamerow, 2020). The shortage of supplies led to an increase in prices, which caused organizations to seek new suppliers, including opportunistic market entrants that increased the risk of fraud and low-quality products (Atkinson et al., 2020). National reserves were distributed without a clear plan for distribution (Handfield et al., 2020). As a result, the complex and constantly changing healthcare supply chains were unable to effectively handle the impact of the pandemic, highlighting a lack of preparedness in procurement (Scala and Lindsay, 2021).

Cascades

According to the Oxford dictionary the cascade effect refers to “a sequence of events in which each produces the circumstances necessary for the initiation of the next” (Oxford English Dictionary, 2006). In geomorphology, cascading effect refers to the transfer of mass and energy through a chain of component subsystems, the output from one subsystem becoming the input for the next. The concept of cascading effect in disaster management is not a new topic. However, the cascading effect is not limited to just disaster management. Cascades can be observed in any complex system which has many interconnected parts. For instance, in supply chains, a disruption in any one of the links can create a cascading effect downstream as well. Given that modern supply chains are highly interconnected forming a web of connections, a disruption in any of the links can have catastrophic effects across the web of interconnected links. This section explores the theoretical position of cascades in disaster, supply chain disruptions and cascades in supply chain.

Cascading hazards

In literature, there are three related terms compounding, cascading and complex disasters. Cutter (2018) presented a commentary on the differences between compounding, cascading and complex disasters. Compounding effects of the natural physical process are the easiest to understand. For instance, an earthquake can lead to a submarine landslide leading to a tsunami. Here the earthquake is a triggering event while the submarine landslide is a secondary effect, and the tsunami is a tertiary effect. There are many examples of such compounding effects, such as an earthquake (triggering event) producing a submarine landslide (secondary), which in turn generates a tsunami (tertiary). This direct causal chain, variously referred to as the toppling dominoes or the domino effect of natural events, helps to identify all the pathways from a single

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trigger to its singular or multiple responses. However, these are still not exactly compounding disasters. Compounding effect of the disaster refers to a situation when a primary disaster either triggers a secondary disaster, or significantly increases the risk of a secondary disaster. For instance, a lightning causing a wildfire or a wildfire destroying slope vegetation and pouring rain leading to mudflows (Gill and Malamud, 2014). The compounding interaction between the events occurs either temporally, or spatially, or including both dimensions. However, it is important to note that the classification of events as primary, secondary, and tertiary while defining compound disasters can be erroneous and misleadingly prioritizes the timing of the event over the damage or impact (Cutter, 2018).

Cascading hazards, on the other hand, consist of hazards occurring as a direct or indirect result of an initial hazardous event (May, 2007). For an event to be a cascading hazard, the cascading (subsequent) events should occur in succession in both time and space, suggesting that there are sufficient forces or energy in the initial event to trigger the subsequent events in the physical system itself. As understanding of natural hazards causes, propagation, and impact have improved with advancements in systems thinking, process-response modelling, and nonlinear models, there was increased recognition of the role of triggering events in perturbing the overall system through undermining, compounding, or blocking systems' response mechanisms (Cutter, 2018).

With the increased connectivity between various system that characterise the modern life, the risk of these systems being affected by the various perturbations have also become significant. The support systems like ecology, power grids, climate, government, and trade are examples of complex adaptive systems, which have non-linear characteristics of behaviours, and predicting the impact of a hazardous event on such systems is not easy. It is possible that the system might return to its original equilibrium after a disruption or might find a new equilibrium. However, if one considers anthropogenic hazards along with natural hazards, the profile of overall hazard becomes extremely complex to predict: (Gill and Malamud, 2017).

From cascading hazards to cascading disasters

Unlike the causal pathways that can be used to describe compound or cascading hazards, cascading disasters are more complex in nature and cannot be described using linear mechanisms. To better understand cascading disasters, we must often rely on non-linear causal models. These causal loop models are used to understand the causes and effect relationships between numerous factors that may lead to cascading disasters. Models can help unpacking the interconnectedness and interactions of hazards and accumulated vulnerabilities

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within a system. While not all natural disasters have cascading effects, the magnitude of cascading effect depends upon the context within which these natural disasters occur. In contrast to cascading hazards, cascading disasters have a greater impact over temporal and spatial dimension and often affect the marginalised and vulnerable communities the most. Pescaroli and Alexander (2015, pp. 65) give an extensive definition of a cascading disaster.

> *Cascading disasters are extreme events, in which cascading effects increase in progression over time and generate unexpected secondary events of strong impact. These tend to be at least as serious as the original event, and to contribute significantly to the overall duration of the disaster's effects. These subsequent and unanticipated crises can be exacerbated by the failure of physical structures, and the social functions that depend on them, including critical facilities, or by the inadequacy of disaster mitigation strategies, such as evacuation procedures, land use planning and emergency management strategies. Cascading disasters tend to highlight unresolved vulnerabilities in human society. In cascading disasters one or more secondary events can be identified and distinguished from the original source of disaster (Pescaroli and Alexander, 2015).*

What sets cascading disasters apart from compound or cascading hazards is the reliance and interaction of socio-technological systems within which societal functions operate. The failure of socio-technological systems, such as critical infrastructure, including, power stations, transportation systems, and water systems, can lead to large-scale impact on the lives of people who are far away from the original source of the disaster. There are many examples of such events. For instance, during the 2010 Icelandic volcano eruption, the air transport between Europe was affected for over a week. Similarly, 2011 Tohoku earthquake in Japan led to the nuclear meltdown, leading to shutting down of the entire city and it affected the manufacturing and sale of semiconductor chips causing a worldwide shortage of the same. This shortage further affected multiple industries, including car manufacturers and IT industries, across the world. More than the multidimensional and interconnectedness of the commercial operations, it is the societal dependency on critical infrastructure that often leads to unexpected and unanticipated failures that elevate a cascading hazard to a cascading disaster (Cutter, 2018). Furthermore, the dependency of societal functions on the critical infrastructure is also resultant of historically accumulated systemic vulnerabilities in a way that also small-scale accidents can have cascading impacts across the society.

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Social cascades

Social cascades are effect of a cascading disaster on the societal functions. These effects often go much beyond cascading disasters and its impact on societies. Social cascades refer to the impact of a hazardous event or a disaster on the sociocultural, economic, and political institutions of a society. Social cascades can affect the social fabric and interconnectedness of a community life including the pre-existing social networks, indigenous behavioural experience which has been a part of the society. While people often see the triggering event as a discrete event, by the second and the third event it is no longer a single event but an intertwined set of compounding disasters. While the domino effect affects the recovery trajectories, it also exposes the pre-existing vulnerabilities within communities. The concept of disaster cascades points out the effect that multiple successive disasters can have on social existence, historical memory and damage sustained by the community which might be irreversible in many instances: (Cutter, 2018).

Theoretical model for cascading disasters

The definition of a cascading disaster was discussed in the previous section given by Pescaroli and Alexander (2015). The phenomenon that distinguishes cascading disasters from multiple or complex disasters is the escalation point. This is the critical juncture in the chain of events where the concatenation of different events creates an impact which is larger than the initial triggering event could have created. Often, the impact becomes more severe and complex as it passes through the stages as mentioned in table 3. For example, during the 2011 Fukushima accident, only a small number of people lost their lives due to the earthquake. The more devastating impact was produced by the tsunami that followed the earthquake. Furthermore, the damage caused to the Fukushima Dai'ichi Nuclear plant led to a nuclear contamination which might take decades to be cleared off (Hindmarsh, 2013).

In defining a cascading disaster, the intensity and magnitude of the disaster plays a significant role. While both these terms (intensity and magnitude) feel to be similar, there is some ambiguity in their understanding. For instance, while the damages caused by an event can be defined in terms of the scale, the physical intensity of the event causing damage is usually defined in terms of the magnitude (Alexander, 2018). However, in a cascading disaster, the intensity and magnitude are not dependent on the trigger event, but the concatenation of a set of events that have followed since the trigger event. Alexander (2015) proposes a magnitude scale for cascading crises, incidents, and disasters. The operational definitions for the term crisis, incident and disaster are given in table 1. The scale has six levels starting at zero through five. Level 0 denotes a simple or

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major incident while level 5 denotes a catastrophe with complex consequences. Table 2 gives a detailed explanation for each of the levels of the scale.

As the world we are living in is becoming increasingly complex and interconnected, the risk of cascading disasters is becoming increasingly high. All kinds of hazards, such as storms, cyber-attacks, and climate induced disasters, have direct or indirect effects on the critical infrastructures, which in turn affects the society at large, and especially the vulnerable populations. The impact can propagate through the failure of critical infrastructures. Alexander and Pescaroli (2018) have identified five risks that form a part of complex disaster impact. These are: (a) *Compound risks* are the risks associated with the interaction of different extreme events or their drivers, such as storms, the climate change, and the sea-level rise. These events can also be purely coincidental. (b) *Interacting risks* are the risks created due to environmental drivers that can lead to primary and secondary impacts, as with seismically induced mass movements. (c) *Interconnected risks* are created due to the interaction of natural and human systems. This type of risks includes the so-called ‘na-tech’ events, in which a natural impact triggers a technological one. (d) *Cascading impacts* disrupt critical infrastructures and intricately linked organisational systems. (e) Finally, *complex disasters* may involve elements of any or all the previous four types of risks. The same is summarised in figure 6 given below.

Table 2: Definition of terms used in magnitude scale.

Term	Definition	Source
Crisis	A threatening condition that requires urgent action	UNISDR (2009)
Incident	A sudden event, usually resulting in an emergency, that requires a response from one or more agencies. Incidents are more restricted in scope and consequences than are disasters	Alexander (2002)
Disaster	A serious disruption of the functioning of a community or a society involving widespread human, material, economic or environmental losses and impacts, which exceeds the ability of the affected community or society to cope using its own resources	UNISDR (2009)

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Table 3: Magnitude classification of cascading incidents, crises and disasters (Source: Alexander, 2015)

Level 0 Simple incident or major incident.	*No evidence of significant cascades* or escalation points. Simple, direct, linear cause-and-effect relationships between the primary impact driver and its consequences.
Level 1 Major incident, of limited complexity.	*Evidence of simple, short cascades*--i.e., secondary effects of the main or starting impact-effect relationship. There are no escalation points, no major interconnections, or interactions beyond the early 'consequences of consequences' relationship.
Level 2 Major incident or small disaster, with some complex consequences.	*Limited cascade chains*. The effects of the initial event propagate to tertiary levels in which there are significant complications or secondary emergencies at one remove or more from the triggering cause-effect event. The secondary emergencies may be as important or as pressing as the primary event. There may be escalation points, as new fields of vulnerability are penetrated by the extending chain of events.
Level 3 Disaster, with complex consequences.	*Significant cascade chains can be detected*, with at least one escalation point. Different sectors of vulnerability are involved (physical, environmental, institutional, economic, social, etc.), and interaction occurs between them in an identifiable manner. There are complex interconnections between subsystems.
Level 4 Disaster, with substantially complex consequences.	*Cascades are easily identifiable* in the effects of the disaster. Escalation points exist where vulnerability fields and states are encountered. Cascades substantially prolong the emergency and lead to effects that may outlast or overshadow the initial triggering event. The consequences of the disaster are complex on a wide variety of levels, and they extend into many distinct aspects of daily life, which changes very significantly for the duration of the emergency and a substantial part of its aftermath.
Level 5 Catastrophe, with overwhelmingly complex consequences.	*A major initial impact sets off long causal chains of cascading consequences*, some of which, through identifiable escalation points, generate secondary causal chains. All of these extend into many or most aspects of normal daily life and cause very substantial disruption or total shut-down. Concurrent events occur or are triggered by compounding interconnections.

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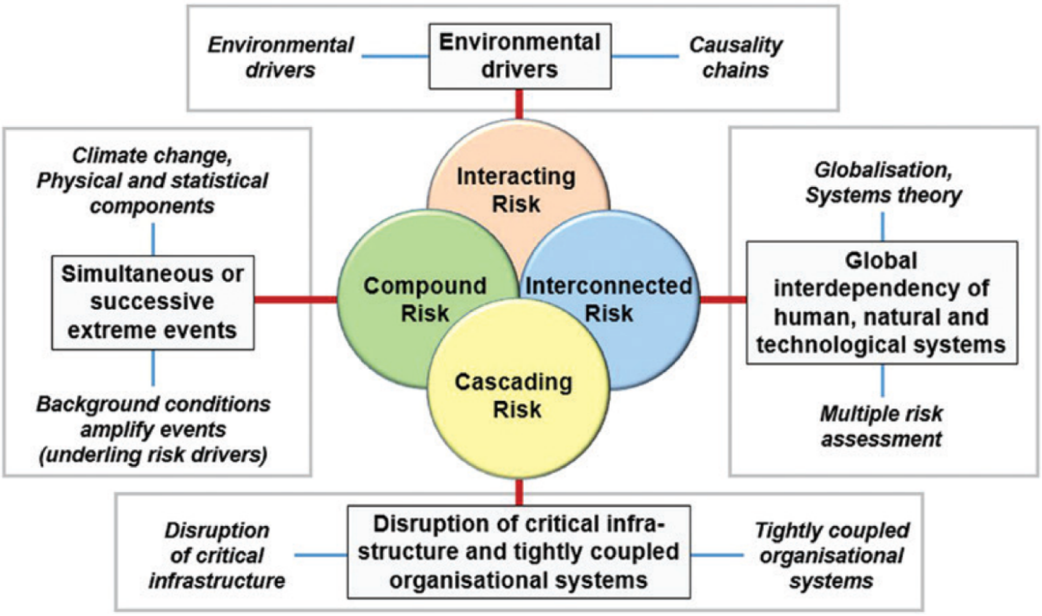

Figure 6: Compound, interconnected, interacting and cascading disasters. Source: Alexander and Pescaroli (2018)

In disaster studies, cascading disasters is still a novel concept. Much of the existing studies on the impact of cascading disasters is studied based on the failure of critical infrastructure. For instance, Pescaroli et al. (2017) studied the prolonged, wide-area power failures and their cascading impacts on people, activities and processes that depend on the supply of electricity. In majority of cases, it's not just the triggering event, but the failure of critical infrastructure is the driver of cascading disaster.

Supply chain disruptions and cascading effects

With elevated levels of global interconnectedness, a disturbance in parts of the globe can have long and disastrous effects on the other part of the world though supply chain disruptions. While risks associated with supply chain disruptions are usually built into the contingency planning process in business, the level of preparedness might vary across the supply chains. For instance, some supply chains might be prepared for minor disruptions of safety stocks and alternative suppliers but may not be prepared for large scale disruptions caused by either natural disasters or a global pandemic as was witnessed in the case of the COVID-19 pandemic. In this context, Ivanov (2022, pp. 1415) defines supply chain viability as:

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"*a dynamically adaptable and structurally changeable value-adding network able to (i) react agilely to positive changes, (ii) be resilient to absorb negative events and recover after the disruptions, and (iii) survive at the times of long-term, global disruptions by adjusting capacities utilizations and their allocations to demands in response to internal and external changes in line with the sustainable developments to secure the provision of society and markets with goods and services in long-term perspective*".

The impacts of COVID-19 on supply chains were far more disruptive than any localised disaster would have. The pandemic-induced disruptions have three specific characteristics that make them distinct. Firstly, the pandemic had a long-term disruption existence and was unpredictable in its scaling. Secondly, the pandemic caused simultaneous disruption propagation in the SC (i.e., the ripple effect) and epidemic outbreak propagation in the population (i.e., pandemic propagation). Finally, pandemic also caused disruptions in supply, demand, and logistics infrastructure: (Ivanov, 2020). These characteristics were not unique to COVID-19 but were observed previously in SARS, MERS, Ebola, and Swine flu outbreaks.

