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Improving the resilience of supply chains against disruptions like the Covid-19 pandemic

Supervisor
Ch. Prof. Marco Tolotti

Graduand
Francesca Putti
Matriculation Number: 879105

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Introduction

Supply chains have seen an exponential increase of complexity during the decades, mainly due to the growing degree of globalization and the subsequently ever-growing number of actors involved. Despite the benefits that a larger network can bring to businesses, it has also increased their exposure to risks, resulting in significant losses, both of economical and strategical nature, and sometimes even shutdowns.

The recent worldwide pandemic of Covid-19 has proven the magnitude of this interconnectedness by leaving no aspect of our life entirely unaffected. What in the eyes of optimists seemed to be just a small inconvenience concerning a limited area of China, quickly became a historically momentous event due to the extremely linked world it arose in, which provided a fertile ground for a chain of events resulting in the involvement of countless economies and industries.

This work aims to investigate the impacts that possible disruptions can have on supply chains and how companies can improve their ability to overcome them. Two main subject matters contribute to this research question: an analysis of the case of the Covid-19 pandemic and its consequences on businesses, particularly their supply chains, and an account of how the resilience of companies can be strengthened.

Specifically, Chapter 1 explains how supply chains have evolved over the years, provides some definitions, discusses its main goals and attributes, and then focuses on some relevant and noteworthy features that characterize them.

Chapter 2 offers an account of how the pandemic caused by the Coronavirus first broke out and analyzes, providing relevant examples, the specific impacts it has caused to supply chains, breaking them down by areas of concern.

Chapter 3, on the other hand, focuses on increasing resilience by first introducing why assessing risks and increasing resilience is a fundamental activity for companies. It then formalizes how the risk management process develops and how managers could apply it to reap its benefits. The chapter, then, discusses some of the strategies that have been proposed in the literature or implemented by companies to increase preparedness for potential risks or mitigate their negative effects.

Finally, Chapter 4 offers a methodological approach that can be used by decision-makers to reach a more informed evaluation on the best strategies to implement in order to reduce the risk exposure of the company. Particularly, basing the methodology on the theory of decision trees, it investigates the effect of some of the strategies discussed in Chapter 3, considering both their individual and joint implementation. Additionally, it provides some insights and reflections on how the technique can be further customized to fit the features and needs of the company under consideration.

1 The supply chain

The current chapter will present a broad overview of the basic concepts surrounding supply chains with definitions and descriptions to provide a good understanding of the subject matter, necessary for the full comprehension of the next chapters and the issues they discuss.

1.1 History

Since ancient times, the main catalyst of the progress and growth of civilizations has been the exchange of information, goods, and services with neighboring cities and communities. Ancient Rome is the perfect example of great organizational efforts: thanks to its advanced road system, postal service, and fleet, the roman empire was able to become one of the first global forces. Trade, however, is only as effective as the underlying network of operations is. The ability to store and move goods efficiently and adequately is vital to the success of a broad network of exchanges. (Zijm, et al., 2019)

According to the website Logmore (2019), “the first example of production with a truly global supply network was most likely rum. The supply chain in this case started with slaves who were moved from Africa to the Caribbean to grow the sugarcane, which came from India, and it ended in distilleries in the US.”

The history of supply chain management starts with logistics. In 1911, Fredrick Taylor wrote “*The Principles of Scientific Management*”, focusing his research on the improvement of loading processes inside factories, which at the time were manually carried out. After that, studies on logistics problems intensified in the

1940s during World War II to improve military operations. Particularly, during this time and the following decade, the focus was on increasing efficiency through the use of mechanization of the most labor-intensive processes, like material handling, along with the improvement of space utilization in warehouses. The trend of standardization followed through the 1950s, too, with the rise of intermodal containers and intermodal transportation, critical for the process of globalization that supply chains were undergoing (Veridian, 2018). "Containerization not only increased the quantity of available space for goods, but also increased the speed of the freight movement while decreasing the cost. The speed increase came from more effective warehousing processes as well as transport terminal efficiency." (Logmore, 2019).