In the past few decades, the supply chains have moved towards efficiency and cost reduction. Some of the ways to improve the efficiency of supply chain is to leverage the economies of scale, reduce the safety stock and focus on sole source of suppliers to be strategically integrated to the supply chain planning. With the improvements in the data capturing mechanisms and data analytics, the centralized supply chain planners got better insights into the supply chain process which were previously a black box. Armed with the computational power for better visibility into the supply chain process, the managers across the world were able to save billions of dollars though supply chain process optimization. However, the major side effect of these optimizations was that the supply chains became extremely fragile and would break down even at the slightest disruption since not enough cushions were built into the process. This was most evident during the COVID-19 pandemic when the supply chains were under severe stress owing to supply and demand shocks. A report by the corporate data analytics firm Dun & Bradstreet says that 51,000 companies around the world have one or more direct suppliers in Wuhan (the epicentre of the COVID-19 outbreak) and at least 5 million companies around the world have one or more tier-two suppliers in the Wuhan region, where COVID-19's was first discovered. Moreover, 938 of the Fortune 1000 companies have tier-one or tier-two suppliers in the Wuhan region (Dun and Bradsteet, 2020).

Just like the cascading disasters, the disruption at one point in the supply chain also has a cascading effect across the whole supply chain network (SCN). The

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propagation of a disruption through and its associated impact is called the *ripple effect*. A ripple effect is distinct from the well-known bullwhip effect. It manifests when the impact of an SC disruption cannot be localized or being contained to one part of the SC and cascades downstream, resulting in a high-impact effect on SC performance (Dolgui et al., 2018). The ripple effect considers structural network dynamics in the SC while the bullwhip effect characterizes the oscillations in operational parameters. The ripple effect is initiated by a severe disruption and describes the propagation of the impact of this disruption downstream the SC, e.g., in terms of propagation of the disruption of demand fulfilment capabilities of supply network because of a severe disruption. In more severe cases, the ripple effect can cause some nodes and arcs in the network to become temporarily dysfunctional, e.g., due to a material shortage. The bullwhip effect, on the contrary, is launched by a small operational deviation which gets amplified in the upstream direction. The literature has explored the impact of bullwhip effect on supply chain in the past while the ripple effect due to supply chain disruptions is yet to be explored in greater detail: (Dolgui et al., 2018).

To understand the supply chain ripple effect, it is imperative to understand the risk propagation in SCN. In practice, a disruption to a SCN often begins locally, with a trigger event affecting any one or group of nodes in the network usually located within the same vicinity. This impact spreads to other firms (or nodes) through their relationships. Consequently, the impact might affect the parts of the network through a set of cascading impacts and affect the nodes which are far away from the origin of the impact. The extent to which the impact propagates in the supply network is also a testament to the resilience of the network. Ignoring this ripple effect may result in misperceiving the nature of SCNR and underestimating the systemic risk faced by the supply chain (Li and Zobel, 2020). The risk in a SCN is defined beyond the boundaries of the focal firm and depends on resilience of the individual members, the processes that connect these members and other network properties. Dolgui et al., (2018) discuss the main reasons for the systemic vulnerabilities which make the SCNs more prone to ripple effect when presented with a disruption in any or multiple nodes withing the SCN. These reasons can be broadly classified into four main categories, i.e., sourcing strategy risks, production planning risks, inventory management risk, and control risk. Figure 7 summarizes the main risks.

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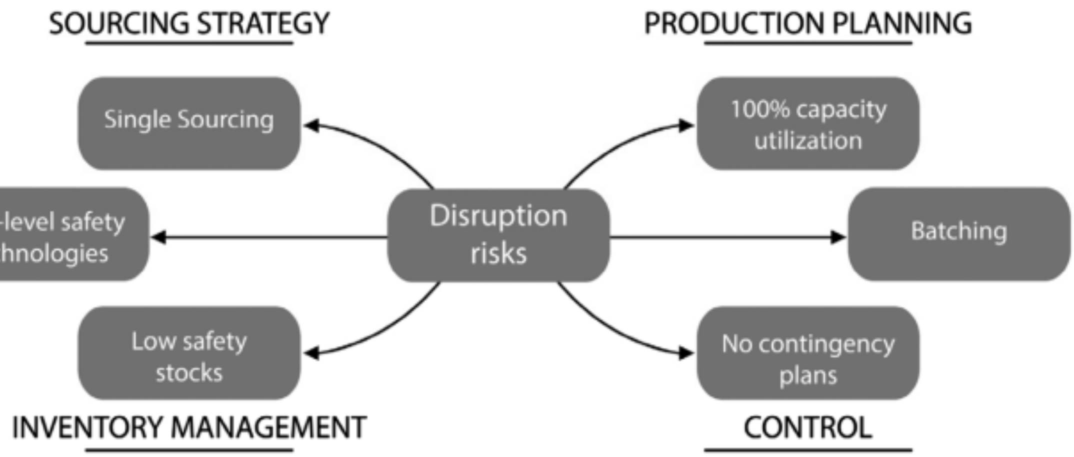

Figure 7: Main reasons for ripple effect in supply chain network
Source: Dolgui et al. (2018)

Systems thinking and complex disasters

Anderson and Johnson (1997) defined a system as a group of interacting, interrelated, or interdependent components that form a complex whole. A system can include both tangible and intangible components. A tangible component can include equipment, machinery, buildings, physical space, etc. Intangible components, on the other hand, include, for example, culture, behaviour, process, procedures, relationships. Systems differentiate themselves from the collection of sub-systems or components in the fact that the components of the system have specific nature of interconnectedness and serve together for a purpose and to function optimally. Systems in turn might have sub-systems which are again a combination of both tangible and intangible components functioning together for a specific purpose. The components of the system and sub-system are dynamically related to each other in a way that a change in one component of system or sub-system can have an effect within other parts of the system or sub-system. These effects are usually propagated through feedbacks and direct linkages between the interacting parts.

Peter Senge (2006) in his classic book called "The Fifth Discipline" defined systems thinking as a framework for seeing interrelationships rather than things, for seeing patterns of change rather than static snapshots. It is a set of general principles distilled over the course of the twentieth century, spanning fields as diverse as the physical and social sciences, engineering, and management. During the last thirty years, these tools have been applied to understand a wide range of corporate, urban, regional, economic, political, ecological, and even

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psychological systems. Systems thinking is a sensibility - for the subtle interconnectedness that gives living systems their unique character. Today systems thinking is needed more than ever because we are becoming overwhelmed by complexity. Systems thinking has been used in various research disciplines to identify the intricate linkages within complex systems and their interactions with other systems. Systems thinking focuses on understanding the problem as a part of an extensive system with interconnected sub-systems with feedbacks. Systems thinking can also be used in analysing potential short-term and long-term impacts of a strategy, without assuming that a particular strategy will lead to a positive effect on all other parts of the system. System thinking is an effective tool when studying large complex systems with multiple interlinkages.

An event involving disaster management is a good example of a complex system where multiple entities interact in a chaotic environment. The organizational approach to handling challenges associated with disaster management can be modified and better understood using the systems thinking method. Systems thinking emphasizes the dynamic character of processes. It is important for planners and governments to continuously engage in long-term mitigation measures. Furthermore, effective communication between stakeholders and different subsystems can help in achieving both the specific goals of the stakeholders involved and the general goals of the disaster management system. The environment should constantly be analysed when making decisions, developing policies, and putting them into action because the environment is a component of the system. The highest level of leadership must continue to buy into and own the agenda, as with any other agenda. All managers need to be aware of the role of their departments and of their own roles in the disaster management system. Support can be acquired in changing the most deeply ingrained mental models, habits, and structures and patterns identified in the company by outlining company's values and the eventual impact of disasters on the departments because of system interconnection.

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METHODOLOGY

To study the impact of COVID-19 on the supply chain disruptions and the subsequent impact on food, energy, water, and health has all characteristics which are ideal for the use of system dynamics. These characteristics are:

- the problems are dynamic (developing over time).
- the root causes of the dynamics are not clear; different stakeholders have different perceptions.
- past solutions have not worked; solutions that fail to consider how the system will respond will fail to produce desirable long-term results.
- implementing change will require aligning powerful stakeholders around policies that they agree to have the highest likelihood of long-term success.

The fields of systems thinking, and system dynamics bring three important patterns of thought to this study. These are 1) thinking dynamically, 2) thinking in feedback loops, and 3) thinking endogenously. *Thinking dynamically* means considering issues as they have evolved and will manifest themselves in the future. Behaviour over time plot is one of the main tools for facilitating dynamic thinking. Drawing these plots across time enables groups to shift their attention from discrete dramatic events to the ongoing, frequently almost constant pressures that give rise to the discrete events we observe. (Howick et al. 2006.) *Reasoning in feedback loops* is centred on circular causality, or the expected long-lasting ripple effects of system players' activities (Richardson 1991). Feedback loops are a source of policy resistance: Planners have the chance to circumvent the innate tendencies of competitive systems by discovering, reinforcing, and balancing feedback loops that are active or latent in the system structure. *Thinking endogenously* is the most powerful part of systems thinking. Although it develops from feedback concept, it serves as its foundation (Forrester 1968; Richardson 1991). Thinking endogenously is extending the border that normally surrounds our thinking about a problem to the point where underlying causes are perceived as connected in circular causal loops with internal forces over which we may have some control rather than as autonomous forces from the outside. Many disparate schools of thought are motivated by "systems thinking," but at their foundation, they are all focused on identifying endogenous drivers of system activity.

System dynamics literature often uses a tool called group model building (GMB) to identify the complex relationships between the various entities and sub-systems (Vennix et al., 1999). GMB helps guide problem definition, system conceptualization, model building and refinement, and model use. GMB has been the choicest approach for the system dynamist for three main reasons. First, to capture the required knowledge in the mental models through the various

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stakeholders. Second, to increase the chances of implementation of model results, and, finally, to enhance the stakeholder learning process (Vennix, 1999).

Solving messy problems

GMB is a preferred tool to explore complex intervention situations that require a significant understanding of both semi-structured and ill-structured decision situations that are seen in practice. Previous studies have employed GMB interventions to work with management teams on less tangible, ill-defined strategic issues, labelled by some scholars as messy problems (Ackoff, 1979), i.e., situations in which there are significant differences of opinion on the problem or even on the question of whether there is a problem. The first step to understand why GMB is an effective tool is to understand the origins of messy managerial situations (i.e., why opinions differ so widely) and to identify the most important deficiencies that occur in teams dealing with these types of problems when trying to reach an agreement. These deficiencies can be broadly divided into two: one, individual sources of messy problems due to limited information processing capacity at an individual level and, two, group sources of messy problems, wherein a group, the deficiency might arise due to in-group interactions and the self-fulfilling nature of reality construction in groups. (Vennix, 1999.)

Individuals as a source of a messy problem

Research over the past decades has demonstrated that the information processing capacity of an individual is limited (e.g., Simon, 1985) and that humans employ biases and heuristics (e.g., anchoring and adjustment, the representativeness heuristic, and the availability heuristic) to reduce mental effort while making decisions (Hogarth, 1987). Research into the area of cognitive maps has also illustrated the restricted character of human information processing. Humans have trouble thinking in terms of causal nets (DoÈrner, 1980) and are incapable of entertaining imbalanced paths and feedback loops in their cognitive maps. It has been identified that even extensive training or “expertise” may not alter this kind of biases. Furthermore, experiments in dynamic decision-making have revealed that people tend to ignore feedback processes, which produces detrimental results (Sterman 1994). And again, explicit training in understanding the feedback structure of the system has no impact on people's ability to manage such a system effectively (Maxwell et al., 1994).

For instance, psychologists have discovered that having varied prior knowledge might result in quite diverse interpretations of the same circumstances (Vennix, 1999). Selection and interpretation are significantly influenced by one's professional background or position within an organization, in addition to the impact of prior knowledge. Humans are social beings, and therefore their interpretations are affected by what other people believe, which further

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complicates the situation. The world we experience daily is an intersubjective one that we share with others. Depending on the situation, similar information will be perceived in diverse ways.

Conclusions from research in human information processing about system dynamics and Group Model-Building seem straightforward. Qualitative modelling has been widely discussed in the system dynamics literature. Advocates of the use of qualitative modelling have argued that in several cases quantification may either decrease the model's relevance for an audience or can even be dangerously misleading (Vennix, 1999).

Groups as a source of messy problems

Messy problems that arise in groups are often the result of poor group communication and the self-fulfilling nature of how groups generate reality. Groups may exhibit several flaws. The generation and evaluation of information are cognitive activities that are frequently mixed up. This is a result in part of our strong tendency to assess what is stated, which limits our capacity to pay attention (Rogers and Roethlisberger, 1988). By adding more structure to the conversation, the group's performance and commitment to a decision will improve. Specific group process approaches include brainstorming, Delphi, and the Nominal Group Process (Vennix, 1999). The absence of critical inquiry or, in extreme cases, its purposeful suppression, which can result in conditions of groupthink, is another issue in groups. Refusing criticism and avoiding differences of opinion has a detrimental effect on the calibre of decisions (Smith et al. 1986). In this context, specialized group process techniques that encourage disagreement, such as Devil's Advocate and Dialectical Inquiry, can be useful. The largest issue in complicated managerial circumstances, though, is team communication. Along with the propensity to judge and the inability to listen, defensiveness is a third barrier to effective group communication. Low-quality communication results from defensiveness, which in turn (a) lengthens decision-making processes, (b) lowers decision quality, and (c) prevents group creativity (Vennix, 1999).

Group model building (GMB)

GMB is a system dynamics model building process which involves multiple stakeholders that are involved in the model building exercise. In literature, often the stakeholders are replaced with the word "client" since traditionally GMB was used to build models of the real-world phenomenon for the organization who hired experts in system dynamics. However, over the years, multiple researchers have been using GMB to build models for their studies and hence, "stakeholders" has been used as a more encompassing term. A typical GMB process involves various members from the stakeholder group, however, this is more of a

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guideline and not a fixed rule. GMB process is a tool that forms part of soft operations research tools. GMB is a versatile tool that can be used for several purposes depending upon the goal of the modeler or the "client". A typical use of the model can be to understand a problem scenario with greater clarity and explore the robust solution strategies which can be used to solve the problem. Robust solution strategies are those solution strategies that provide desirable outcomes under uncertainties either arising from the changes in the operating environment of the system and/or the changes in the system itself. Hence, the goals of GMB and thereby system dynamics are at the systemic organizational level. The aim is to understand either the effect of the process (if things are done differently) or the outcome (things affect differently).

Basic concepts and ideas

There are two main approaches for the GMB that can be found in the literature. The first approach was pioneered by Radboud University Nijmegen in the Netherlands while the second originated from SUNY at Albany (Graham, et al., 1992; Vennix, et al., 1997). In an early application at Radboud University, participants were involved in a Delphi study consisting of mailed questionnaires and workbooks, followed by workshops. GMB an open approach which allows for the use of preliminary model for a start from nothing, uses individual interviews, documents, and group sessions, qualitative or quantitative modelling, and small as well as large models. Vennix, et al., (1997) provide a set of directions to choose from these approaches. Andersen and Richardson (1997) provide many "scripts" that can help in setting up modelling projects. The procedures described are a long way from the earlier descriptions of a set of steps that prescribe standard approaches applicable to most modelling projects. Instead, the guidelines offered have more the appearance of toolboxes, from which the appropriate technique can be selected based on problem characteristics and the clients involved.

GMB is conducted with a group of at least six and up to 15 people. The group is guided by at least two persons: a facilitator and a modeler/recorder. The group is seated in a semi-circle in front of a whiteboard and/or projection screen, which serves as a so-called group memory. A projection screen is typically used when a model is constructed with the aid of system dynamics modelling software with a graphic interface (e.g., Vensim, Powersim, iThink). This group memory documents the model under construction and is used as a parking lot for all kinds of unresolved issues which surface during the deliberations of the group. A separate whiteboard is used to depict the reference mode of behaviour and record comments or a preliminary model structure. As the model is visible to all participants, it serves as a group memory that at each moment reflects the content of the discussion up to that point. A group model building session is

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conducted in the so-called chauffeured style, where only the facilitator uses electronic support and projection equipment, while participants do not have access to electronic communication media (Rouwette et al., 2002).

The role of liaison between the organization and the modelling team is performed by the gatekeeper. Apart from the gatekeeper, the facilitator, and the recorder, two other roles may be important in a modelling session (Richardson and Anderson, 1995). In principle, the group follows the normal steps in the construction of a system dynamics model. This means that the first step is the identification of the strategic issues to be discussed, preferably in the form of a so-called reference mode of behaviour. The next step is to elicit relevant variables with which the model construction process can be started. Depending on the type of problem this will take the form of either a causal loop diagram or a stocks and flow diagram and is referred to as the conceptualization stage. Subsequently, the modeller woks on the model separately after the initial GMB and refines the model. In this stage, the group is only consulted for crucial model formulations and parameter estimations. In the end, the model is shared with the reference group to get feedback and to finalise the behaviour captured through the model.

Research approach

This study was carried out as a part of the Work Package 4 of the EU project titled “sCience& human factOr for Resilient society” (CORE) under the task 4.3. The purpose of this task is to develop a systems dynamics model and policy briefs of cascades across events, sectors, and supply chain disruptions. For this study, the COVID-19 is used as the base case to identify the impact of the supply chain disruption across various sectors, i.e., food, energy, water, and health supply chains. An exploratory approach of using system dynamics GMB method was adopted to gain an understanding of the complex nature of supply chain disruptions due to COVID-19. Due to the exploratory nature of the research, the discussion was semi-structured to enable the researchers to discover varying causal influences that participants perceived to occur in practice. The main steps followed during the research process is shown in figure 8 below. The subsequent sections broadly explain the main parts of the research process.

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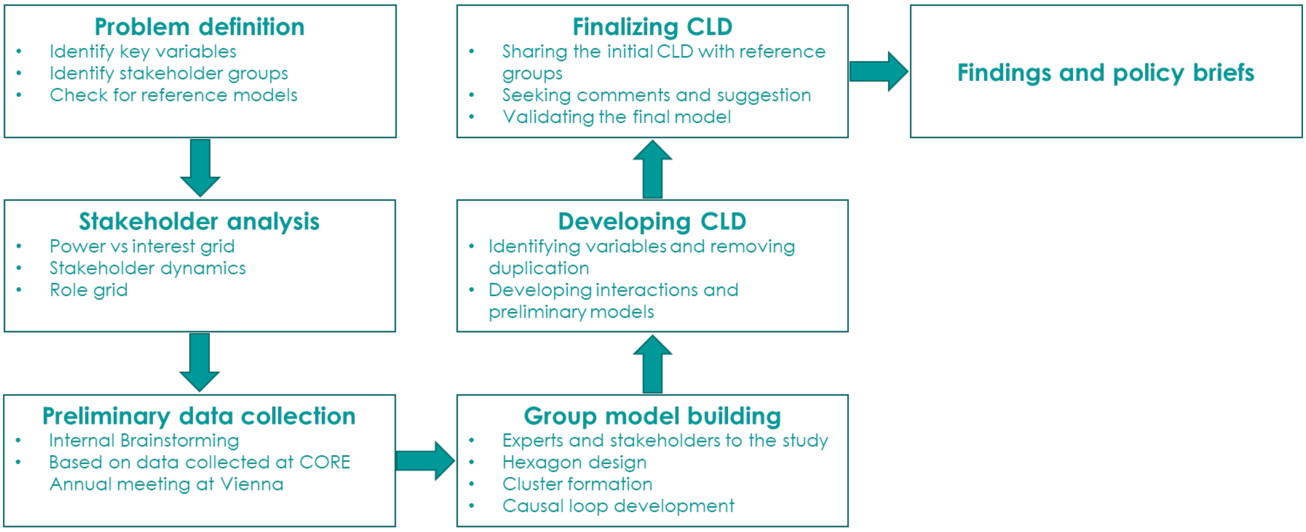

Figure 8: Research process for this study
Source: Authors

Problem definition and research

The main purpose of the study is to understand the cascading effects of supply chain disruptions across the sectors, such as food-energy-water and health. Whilst cascading disasters have been studied in the past, cascades across sectors (e.g., in the health-energy-food-water nexus) have been less in focus. More recently, the COVID-19 pandemic has highlighted societal vulnerabilities to supply chain disruptions, in the health but also in the retail sector. Hence, this study maps cascades across events and adds the layers of supply chain cascades to the analysis. For the study, the authors were the *gatekeepers* to identify the boundaries of the study and identify the relevant people from relevant organizations and the CORE consortium who can be used as resource persons for the study. The research process was divided into three main steps, as described below.

- The first step included an initial literature review and identifying the main set of impacts on food-energy-water-health due to supply chain disruptions caused by to COVID-19. The main finding of this stage is summarised under the literature review section of this report.
- The second stage involved initial data collection based on a questionnaire developed by the *gatekeepers* which was shared with the consortium members to gather insights into the impacts of supply chain disruption due to COVID-19. The data collection of this stage was carried out during the Annual conference among CORE partners in Vienna on 28-29 September 2022. During the conference, the structure of the questionnaire with open-ended questions was first introduced to the attendees and then

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subsequently was shared with them. The questionnaire had two parts. In the first part, the respondents were asked to mark various stakeholders based on their power and interest to influence on the societal impact of COVID-19 on grid. The second part of the questionnaire captured the direct and indirect impacts of lockdown, beginning of unlocking (with certain restrictions) and beginning of back to normalcy on food, water energy and health. Subsequently, after the annual conference, the questionnaire was shared with the rest of the consortium members who were not present in the annual meeting. The questionnaire is given in Annex 1.

- The third stage involved a group model building workshop at HANKEN School of Economics, the HUMLOG Institute, where participants involved developed the initial set of relationships between the variables and helped to identify an initial set of relationships. Subsequently, the variables and relationships were evaluated, and the final model was developed after multiple rounds. The details of GMB are given in next section.
- The fourth stage involved a final model building and validation where the model was shared with selected consortium members to seek for their inputs in validating and further refining the model. The feedback received was incorporated into the final model.

Group model building (GMB) in this study

For this study, we followed the methodology suggested by Vennix (1999), and Anderson and Richardson (1997). The steps are as follows.

- *Identification of the participants.* As a part of initiating the GMB, the experts at the HUMLOG Institute were contacted and invited to be participate in the GMB. The HUMLOG Institute was established in 2008, after two years of close collaboration and exchanges between several schools, universities, and institutes within the Nordic Countries. It is a joint institute between Hanken School of Economics and the National Defence University in Finland and is hosted at Hanken in Helsinki. Throughout the years, the Institute has worked in close cooperation with several International Non-Governmental Organizations, UN Agencies, and societies from the Red Cross/Red Crescent movement and is considered as one of the top research centres in humanitarian logistics and supply chain worldwide (https://tinyurl.com/mryx56vx).

  The agenda for the day was shared with only those members who had confirmed their participation. The agenda for the day is shown in figure 9 below. Along with the agenda, a detailed script for the GMB was sent by

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email to all the participants. The script was adapted from Hoymand et al., (2012). The script is included under Annex 2.

Agenda for group model building on 09/12/2022

1300-1315	Introduction to CLD and problem
1315-1345	Small group discussion and variable identification
1345-1420	Plenary and discussion - I
1420-1430	Break (Belgium Chocolates and snacks)
14-30-1500	Model building
1500-1530	Plenary and discussion - II

Figure 9: Agenda for GMB (Source: authors)

- *Goal setting and clarifying the purpose and plan of the day*: On the day of the GMB exercise, all the participants gathered in a large seminar hall with audio-visual facilities. As the first step, all participants were requested to sign a consent form which was prepared based on the consent form by the ethics committee of the CORE project. A copy of the consent form is given in annex 3. There were nine participants who attended the GMB exercise (which is in line with the recommendations of 6 to 15 people). They were divided into two groups. To begin the proceedings on the day of GMB exercise, the modeller initially explained the purpose of the day and introduced the causal loop models to the participants. Subsequently, the modeller explained the main purpose of the study and answered all questions from the participants. The modeller shared some figures and charts on the impact of supply chain disruptions due to COVID-19 on food, energy, water and health to help the participants organize their thoughts. These charts and figures are included in figure 10. The participants were then asked to identify the causes, effects and consequences of the supply chain disruption due to COVID-19 on four sectors, i.e., food, water, energy and health. Both groups were asked to separately identify the cause-effect-consequence. This was based on the methodology followed by Purwanto et al., (2019). Figures 11 and 12 show the photographs taken during the GMB exercise.

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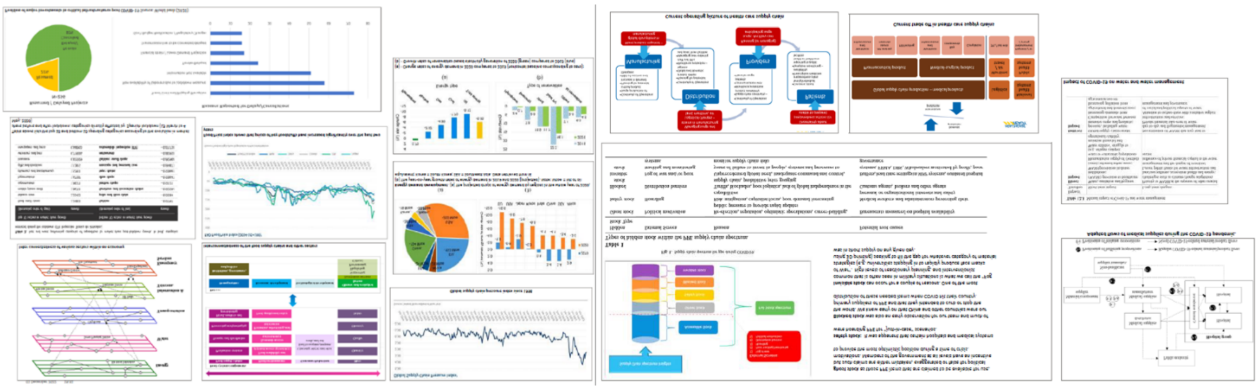

Figure 10: Data shared with the participants for GMB
(Source authors)

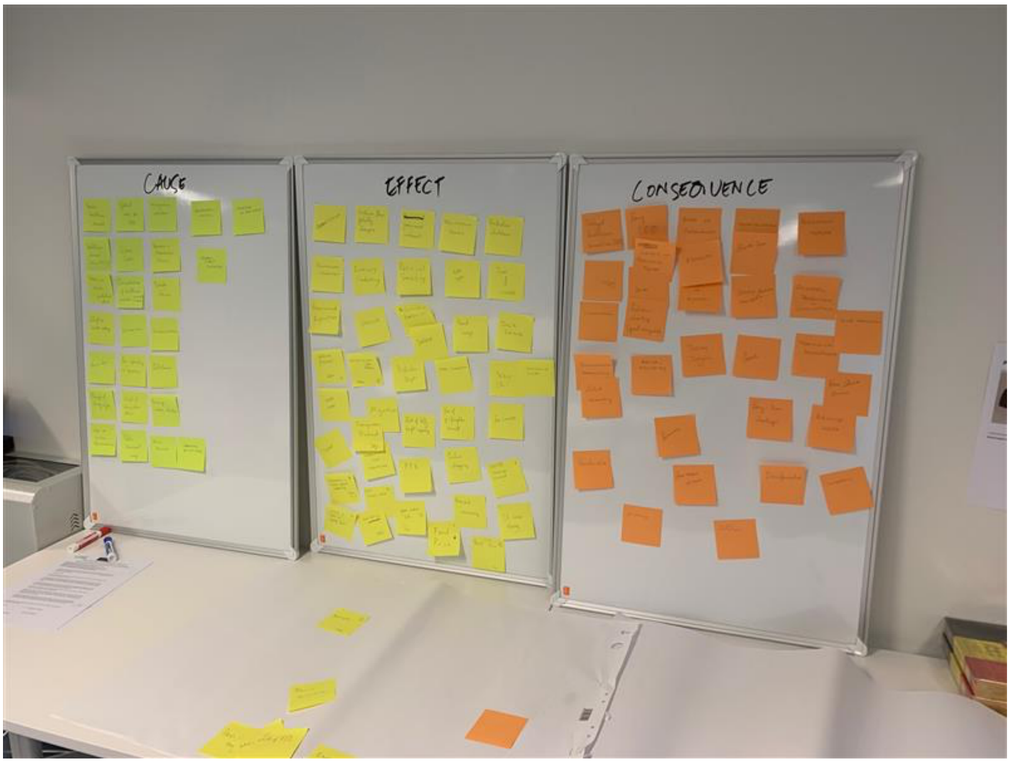

Figure 11: Cause-Effect-Consequence identified during GMB workshop
(Photo courtesy: Authors)

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Figure 12: Participants discussing during GMB (Photo courtesy: Authors)

- *Developing model*: The next stage of the GMB process was to develop the initial causal loop model. After the identification of the main variables in the model, the participants were asked to combine the variables that were similar, i.e., either they were the same variable but worded differently, or they represented a closely related variable. Subsequently, the variables that represented the four main sectors under consideration were combined. Having identified and classified variables based on food, water, energy and health sectors, other variables were identified. The other variables were general in nature and included, for instance, "employment", and "economic activity", which were related to all four sectors and not specific to one sector per se.

  Subsequently, the relationship between each variable was developed based on the group-based discussion. This was carried out in a structured manner. At first, the variables related to food supply chains were taken and the causal loop between the variables was developed. This method was followed for all the other sectors as well, i.e., energy, water, and health. Following that, the cross-sectoral impacts were identified and how the

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sectors (through the variables) have interacted or impacted each other was also identified. Finally, the combined model was discussed, and clarification of any unclear points was sought from the participants.

The first version of the report, which included the model was reviewed by CORE project partners, comments from them were included in the later versions of the report, and model was modified accordingly.

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RESULTS AND DISCUSSION

In this section, the main findings of the group model building are discussed. Based on the discussion in GMB session, we first discuss the general impact of COVID-19 on supply chains and the how the supply chain disruptions have affected the four sectors of interest. Subsequently, a CLD for each of the four sectors is built by adding to the level of complexity. Finally, the impact trees are evaluated to understand the cascading effects of supply chain disruptions across the sector.

General model for supply chain disruption

The impact of COVID-19 on the supply chains was critical owing to the disruptions. At the initial stage, the study focussed on developing an overarching model to capture the impact of COVID-19 on the supply chains and how this affected the total societal resilience. As the COVID-19 cases across the world increased, almost all governments responded by cutting down the interactions among their population, and, as a result, various forms of lockdowns or restrictions were put in place. Some of them included extreme levels of lockdowns where no one could move within and across the boundaries of the nation, and in some other cases, conditional restrictions were imposed on the movement of people. However, the general impact of the increase in the number of COVID-19 cases was the surge of the restrictions limiting the movement of people and goods. The direct impact of these restrictions was, thus, not just the disruption in the flow of the people, but also on that of the goods and services and thereby on the level of economic activity. This had profound impact on supply chains across the globe and led to massive disruptions.

While the governments recognized this as a potential impact of the rapid lockdowns, the impact of supply chain disruptions was far reaching, especially on the critical services. For instance, the lockdowns led to the sudden drop in the shipments of various goods, including both raw material, semi-finished parts and finished goods across the industries. This led to the depletion of the quantities of the products that were available for the various critical services, such as food services, healthcare services, and critical infrastructure services. There were many reports outlining that the supermarkets and stores across the world, especially in Europe and North America, were running out of essential commodities. The major reason for this can be traced to the fact that the modern supply chains are aligned to be extremely efficient and carry as little inventory as possible. With the improvement in the technologies across the sectors, including the cold chain and storage, the supermarkets have been able to ensure that there were enough items on their shelves round the year. However, with the COVID-19 lead restrictions putting a temporary half to the supply flows and the extreme uptick in the demand owing to panic buying led to an extreme pressure on the existing stocks across the supply chains.

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This combined supply and demand shock on the supply chains led to many households and individuals not being able to find essential commodities during the initial phases of lockdown. This subsequently reduced the overall coping capabilities of the societies. This was aggravated by the fact that the lockdown-induced fall in economic activities led to either a job loss or a reduction in the average wage across multiple sectors. Combined with a higher inflation and supply disruptions, the overall coping capacity of many individuals and household was significantly affected.

While the conditions during the lockdown were similar for everyone (in most countries), the impact was not uniform. Multiple studies (see Burlina and Rodrigues-Pose, 2023 for detailed exposition) have identified that the impact of pandemics and income inequality are closely related, and this was the same for COVID-19. Households' decrease of access to work and education are two of the most important drivers of the reduction in well-being both in the short and medium term. Having said that, the impact was not the same across the European Union. It was observed that the countries with the greatest degree of deprivation are a group of Eastern European countries: Bulgaria, Latvia, Serbia, Lithuania and Cyprus. On the other hand, some Nordic countries, such as Norway and Finland —together with Croatia— are those with the lowest degree of deprivation (Ayala, et al., 2022). This disproportionality within the social groups had further adverse effect on the vulnerabilities across the society, where the already disadvantaged were further and disproportionately affected by the lockdown and the subsequent supply chain disruptions and their impact on the critical services.

With an increase in the vulnerability towards COVID-19, the impact on vulnerable groups such as children, people with disabilities, immigrants, etc., had increased significantly. Families with children from poorer communities were particularly hard hit when schools were closed during the lockdowns in different countries as they rely upon school meals to help provide adequate, nutritious food for their children. Furthermore, the way governments and health authorities chose to communicate with communities also unwittingly led to some groups being disadvantaged. For example, in the Netherlands non-native Dutch speakers tended not to engage with information on television as their main source of information. This might be because those who did not speak Dutch well struggled to understand the complex information conveyed in official press conferences (Gary, 2021). Thus, with the vulnerable groups being left exposed to COVID-19, the incidence of the cases saw an uptick. With an increase in the cases across the geographies with vulnerable populations many administrations resorted to further clamping down and extending the restrictions within those areas. This further tightening of the restrictions added to the already existing

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conditions which had led to disproportionate impact of COVID-19 to begin with. This compounding effect has been captured in the Figure 13 shown below, which was arrived at as the initial overarching model for the impact of COVID-19 on supply chain disruptions and its further impact on societal vulnerabilities.

The subsequent section summarises the sector base models, for food water health and energy and how they interact with the overarching model.

Causal model on supply chain disruption and food sector

This section discusses the impact of supply chain disruptions caused by the lockdown and restrictions imposed by the governments across the world to curb the spread of COVID-19. One of the main challenges during the peak lockdown and subsequent period after the lockdown was the availability of food items in the supermarket shelves and rapid increase in the price of the food items. The participants of the GMB also noted this and identified food availability and the food price as the key variables in the identifying the impact of supply chain disruption due to COVID-19.

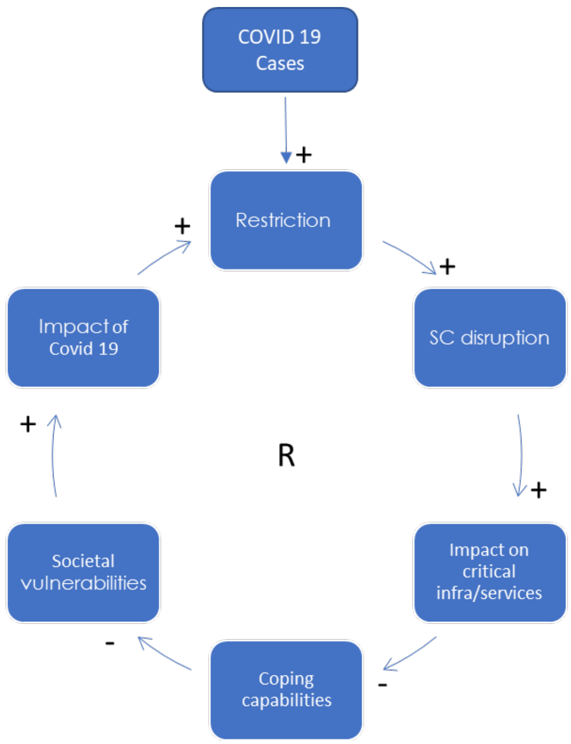

Figure 13: Overarching model for the impact of COVID-19 (Source: Authors)

To curb the increase in the number of COVID-19 cases, restrictions and lockdowns were implemented across local as well as international borders. The risk of infection combined with the lockdown measures increased fear and panic

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among the people. The fear and anxiety were not just because of the lockdown but also due to the uncertainty regarding the extent and the duration of the lockdown. One of the impacts of this lockdown induced fear was a marked uptick in the acute additional demand for the essential items especially food items. This is shown by the reinforcing loop RF1 in figure 14. While most supply chains were equipped to handle regular demand, they were not equipped to handle an extreme and acute spike in the additional demand that was the direct consequence of the fear and anxiety induced by the lockdown and the general increase in the number of COVID-19 cases. Moreover, buffer inventories were quickly depleted. Thus, the food availability across multiple points of sale was significantly affected by the rapid depletion in the buffer inventory as well as panic buying and thereby causing an acute spike in demand.

The next critical factor which affected the food availability was caused by the reduction in economic activities, which again, was the direct impact of the restriction and lockdowns. With the reduction in the economic activities many businesses were forced to close or temporarily stop their operations. This had led to massive layoffs and increase in the number of unemployed people in the society. The direct impact of the many of the business closures was production and the food production capability across the supply chains. While food industry and the related services were exempted from the lockdown, deceptions upstream the supply chains had critical impact on the food industry. For example, the manufacturing companies which either used to manufacture raw materials or semi-finished products used in the food industry, such as packaging and other machine parts, we're not exempted from the lockdown. And hence, the disruptions in the upstream of the supply chain had cascading effects across the downstream which eventually affected the food production capabilities within the supply chain. Furthermore, the cold chains were also disrupted which led to a massive wastage of food products, such as dairy and meat products, causing also a massive pressure on the primary raw materials that were used in manufacturing value added products from dairy and meat.

The third critical factor which influenced the food availability in the stores was due to the lack of availability of labour which was critical in labour intensive processes, such as harvesting, the produce, and meat industry. During COVID-19 lockdown, the cross-border migration of the seasonal labourers working in harvesting was stopped abruptly. With no migrant labour available and a short harvesting window, a lot of produce was left on the field and was damaged. Hence it was observed that an entire season of produce was damaged. This put a significant stress downstream the food supply chain and lead to a rapid increase in the food prices. While special provisions were made to ensure that the movement of the migrant labourers across the borders in the European Union was not affected, by the time these decisions were taken, most of the produce

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had already been damaged and in many cases, it was too late to harvest and process.

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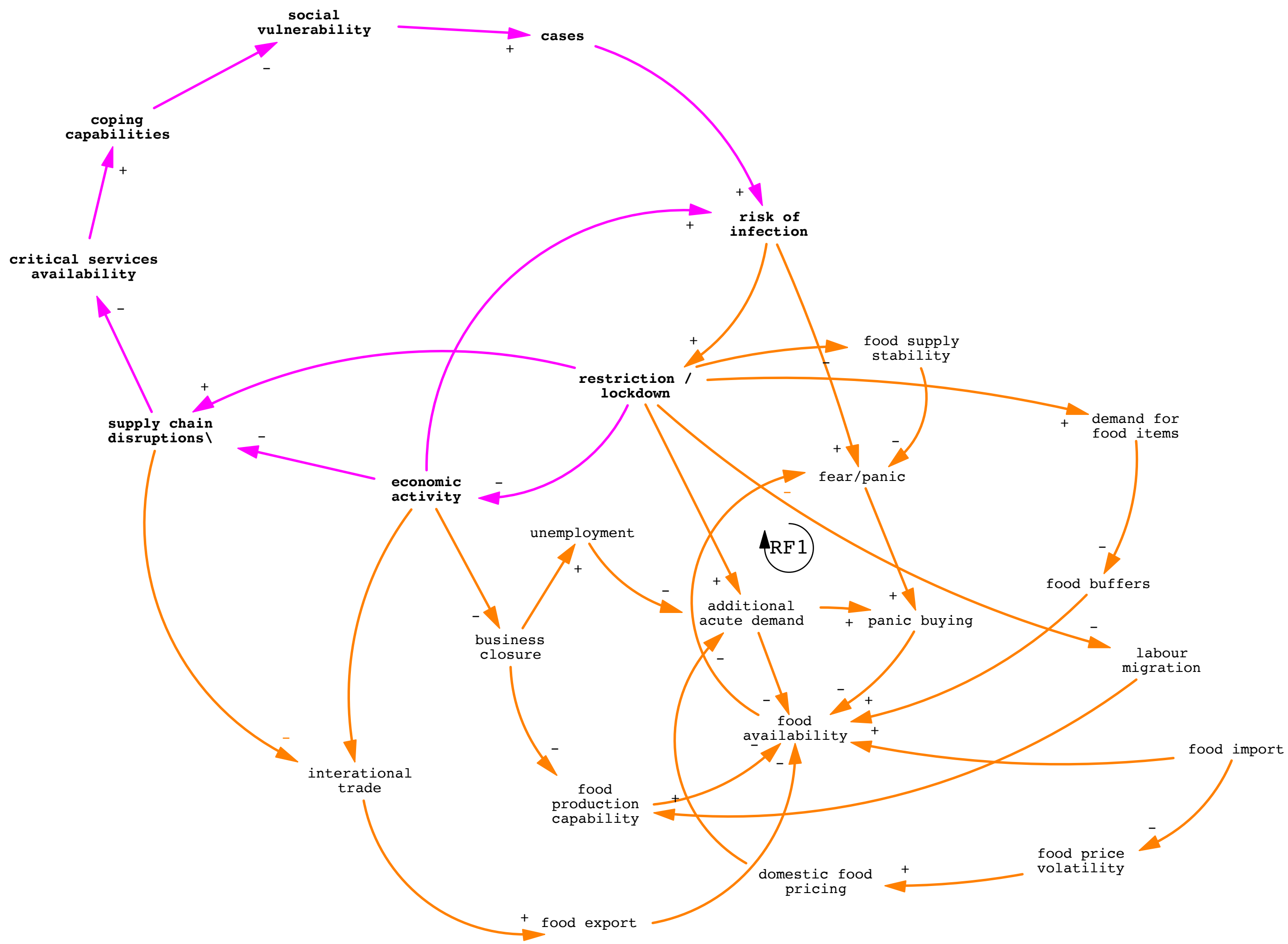

Figure 14: Effect of supply chain disruption on food sector (Source: Authors)

While importing essential food items, such as wheat, owing to the massive global demand, the wholesale prices for the imports increased significantly higher than in usual times. Further, many countries responded with sanctions to ensure that their own people were not affected by the shortage of food. The Figure 14 below captures the essence of the above discussion. It is visible in the figure that food availability is the central variable which is affected by the food production capability in the supply chain, the acute additional demand caused by panic buying, food buffers, and the amount of food imported.

Causal model on supply chain disruption and energy sector

The total energy consumption in any economy is a sum of industrial energy consumption and the household energy consumption. The energy generation and transmission processes are also based on the consumption patterns. As discussed in the previous section, the direct impact of lockdowns and restrictions was the reduction in the economic activities. This sudden reduction in the economic activities had a significant impact on the energy sector, especially on the profitability and the energy generation capabilities of the energy companies. This can be understood by looking at how the energy consumption profile had changed during the initial phases of lockdown.

As mentioned earlier, the total energy consumption within an economy depends both on the domestic as well as the industrial consumption. Usually, the peak industrial load and the domestic loads are during the morning and evening hours respectively. However, due to the lockdown, the peak industrial load was significantly reduced in the morning hours, and the domestic load was distributed across the day. Further, while there was some increase in the domestic load due to the remote working which was popular during the lockdown, it was not significant enough to match up to the industrial demand. This change in energy consumption pattern had two significant impacts. First, the total revenue generated by the energy companies had significantly reduced while the maintenance expenses had gone up. Since most of the revenues for energy companies come directly from the industrial consumption, a significant drop in the industrial consumption led to a loss of revenues for many energy companies. This was a particularly difficult time for smaller energy companies, especially those who did not have their own generational capabilities but acted mostly as intermediaries between large energy companies and the consumers. During this time there was a significant consolidation of the energy providers since many companies could not manage their revenue deficit and had to be merged with other energy companies. This further contributed to redundancies in these companies adding to unemployment.

Another significant impact on the bottom line of the energy companies was the increase in the maintenance expenses. Since the transmission and the generation capabilities are tuned to the consumption patterns, any sudden change in this consumption pattern requires load balancing across the transmission lines. The load balancing exercises are extremely time consuming as well as intense processes which cannot be conducted without any planning.

It was observed that the energy companies had to restructure their load balancing across the transmission lines which affected their maintenance schedule as well as created stress on the lines, thereby requiring more maintenance than expected (Ghennai, et al., 2021). However, the supply chain disruptions and non-availability of spare parts affected maintenance schedules and caused many companies not being able to operate at 100% capacity. In Figure 15, RE1 represents the reinforcing loop under pre-COVID conditions while BE1 represents the balancing loop capturing the impact of restrictions and slowdown in economic activities due to COVID.

The second impact of the change in consumption patterns was the need to depend more on the non-renewable sources of energy. Since the profitability of the energy companies had reduced significantly, almost all energy companies and the governments reduced or stopped the funding for green energy transitions. This was further affected by the supply chain disruptions since multiple components required for solar power generation, including solar panels, are primarily manufactured in China. Combined with supply chain disruptions and a lack of funding for the green energy transition, the energy generated through green energy sources significantly reduced during the COVID times. Furthermore, many governments and energy companies have decided to freeze any major investments in the energy sector until the situation stabilises. This is captured by the reinforcing loop RE2 and the balancing loop BE2 in the Figure 15. The loop RE2 is a positively reinforcing loop without being affected by COVID while the loop BE 2 is the balancing loop which captures the impact of COVID and the associated disruption in supply chain and international trade.

Figure 15 given below captures the essence of the proceeding discussion. It can be observed from the figure that the total energy consumption has a direct impact by the reduction of economic activities due to the lockdown. This reduction in the total energy consumption has also affected the revenue of energy companies which in turn has affected the profitability of the companies and thereby any investments in both maintenance as well as green energy transitions.

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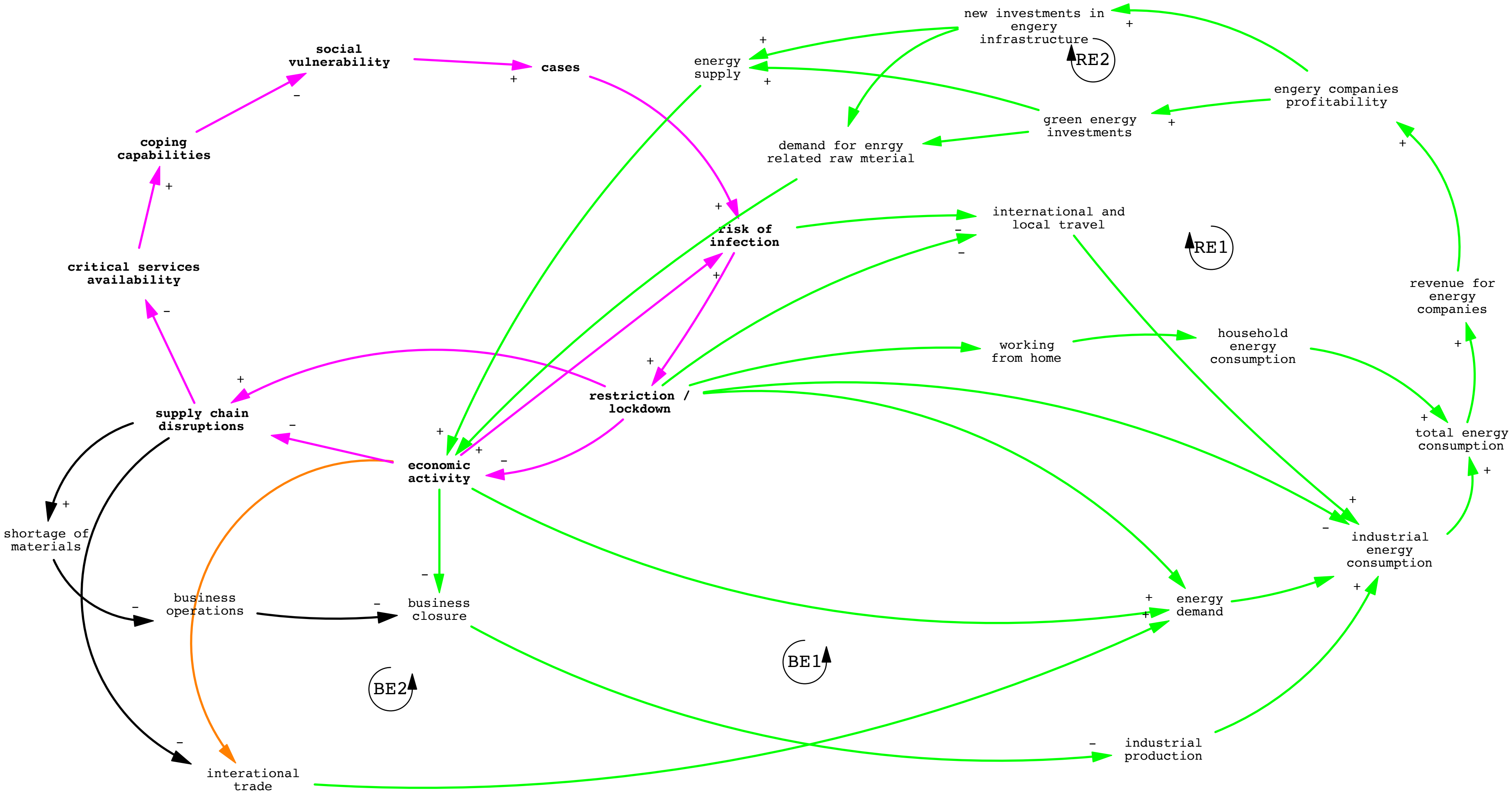

Figure 15: Effect of supply chain disruption on energy sector
(Source: Authors)

Causal model on supply chain disruption and water sector

While there are multiple studies on impact of COVID-19 on various sectors, the impact on water sector has not received much attention. However, it is not to say that the impact has been any less. This section discusses the main impacts COVID-19 had on water sector and how through the GMB. The causal loop model helps to understand these impacts.

As discussed in the previous sections, the lockdowns had a significant impact on the water industry as well. Due to the lockdowns and increase in the remote work, people spent significant amount of time indoors. Therefore, the domestic water consumption increased significantly. On the other hand, the industrial water consumption reduced which had significant impact on the revenues generated by the water companies. However, the lockdown induced domestic consumption had a lot more impact than merely an increase in the domestic water consumption. With a significant amount of time spent indoors, people started using more water at home for water intensive activities, such as gardening, swimming pools, etc. Furthermore, it was observed that people were flushing down and putting things that were not supposed to be put into the drains. For example, due to toilet paper shortages, alternatives to replace toilet paper, which were not supposed to be flushed in the drains, were used (Ong and Nielsen, 2020). These kinds of behaviours cost significant blockages along the drains and sewers, which put additional pressure on the water companies in terms of maintenance. Thus, given that the household consumption of water significantly increased water production also became more expensive. This is because an increase in the household demand offset the reduction in the non-household demand, and as a result, the water production cost for the companies significantly increased during this time. This is represented by the negative reinforcing loop RW2 in the figure 16. RW2 captures the impact of the reduction in the revenues of water companies due to the restrictions and lockdowns, and the resulting substantial reduction in the industrial water consumption, and the increase in the domestic water consumption.

The second biggest impact of COVID-19 on water sector was the halting or slowing down of engineering investments in improving the water and sanitation systems. For example, Ofwat, the water management authority in the UK had given clear instructions to the water companies to meet core service obligations, which is, to provide water and wastewater services and not to prioritise engineering projects in the meanwhile. This mandate was also due to the lack of temporary and seasonal labourers who are critical in large scale engineering projects. The availability of these labourers was caused by the border closures and lockdowns. The supply chain disruptions also had an impact on procuring raw materials and parts which would have been used in these engineering projects. Furthermore, the COVID-19 pandemic further disrupted the sector's demand and growth projections. With an increase in the domestic water consumption, many water companies were wary about whether this could be a long-term shift in the water consumption patterns. Another major impact on the revenues of the water companies was the non-payment of dues by businesses. Due to the lockdown, both industrial and non-industrial small-scale businesses had to be shut down temporarily. This affected the revenue streams of small businesses and many of them did not have the capability to pay for the outstanding bills of the water companies. This led to an increase in the accounts receivable for the water companies, which further affected the revenues and financial outlay for large scale engineering projects. This is shown by the reinforcing loop RW4 in Figure 16.

Finally, the third significant impact of supply chain disruptions due to COVID-19 was on the quality of water itself. While multiple transmission modes of COVID-19 were being closely evaluated, it was identified that COVID-19 virus could be transmitted through water as well. It was observed (Ong and Neilsen, 2020) that COVID-19 could be transmitted through the sewage systems from residential (toilet, shower, washing, etc.) and through medical centres. The lack of proper disinfection can also cause transmission. Moreover, it was identified that there were increased viral levels in the treated wastewater, which indicated that the wastewater treatment did not have an adequate efficiency to remove COVID-19 viruses. One of the main reasons for this lack of efficiency in filtration systems was due to the age-old equipment that had not received proper maintenance or in many cases were passed their due life (Renukappa et al., 2021). Furthermore, it was also identified that in many cases the water companies were not able to source the chemicals and components for the filtration systems due to the supply chain disruptions. Since many are of the chemicals used in the water filtration systems are not manufactured within Europe and are usually imported from Asia, the disruption of the international trade led to a severe shortage of chemicals required for the water filtration. This is jointly represented by the reinforcing loops RW1 and RW3. RW1 is a positively reinforcing loop which captures the impact of household water consumption for WASH demand which has a positive impact on reducing the risk of infection. However, RW3 is a negatively reinforcing loop representing the impact of supply chain disruptions due to the restrictions and lockdowns on the availability of industrial cleaning material which had an impact on the water maintenance system and, thereby, the quality of water increasing the risk of infection through the water systems.

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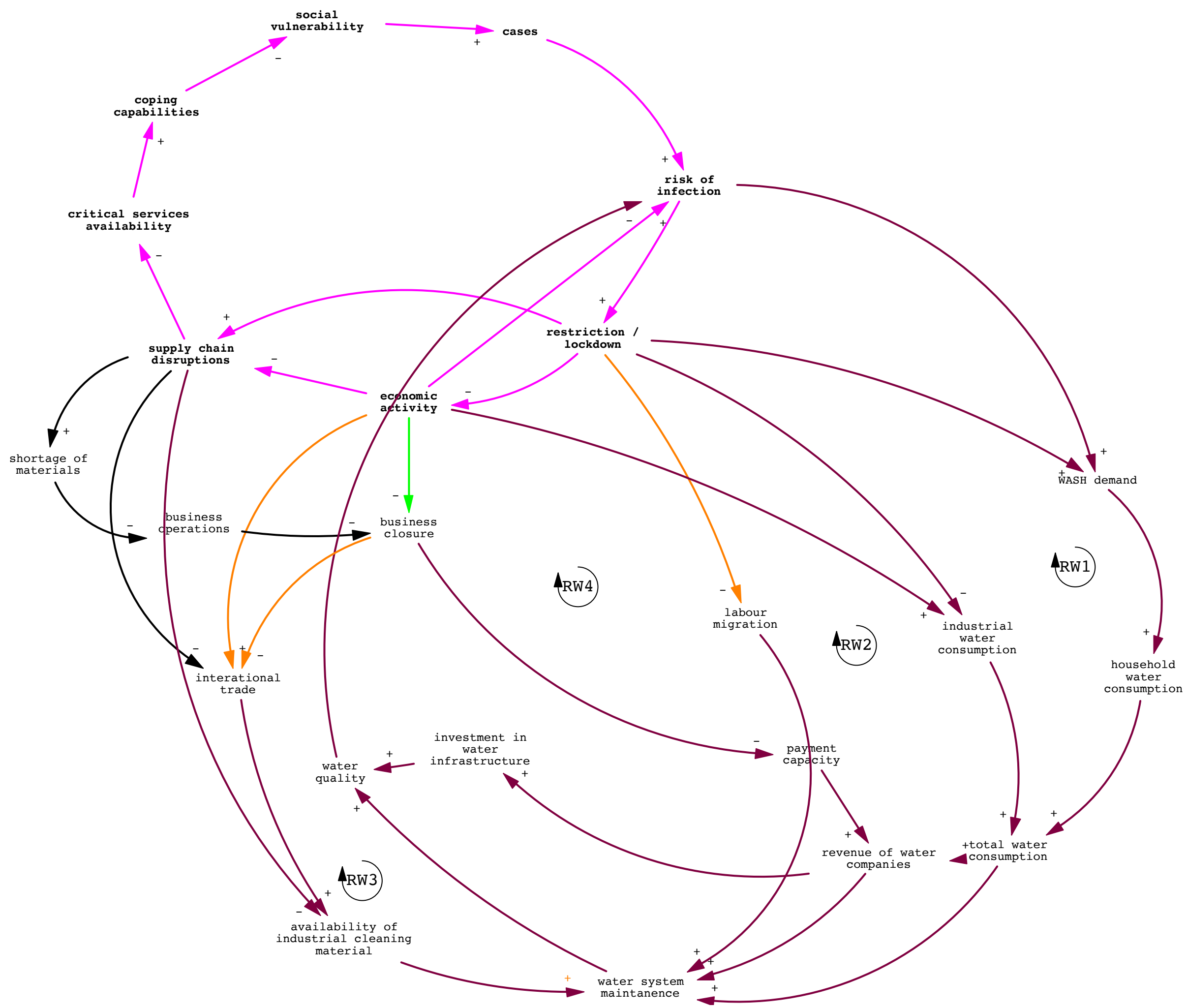

Figure 16: Effect of supply chain disruption on water sector
(Source: Authors)

As shown in Figure 16, the water quality has a direct impact on the risk of infection, which further effects water for WASH. While the risk of infection leads to further restrictions or lockdown, it has a direct impact on the industrial water consumption. The reduction in the economic activities lead to business closures and the payment capability of both individuals and businesses thereby further reducing the revenue for water companies. Furthermore, the supply chain disruptions led to shortages of materials and availability of industrial cleaning items. All these factors affect the maintenance of water systems which further negatively affects quality of the water, and the loop continues.

Causal model on supply chain disruption and health sector

The impact of COVID-19 on health sector cannot be paralleled to any other. While the health sector was affected across the world, a careful analysis reveals that there are some parallels across multiple countries. The section delves deeper into the basic challenges that led to the widespread impacts of COVID-19 on the health sector. Figure 17 shows a causal loop diagram that illustrates the main challenges that affected the health sector during the peak of COVID-19. As shown in the figure, the healthcare delivery during COVID-19 was affected the most which subsequently had a significant effect on the coping capabilities and societal vulnerability. The healthcare delivery was primarily affected by the pressure on healthcare infrastructure, availability of healthcare professionals, availability of medicines, and equipment, such as PPE. The increase in the number of cases of COVID-19 led to an increased number of hospitalisations especially for those with pre-existing conditions or co-morbidities. With an increased number of hospitalisations, the pressure on the hospital infrastructure, increased significantly since there were already other patients who were under treatment or who required non-COVID related treatments. With the pressure on the hospital infrastructure, mounting up significantly and quite rapidly during the peak COVID times, the healthcare delivery was affected for both COVID and non-COVID patients. This reflected in the availability of ICU beds across EU. For example, the Norwegian ICU registry reported an average length of stay of 17 days in October 2020, showing that patients spent an average of 16 days in the ICU, with the variation likely related to the different time of measurement. Furthermore, data from the OECD/European Union reported ICU occupancy levels of 78% in Italy at the height of the outbreak. Hospital resource utilisation also depends on demographics and morbidity of infected population groups, treatment pathways, and service delivery patterns, etc. (Berger, et al., 2022). With the healthcare delivery being affected, the coping capability of the society was also affected leading to a greater amount of social vulnerability and further leading to an increase in the number of cases. This reinforcing loop is represented as RH1 in Figure 17 below.

With the number of patients getting hospitalised COVID-19 had a significant impact on the healthcare professionals as well. Since the healthcare professionals were in close contact with the COVID patients, their risk of infection was very high. There were multiple cases of healthcare professionals contracting COVID and many even lost their lives. Furthermore, the numbers of healthcare professionals in many countries were not enough to handle a surge in the number of patients. With the number of healthcare professionals being affected by COVID increasing due to the contacts with the affected patients, the availability of healthcare professionals reduced significantly. In many cases, the available healthcare professionals had to take long working shifts, which affected both their mental and physical well-being. The lack of availability of healthcare professionals further affected the healthcare delivery, which was already under stress from the pressures on the healthcare infrastructure owing to the COVID-19 related hospitalisation. This is represented by the next reinforcing loop marked as RH2 in figure 17.

The third significant impact on the healthcare delivery can be traced to the supply chain disruptions caused by the restrictions and lockdowns imposed during the initial phases of COVID-19. With the closing of the borders, supply chains across the globe were disrupted. This also had a significant impact on the availability of both raw materials as well as subcomponents used in the manufacture of medical equipment, especially the ones like ventilators. During the peak COVID times, the demand for ventilators and PPE had skyrocketed. However, most of the manufacturing of these items were dependant on China and other South Asian countries which were the worst affected. Hence, many countries in Europe had to either depend on the national stockpile or come up with in-house manufacturing capabilities for ventilators and other equipment, including PPE, required for managing COVID. While this was managed with some degree of success; the shortages of raw materials and a lack of medical production capabilities had a significant impact on the number of units that could be manufactured. This has been captured in the reinforcing loops RH3 and RH4 in Figure 17.

During GMB, participants identified that risk of infection and the challenges associated with the healthcare delivery had a direct impact on increasing levels of fear and anxiety due to COVID-19. This led to a rapid uptick in panic buying of PPE and sanitizers across the countries. Even though this led to a rapid decrease in the buffer stocks, many had resorted to buying them at a premium. This had led to a reduction in the availability of PPEs. During this time, governments, and media agencies played a significant role in both informing as well as encouraging the people to use PPEs. The benefit for people using them was the reduction in the risk of infection, and thereby reducing the stress on healthcare infrastructure and improving the healthcare delivery process. This is the balancing loop represented by BH1 in the Figure 17.

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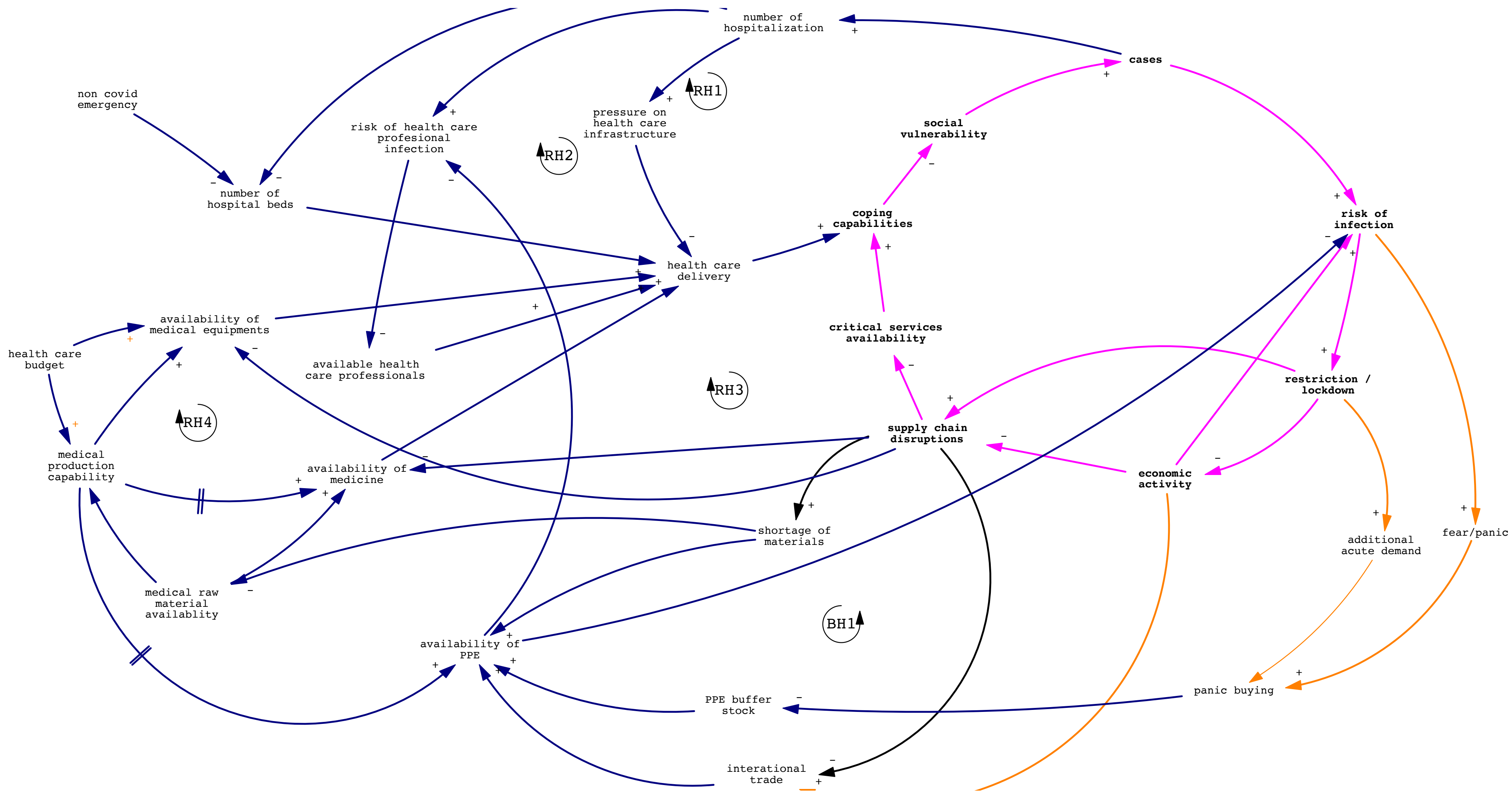

Figure 17: Effect of supply chain disruption on health sector (Source: Authors)

Combined model of supply chain disruption

In the previous sections, the impact of COVID-19 led supply chain disruptions on food, water, energy, and healthcare infrastructure were discussed in detail. While the impact of COVID-19 on each of these sectors can be analysed separately, it is important to understand the combined effect COVID-19 had on all the sectors together. Figure 18 shows the combined model of supply chain disruptions on food, water, energy, and health sectors. They have been marked in coloured segments, as shown in the Figure 18. To further explain the combined model, we consider three model variables from the figure. These variables are lockdown/restrictions, supply chain disruption and coping capabilities.

The effect map of lockdown/restriction is illustrated in Figure 19. It can be observed that the direct impact of lockdown/restriction was the additional acute demand for food and personal protective equipment, and a significant change in the food consumption patterns, which had affected the amount of buffer that supply chains usually carry to mitigate variations in the demand. Lockdown/restrictions also had a significant impact on the economic activities which had a cascading effect on business closures, energy demand, industrial water consumption, international trade, risk of infection, and even supply chain disruptions. Another significant impact due to the lockdown and restriction was on the availability of labour, in particular, in sectors which are highly labour intensive and dependent on migrant labourers, seasonal workers, and low skilled or semi-skilled workers. Thus, the industries that were primarily affected were agriculture, construction, infrastructure maintenance, small scale manufacturing, and mining, which had a cascading effect both in terms of a lack of human resources to continue the operation and non-availability of raw material or semi-finished goods for further down in supply chain. This again had cascading effects in food, water, health, and energy sectors as described in the previous sections.

The effect map of supply chain disruptions is shown in Figure 20. As discussed in the previous sections, supply chain disruptions had far reaching and extensive implications on food, water, energy, and health sectors. While ensuring social distancing between people was one of the most effective ways to curb the spread of COVID-19, it had far reaching implications on both the movement of people and goods across the world. We live in an extremely connected world with supply chains ensuring that the producer and consumer need not be within a geographical proximity to be able to use or consume a product.

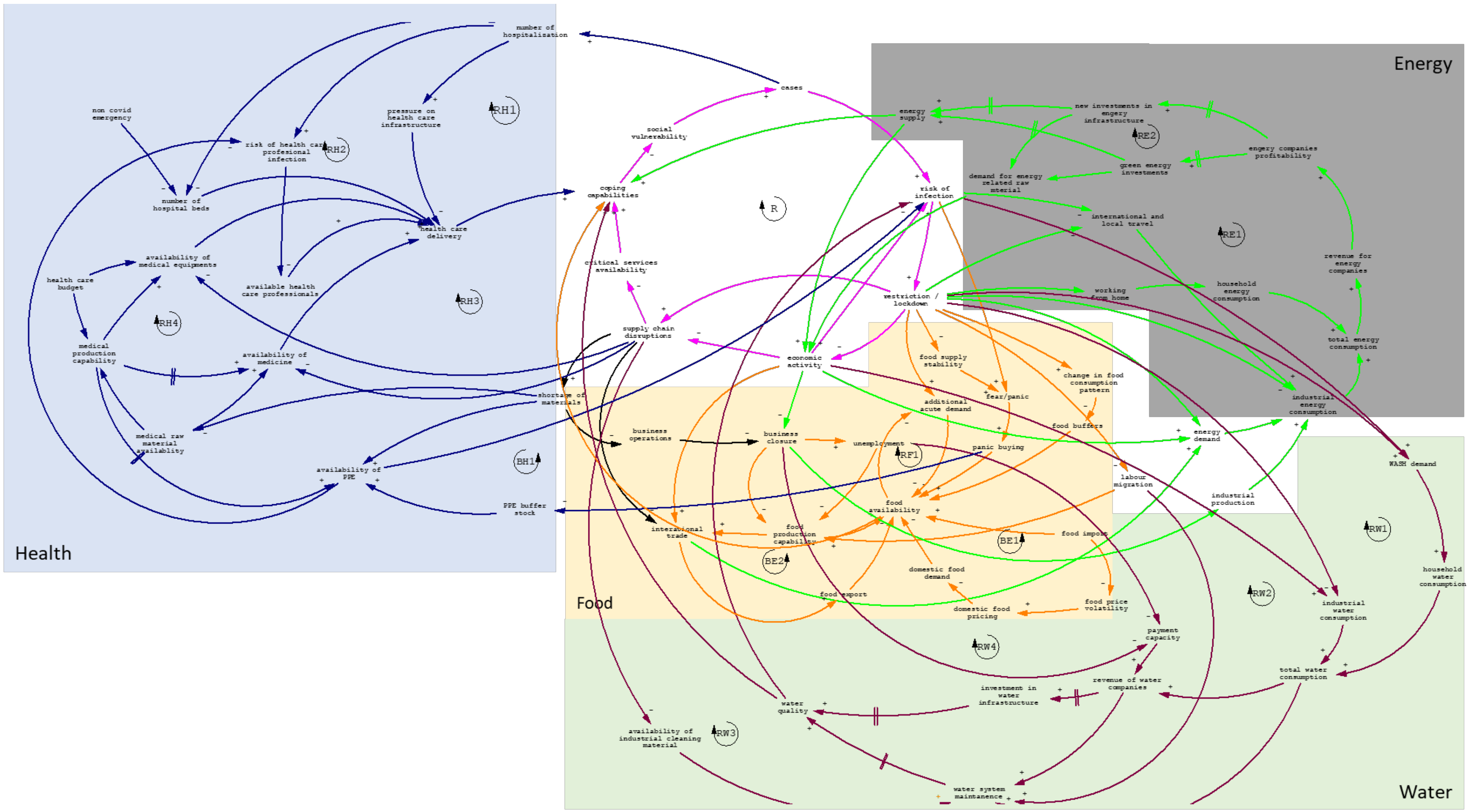

Figure 18: Combined model on supply chain disruption (source authors)

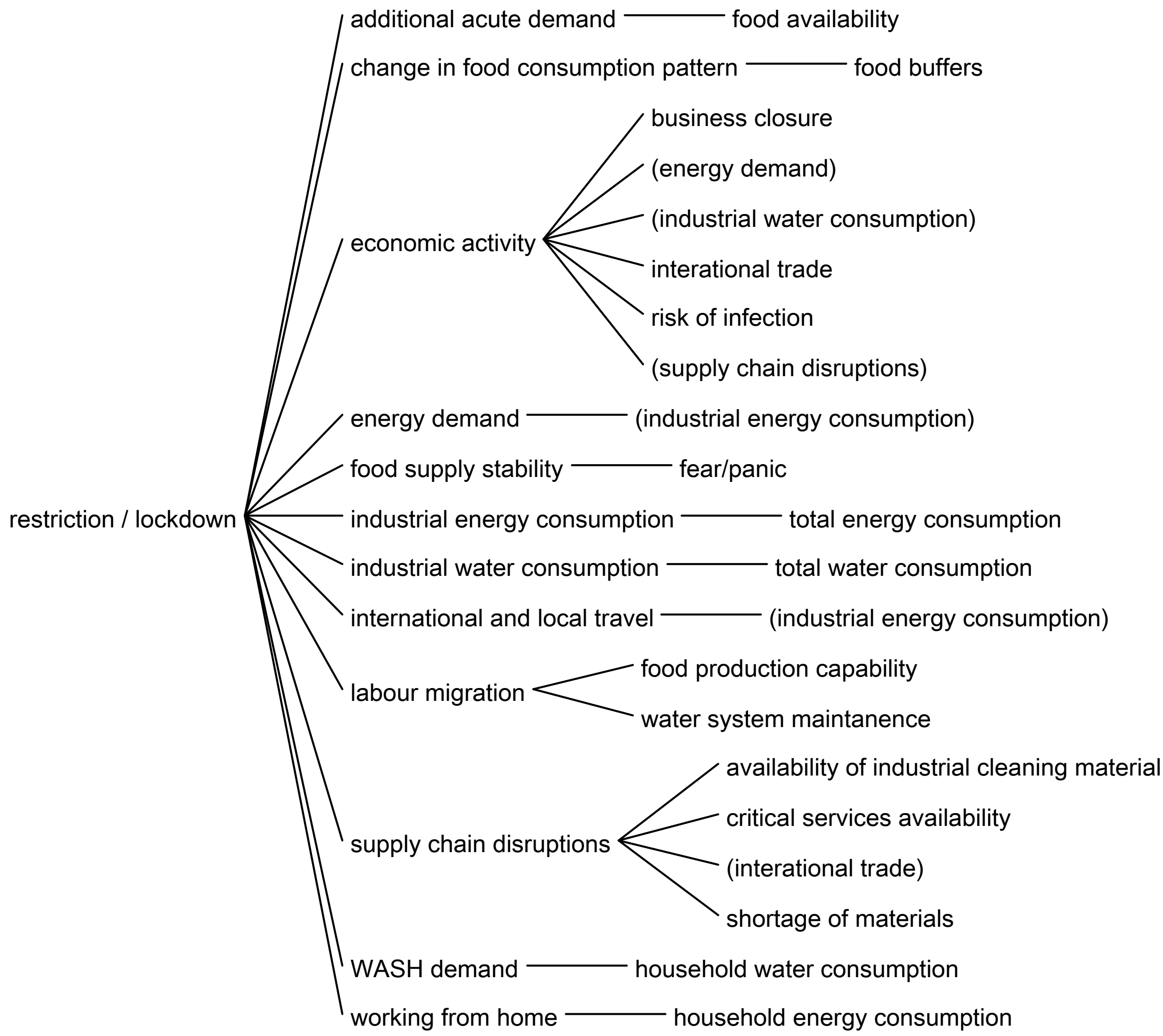

Figure 19: Effect map of restrictions and lockdown caused by COVID-19 (Sources: Authors)

Figure 20: Effect map of supply chain disruption caused by COVID-19 (Sources: Authors)

However, COVID-19 showed that we cannot take the systems that have operated flawlessly in the past for granted. Any disruption in the supply chain can have far reaching consequences on the operational capability of systems across geographies and can have severe impacts on the ability of various sectors, such as food , water, health and energy, to provide services to the population.

Finally, we consider the impact of lockdown/restriction and supply chain disruption on capabilities of the society. As previous studies have shown, the access to necessities during a crisis can have far reaching impact on the coping capability of a society towards the crisis. Here, the necessities such as access to food, water, energy and healthcare services had a direct impact on the coping capability of society towards the COVID-19 pandemic. Figure 21 captures the impact of critical services availability, energy supply, food availability, healthcare delivery systems, and water quality on the coping capabilities of the society towards COVID-19.

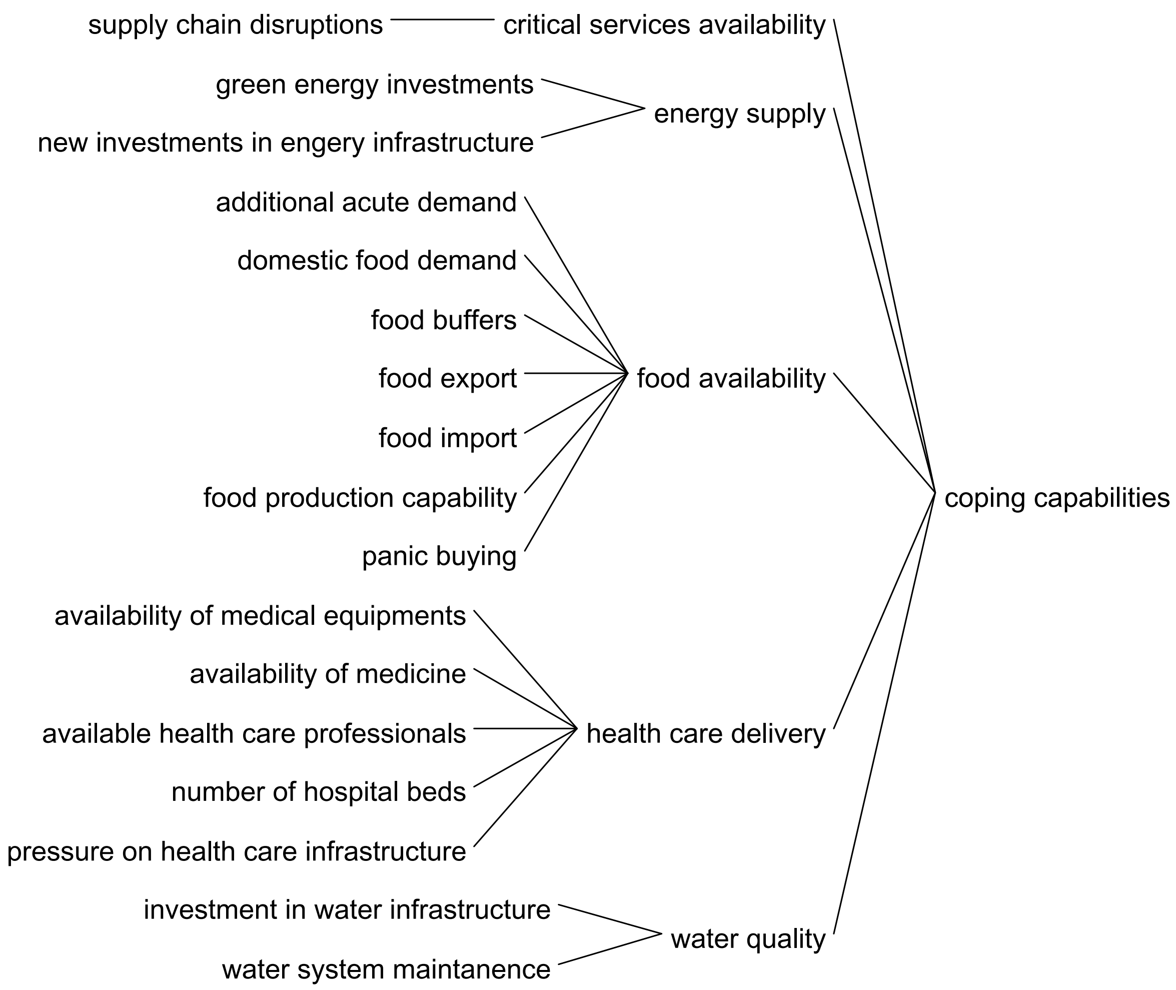

Figure 21: Effect map of coping capabilities towards COVID-19 (Sources: Authors)

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POLICY BRIEF

The impact of COVID-19 on the lives of people and the businesses across the world has been devastating. While COVID-19 itself had direct effects on the health and lives of the people, much of the damage across the globe was indirect due to lockdowns and restrictions imposed, which in turn led to supply chain disruptions causing both demand and supply shocks simultaneously. This section discusses some of the policy implications that both businesses and governments could take into consideration to protect themselves against similar supply chain disruptions in the future.

Policy recommendations for the businesses

The challenges businesses face is to make their supply chains more resilient without damaging their competitiveness. To meet this challenge, the managers should first understand the sources of their vulnerabilities and then consider a series of steps that can be taken to ensure that these vulnerabilities do not cause disruptions in future. Some of them are listed below:

- *Identify hidden risks*: modern products often incorporate critical and sophisticated components sourced from various suppliers across the globe. This makes it extremely difficult for a single firm to have both technological and manufacturing capabilities to produce complex products entirely alone. To gain competitive advantage, companies depend on suppliers who specialise in specific components. While this may be beneficial in terms of having competitive advantage, it creates vulnerabilities within the system. Hence, firms are vulnerable because of a single supplier dependence for a critical component. Therefore, businesses must do complete risk mapping of their supply chain and identify where the risks lie. One of the ways to identify the most vulnerable position within the supply chain is to map the processes and categorise the suppliers into low, medium, or higher risk categories. Further, companies must identify alternate sources and develop a geographically spread supplier base to lower the risks associated with medium and high-risk categories. Managers should also consider regional strategies in line with political scenarios and potential geopolitical tensions.
- *Revisit the trade-off between efficiency and variety:* Traditional supply chain theories often try to balance the trade-off between efficiency and variety. But during the pandemic, there was a significant change in the consumption patterns, which led to a surge in demand for many product categories that manufacturers struggled to ship from one market to the other. For example, when the demand from the restaurants completely plummeted during the lockdown, the SKUs designed for the restaurant consumption could not be repackaged and sold to the retail consumers. This led to a significant shortage for the retail consumers while having an

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oversupply of bulk quantities usually used in restaurant industry. One of the ways companies can protect themselves against similar situation in the future is to ensure that companies do not hold large numbers of SKUs. Multiple SKUs also make forecasting more difficult.

- *Leveraging the advantages of process innovation*: In recent years, there has been a renewed interest in onshoring manufacturing activities instead of offshoring. When the manufacturers entice the suppliers to move along with them to a closer location, this opens opportunities to innovate on the processes in joint fashion. This also opens capabilities for organisations to re-evaluate their routines and revisit the assumptions built in the original design process. Process innovation can come by using automation since the cost of automation is declining continuously and can work in association with human touch can ensure that people do not have to work in unsafe conditions. The pandemic has also made automation attractive because it can ensure social distancing in the factories. Manufacturers can also use continuous flow manufacturing which could increase the resilience of supply chain for small and generic drug makers. Finally, additive manufacturing, also commonly known as 3D printing, can also be used to develop complex shapes without being dependent on speciality manufacturers.
- *Managing networking capital*: one of the main reasons for the bankruptcy of many small businesses was the lack of working capital to maintain day-to-day operations. It is often seen that small businesses operate on small amounts of working capital. This is often due to long periods between cash receivables and relatively smaller periods of cash payables. As the financial function works on the accounts payable and receivable, supply chain leaders should focus on freeing up cash that is locked in other parts of the value chain. This could include reducing the finished goods inventory and unlocking value within processes through a strong governance. Further, firms should focus on improving logistics through smarter fleet management. Most importantly, firms should test their financial situation and evaluate their level of resilience in terms of how much pressure they can handle in case of a supply chain disruption.

Policy recommendations for governments

While businesses are best suited to assess the risks in supply chains and take mitigating actions, public policies and the government can play an important role in boosting the resilience of companies. This section gives some policy directions that governments can consider for an enhanced supply chain resilience.

- *Develop national level risk assessment tools to identify risk:* The government should develop risk management frameworks at both national and local governance level that include a supply chain perspective. This framework

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should include a detailed review of potential risks and identify priorities in terms of government actions. The government should focus on identifying different types of risks, especially supply chain risks pertaining to essential goods and services. The risk identification should not be limited to the supply chains but should comprise the entire value chains, including mechanisms to identify diverse sets of vulnerability indicators (as mentioned in the introduction sector). Governments should focus on creating efficient regulations through international cooperation to ensure free movement of goods and easy movement of labour. Mechanisms should be put in place to detect and anticipate crises by monitoring vulnerabilities and risks in supply chains, including an international exchange of information and early warning signals. Finally, the focus should be on developing national strategies for the governance of critical risks that that can lead to supply chain disruptions. The national leadership should focus on engaging all actors both at national and local government levels to create partnerships with the private sector and to be responsive and share responsibilities in line with national strategies.

- *Develop policies to minimise exposure to shocks*: The focus of government should be to minimise shocks by ensuring availability and accessibility of critical services to their citizens. This entails an efficient operation of infrastructures through trade, procurement, and regulatory flexibility. Ensuring the resilience of critical infrastructures during shocks underpins on the flow of goods, services, and people. Keeping in line with the recent Critical Entities Resilience (CER) directive by the European Union, the focus should shift from an asset protection to ensuring systemic resilience owing to the increased interconnectedness and interdependence between infrastructure assets and various critical sectors. This should be ensured through a long-term strategic vision for infrastructures and implementing a government approach to managing the threats. The focus should be on promoting evidence informed decision-making to ensure that infrastructure is regularly maintained and strengthened for resilience. Critical infrastructures, such as energy, transportation, finance, water, health, food supply, public safety, critical manufacturing, and defence industry, should be given a priority. Here it becomes imperative for policies to be in place to manage supply chains as a major tool to develop resilience by ensuring availability of goods and services that underpin critical services. Further, government should build international cooperation to avoid exacerbated rivalry between public agencies and private sector through collaborative approach and strengthening public procurement processes. The focus should be on cross-border information sharing on risk management and ensuring the availability of essential goods and contracts to be in place to strengthen procurement under supply chain

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disruptions. From a regulatory standpoint, thermal processes should be made more agile and flexible during crisis situations to ensure a flow of essential components from one country to the other.

- *Build trust through public-private partnerships*: The resilience in supply chain is built at a firm level, however, most firms depend on political infrastructures and macroeconomic conditions to mitigate risk and build resilience. The governments can support firm risk management strategies by reducing their exposure to risk and uncertainties, and the impact of supply chain disruptions on individuals and societies. The focus should be on developing support at the firm level and between the government and private through a transparent business environment and ensure that regulations are not obstacles but help in achieving flexibility and agility. The government should support SMEs in building relationships with suppliers, help identify bottlenecks in their value chains and strengthen financial regulations for firms by creating trust, predictability, and sustainability within the value chain. The government intervention should consider the impact on price and competition and the impact of policies in distorting market and reducing the supply of essential goods. Both public and private sectors should work closely to ensure efficient stockpiling systems and consider upstream agreements to boost the production capacity for essential commodities while keeping in mind also environmental sustainability. Finally, governments should focus on developing joint private-public systems to strengthen resilience of supply chains and to improve the capacity in managing unexpected large-scale disasters.
- *Keeping markets open for international trade*: One of the main challenges during the peak COVID times were the unpredictable changes in the rules and regulations as well as the scope of their application by every government that led to confusion and created difficulties for companies to adapt to the changes. For the companies to be able to manage their operations and build resilience into the supply chain, they need policies and regulations to be stable, transparent, and predictable in nature. The governments should focus on creating both predictability and transparency with rules and regulations and on ensuring that information is made available in a timely and transparent manner. Towards this, governments should reinforce confidence and commitment into rule-based trading to address gaps that might have led to trade tensions. Furthermore, governments should explore additional commitments towards investment agreements to ensure that essential goods and services are available in the wake of a crisis. This can be achieved through general or specific exception clauses in international trade and investment agreements between partners to encourage cooperation during crises. Finally, governments should focus on creating coordinated efforts

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between various national and international governments and firms to develop common approaches for a simplified procurement and supply of essential commodities. This can also be achieved through international regulatory cooperation and mutual recognition agreements.

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CONCLUSIONS

We live in an extensively interconnected world with the ability to source, manufacture, and consume the products from different parts of the world. This is possible because of the interconnected network of supply chains that operate continuously throughout the year. In the past, the impact of supply chain disruptions on businesses have been studied in detail. However, their impact on the lives of common people and there by societal vulnerability has not received much attention. The recent COVID-19 led supply chain disruptions across the world have brought this to the attention of both business owners and policymakers. The importance of supply chains in the modern world cannot be overstated.

This study was carried out as a part of work package 4, task 4.3 under the project CORE to study the impact of supply chain disruptions due to COVID-19 on creating social vulnerabilities. This was explored through the impact of supply chain disruptions on critical sectors, such as food, water, energy, and health. The study explored the interrelationships between actions taken by the governments to curb the spread of COVID-19 on supply chain disruptions and how these disruptions led to creating unforeseen challenges on the aforementioned sectors. Since these sectors are critical to the functioning of the society, it is imperative to ensure that these sectors function without disruptions. The study also explores how the supply chain disruptions had affected the operational capabilities of the four critical sectors and how it has influence on both short term and long-term operational capabilities. The study also suggests policy recommendations for both businesses and governments to protect themselves against system wide supply chain disruptions in the future.

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ANNEXES

Annex 1: Pre GMB data collection questionnaire

sCience & human factOr for Resilient sociEty **(CORE) project**

CONSENT FORM FOR PARTICIPATION IN RESEARCH (Group Model Building)

Project title: sCience & human factOr for Resilient sociEty (CORE)
Responsible researcher: Lijo John, Wojciech Piotrowicz
Research Center: Svenska Handelshögskolan (Hanken), HUMLOG Institute
Address: Hanken School of Economics, PB 479, 00101 HELSINKI, FINLAND
Contact: lijo.john@hanken.fi / wojciech.piotrowicz@hanken.fi

I confirm that I have briefed for the study, and I have had the opportunity to ask questions about the project in general and about this study involving participation in the group model building.

I understand that:

my participation in this study is voluntary, and that a decision not to participate will not have any consequences for me.

I may withdraw my data and myself and discontinue participation at any time without any consequences. I understand that I can only withdraw my data from the research before any findings have been published and/or are included in a deliverable for the study.

the information I provide will be placed in a temporary database for analysis and will be processed confidentially and anonymously by the researchers. No other personal data processing will be done within the research project.

I will not be identified in the written report of the study, but my direct quotes may be used in the written reports or publications.

should the research team during their research find any unexpected information (incidental findings such as e.g., indications of criminal activity), I will be informed of this, and that the researcher team may take actions for disclosure of such information outside the research group.

I agree that the group model building, *with my consent*, can be recorded, photographed and notes will be taken during the group model building		Yes
		No

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and that the recording will be transcribed in order to be analyzed for, and only for, the purpose of the study.

I confirm that I have understood the information I have received, and I agree to participate in the study.

____

____

Participants name | Participant's signature.

____

____

Researcher's name | Researcher's signature

Information for the research group

Participants id. nr: ....

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Elements of a group model building (GMB) script

Field	Description
Work package and task details	WP4|T4.3 Whilst cascading disasters have been studied in the past, cascades across sectors (e.g., in the health-energy-food-water nexus) have been less in focus. More recently, the COVID-19 pandemic has highlighted societal vulnerabilities to supply chain disruptions, in health but also in the retail sector. D 4.3 Combined systems dynamics model and policy brief of cascades across events, sectors, and supply chain disruptions.
Description of activity	Group model building (GMB) workshop on the impact on societal vulnerability due to supply chain disruptions of food-energy-water-health (FEWH) in the context of COVID-19 involving multiple stakeholders in these fields
Participants	CORE consortium partners
Purpose	(1) to improve better understanding of the problem, (2) to align perception (problem framing), (3) to elucidate variables, and (4) to develop qualitative System Dynamic Model (SDM) in the form of CLDs

Please fill in the responses to the following questions. These are open ended questions, and hence feel free respond to them based on your best knowledge.

Demographic questions

Name	
Affiliation	
Designation	
Highest level of education	
Number of years of experience	
Core area of expertise	

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1. Please categorize the following stakeholders into either of the four quadrants. If you feel any significant stakeholder is missing, feel free to include them as well. You can copy the numbers for each of the stakeholder in the

1. Dept of water and sanitation 2. Dept of health 3. Dept of commerce 4. Dept of external affairs 5. Dept of interior/internal affairs 6. Dept of communication 7. Office of head of the state 8. Dept of purchase	9. Dept of energy 10. Dept of food and agriculture 11. Media and communication companies 12. Logistics companies 13. Warehousing firms 14. Hospitals 15. Pharma companies 16. Pharma producers 17. Manufacturing firms 18. Dept of IT 19. Dept of transportation	20. Local communities, 21. Vulnerable communities 22. Shelter homes 23. Charitable organizations 24. International and local NGOs 25. Armed and paramilitary forces 26. Fertilizer companies 27. Chemical industries 28. Dept of public works and maintenance	29. Academic and scientific research organizations 30. Local government agencies 31. Famers 32. Supermarket chains 33. Farmer producer organizations/companies 34. Shipping companies 35. Ports and post management firms 36. IT companies 37. Others

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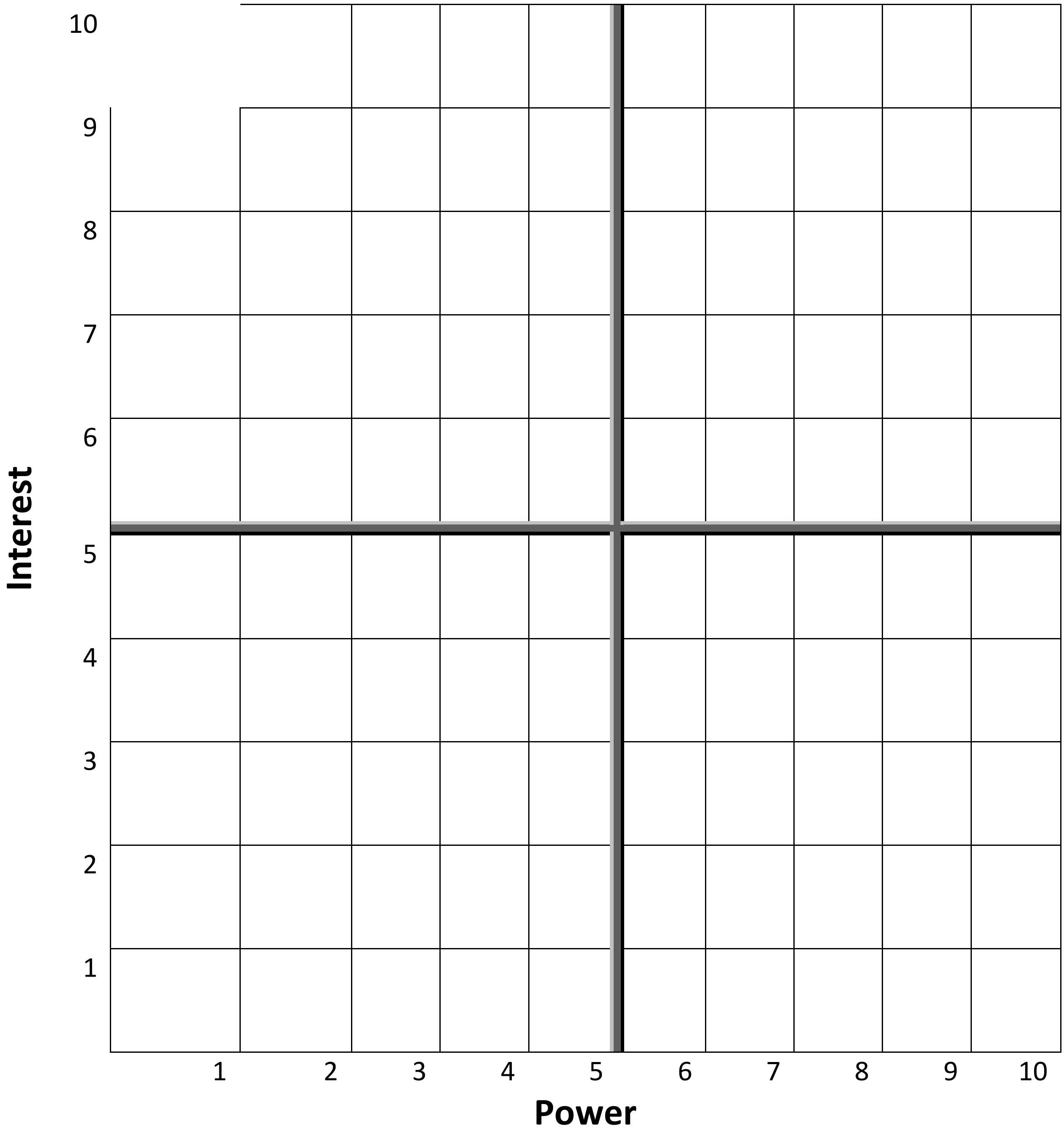

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2. What were the **direct** impact of COVID-19 on the following during the given time frames

	Beginning of Lockdown (complete lockdown with full restrictions)	Beginning of unlocking (with certain restrictions)	Beginning of back to normalcy (with reduced levels of restriction and availability of vaccines)
Food			
Water			
Energy			
Health			

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3. What were the **indirect (unexpected or surprising)** impact of COVID-19 on the following during the given time frames?

	Beginning of Lockdown (complete lockdown with full restrictions)	Beginning of unlocking (with certain restrictions)	Beginning of back to normalcy (with reduced levels of restriction and availability of vaccines)
Food			
Water			
Energy			
Health			

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4. What was the impact of COVID-19 on the **critical infrastructure** related to food, energy, water, and health?

	Beginning of Lockdown (complete lockdown with full restrictions)	Beginning of unlocking (with certain restrictions)	Beginning of back to normalcy (with reduced levels of restriction and availability of vaccines)
Food			
Water			
Energy			
Health			

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5. What was the impact of COVID-19 on the **supply chains** related to food, energy, water, and health?

	Beginning of Lockdown (complete lockdown with full restrictions)	Beginning of unlocking (with certain restrictions)	Beginning of back to normalcy (with reduced levels of restriction and availability of vaccines)
Food			
Water			
Energy			
Health			

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Annex 2: GMB Script

Elements of a group model building (GMB) script

Adapted from Hovmand et al., (2012)

Field	Description
Description	Group model building (GMB) workshop on the impact of supply chain disruptions on food-energy-water-health (FEWH) in the context of COVID-19 involving multiple stakeholders in these fields
Context	This script can be used in discussing important policies that need to be determined by involving several stakeholders
Participants	CORE consortium partners
Purpose	(1) to improve better understanding of the problem, (2) to align perception (problem framing), (3) to elucidate variables, and (4) to develop qualitative System Dynamic Model (SDM) in the form of CLDs
Primary nature of group task	• Presentation. Aligning the same perspective about the topic and methods used in the workshop with all participants • Divergent. Participants come from different institutions within the consortium with varied expertise in various aspects of FEWH and supply chains specifically from planning or research and development division.
Time	Pre-GMB brief (about one month before the event) GMB workshop (preparation ±15 min, main activities ±120 min, ±15 min evaluation)
Materials	Will be conducted online on Microsoft teams using other software tools such padlet.
Input	State-of-the system, basic concept of FEWH and supply chains, causal loops and systems thinking
Outputs	Sub-causal loop diagrams, integrated causal loop diagram on impact of supply chain disruptions on FEWH nexus
Roles	*Modeller*: listening to what being discussed and modelled during the session *Facilitator*: organizing the workshop sessions *Gate keeper*: initiating the project, identifying the participants, supporting the team *Recorder*: documenting all the GMB workshop session either videos or photos
Participants in the workshop	Modeller, facilitator, gate keeper (optional/not all the session), recorder, participants
Steps	**Pre GMB brief (to be completed on 29th and 30th September 2022 at CORE Annual Meeting)** The gate keeper will deliver the opening speech to explain the overview of GMB workshop in general Facilitator will explain the workshop goals, schedules, methods, and everything that need to know by the participants Facilitator will distribute the open questionnaires to the participants and will collect it before the end of the annual meeting.

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Field	Description
	Facilitator will share a doodle poll among the participants to find a common time for GMB session 1 **Introduction session (on the day of first model building)** • Facilitator/modeller will conduct the introduction session to explain about the research overview, system dynamics model (especially how to create CLD), and group model building approach. • Discussion, question-answer session moderated by facilitator/modeller. **Modelling session I** • Facilitator/modeller will present the basic conceptual model based on the literature and the results of the pre-GMB brief with the participants. • Any clarification/questions from the participants will be taken at this point. • The participants will be then sent to their respective breakout rooms with links to padlet and digital while boards. The • Facilitator/modeller will now ask the participants to identify variables, inter-relationships between the variables, give comment/feedback on initial model based on the preliminary conceptual model. • Participants will ask to include additional variables that they deem necessary for the impact of supply chain disruption on FEWH nexus and elicits the reason/argument of each variable and put it in the digital sticky notes. • Facilitator/modeller asked the participants to create individual CLDs capturing the impact of supply chain disruption on food, energy, water, and health. The facilitator will switch between the breakout rooms to assist participants in doing their works. • Facilitator/modeller will invite participant (s) in each breakout room to put their variables/CLD to be shared with others. Other participants we are asked to comment/ask for clarifications on the CLD presented. This step will be repeated for each of the four sectors, i.e., food, energy, water, and health • The comments/suggestion will be noted, and corresponding changes will be made in CLS. • A doodle poll will be sent out to the participants for the scheduling the next session. Also, the feedback will be asked to improve the quality of GMB **Modelling session II (after about one month)** • Facilitator/modeller will present the final digitized version of the CLD using SD software (Vensim PLE). Questions and clarification will be provided on the final individual models • Facilitator/modeller will then send the participants to their breakout rooms and ask them to combine the individual models to a single CLD. They can combine individual variable to come up with overarching variable to improve the parsimony of the model. Facilitator/modeller will provide supervision for the process. • Again, the participants will be brough to the main "room" on Microsoft teams and asked to present their combine CLD. The other groups will be asked to provide feedback and ask for clarifications. • Finally, a combined CLD will be developed based on the consensus drawn by the entire group of participants.

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Field	Description
	• The participants will be asked to share their experience and feedback will be noted. • Facilitator/modeller will digitize the final combined CLD and share with all participants and will seek for any final comments.
Evaluation criteria	• The perception and knowledge of participants to the topic and methods need to be identified by doing short pre GMB questionnaire, to make sure whether we need to take longer time for introduction session or not • All the participants have agreed about the effectiveness of group model building and qualitative dynamics model in analysing the policies and finding the best solution. • Open questionnaire helps participants in understanding the topic and helps facilitator in organizing the sessions
Authors	• Lijo John (HUMLOG, Hanken School of Economics) • Wojciech Piotrowicz (HUMLOG, Hanken School of Economics) • Any other?
Reference	• Hovmand, P. S., Andersen, D. F., Rouwette, E., Richardson, G. P., Rux, K., & Calhoun, A. (2012). Group model-building 'scripts' as a collaborative planning tool. Systems Research and Behavioral Science, 29(2), 179-193.

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Annex 3: Consent form for GMB

sCience & human factOr for Resilient sociEty **(CORE) project**

CONSENT FORM FOR PARTICIPATION IN RESEARCH (Group Model Building)

Project title: *sCience & human factOr for Resilient sociEty (CORE)*
Responsible researcher*: Lijo John, Wojciech Piotrowicz*
Research Center: Svenska Handelshögskolan (Hanken), HUMLOG Institute
Address: *Hanken School of Economics, PB 479, 00101 HELSINKI, FINLAND*
Contact: *lijo.john@hanken.fi* / *wojciech.piotrowicz@hanken.fi*

I confirm that I have been briefed for the study, and I have had the opportunity to ask questions about the project in general and about this study involving participation in the group model building.

I understand that:

My participation in this study is voluntary, and that a decision not to participate will not have any consequences for me.

I may withdraw my data and myself and discontinue participation at any time without any consequences. I understand that I can only withdraw my data from the research before any findings have been published and/or are included in a deliverable for the study.

The information I provide will be placed in a temporary database for analysis and will be processed confidentially and anonymously by the researchers. No other personal data processing will be done within the research project.

I will not be identified in the written report of the study, but my direct quotes may be used in the written reports or publications.

Should the research team during their research find any unexpected information (incidental findings such as e.g., indications of criminal activity), I will be informed of this, and that the researcher team may take actions for disclosure of such information outside the research group.

I agree that the group model building, *with my consent*, can be recorded, photographed and notes will be taken during the group model building and that the recording will be transcribed in order to be analyzed for, and only for, the purpose of the study.

	Yes
	No

I confirm that I have understood the information I have received, and I agree to participate in the study.

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Participants name　　　　　　　　　　Participant’s signature

Researcher's name　　　　　　　　　　Researcher's signature

Information for the research group

Participants id. nr: ....

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Elements of a group model building (GMB) script

Field	Description
Work package and task details	WP4|T4.3 Whilst cascading disasters have been studied in the past, cascades across sectors (e.g., in the health-energy-food-water nexus) have been less in focus. More recently, the COVID-19 pandemic has highlighted societal vulnerabilities to supply chain disruptions, in health but also in the retail sector. D 4.3 Combined systems dynamics model and policy brief of cascades across events, sectors, and supply chain disruptions.
Description of activity	Group model building (GMB) workshop on the impact on societal vulnerability due to supply chain disruptions of food-energy-water-health (FEWH) in the context of COVID-19 involving multiple stakeholders in these fields
Participants	CORE consortium partners
Purpose	(1) to improve better understanding of the problem, (2) to align perception (problem framing), (3) to elucidate variables, and (4) to develop qualitative System Dynamic Model (SDM) in the form of CLDs

Please fill in the responses to the following questions. These are open ended questions, and hence feel free respond to them based on your best knowledge.

Demographic questions

Name	
Designation	
Highest level of education	
Number of years of experience	
Core area of expertise	

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CORE

sCience and human factOr for Resilient sociEty

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ETH zürich

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University of HUDDERSFIELD Inspiring global professionals

HANKEN

SAHER EUROPE

PSCEurope Public Safety Communication Europe

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MTOSafety

RESALLIENCE by sixense

CSEM EMSC

VIGILI DEL FUOCO CORPO NAZIONALE

Croce Rossa Italiana Comitato di Vicenza

ucsa Ufficio Comune per la Sostenibilità Ambientale

Hochschule für den öffentlichen Dienst in Bayern

ÖSTERREICHISCHES ROTES KREUZ

parco archeologico campi flegrei

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