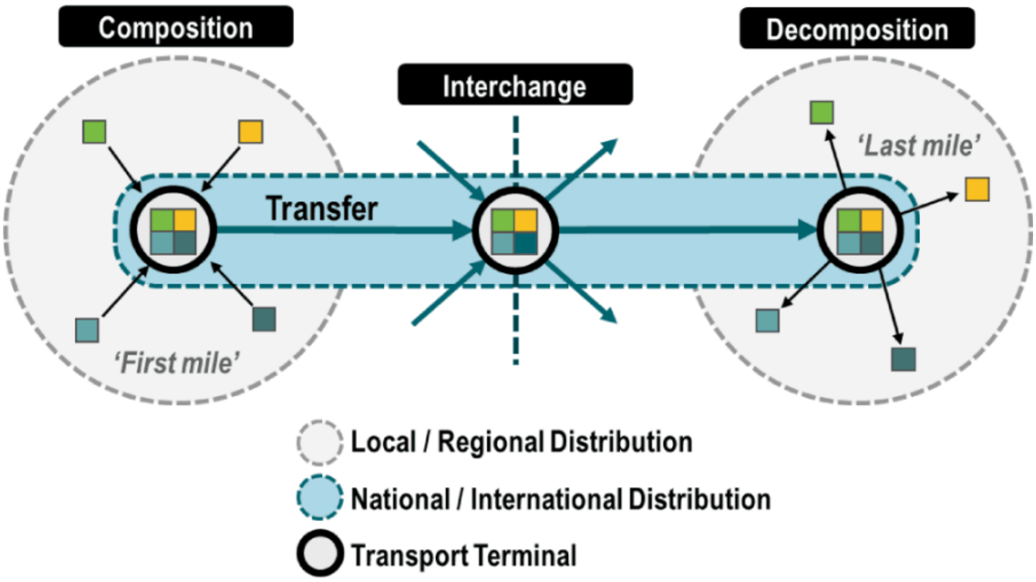


Figure 1 - Intermodal transport chain (The Geography of Transport Systems, n.d.)

With the formation of a dedicated national council in 1963, this decade saw a shift in modes of transportation towards trucks, which then required new scrutiny on warehousing, material handling, and freight transportation, all summarized together with the term “physical distribution”. With the advent of computers, during the two following decades, innovation in logistics increased exponentially, introducing concepts like truck routing, spreadsheet- and map-based planning, algorithms for prediction of issues, and vastly improving the optimization of processes and inventory. Additionally, this period marks the start of increased awareness towards the importance and impact on the bottom line of logistics and supply chain management, leading managers to recognize the opportunities that focusing on optimization could bring for the profits of the company, thus leading to higher investments in new technologies and trained professionals that could help achieve higher efficiency (Veridian, 2018). The 1970s also marked the commercial spread of barcoding, a technology patented two decades earlier. “Its adoption was spurred forward by a standard requiring an identifying number from the US National Association of Food Chains and subsequent research showing large increases in profit from point scale scanning. Once the barcode was adapted to become an internationally used standard, it could be used from for monitoring of the supply chain both globally and internationally.” (Logmore, 2019).

Following the success of Material Requirements Planning (MRP) systems during the 1970s and 1980s, the 1990s saw the emergence of Enterprise Resource Planning (ERP) systems, aimed at integrating the many different databases companies adopted. This structural update allowed greater accuracy and availability of data, leading to easier, more advanced, and more effective planning. Towards the new millennium, the term “supply chain” started gaining mainstream recognition, even though one of the first mentions can be seen in an article of the financial times dating back to the 1980s (Kolenko, 2014). This spread can be attributed to the rise of globalized manufacturing, mainly lead by the growth in the Chinese market. This brought increased complexity of operations due to larger networks of actors involved, connecting multiple countries, legislations, industries, and capabilities. (Veridian, 2018)

Most recently, the diffusion of big data has allowed analytics to evolve and to encourage the adoption of monitoring practices, especially real-time, inside supply chains. This additional step in the management of supply chains allows companies to meet the efficiency needs of stakeholders with the use of technology. Additionally, this newfound supervision allows processes to be more thoroughly scrutinized by authorities and the public, increasing the pressure on firms to maintain high standards of sustainability and social responsibility. (Logmore, 2019)

1.2 Definition and scope of supply chains

A supply chain is the set of activities and processes that allows raw materials to be transformed into finished products. The concept of supply chain "applies to the internal relationships between processes as well as the external relationships between operations" (Slack, et al., 2016, p. 399). It includes every step from sourcing supplies, to building the various components that form the product, to the assembly of said components, and finally to the delivery of finished goods to the final point of sale. (Zijm, et al., 2019)

Supply chain management, therefore, is the handling and coordination of all activities, relationships, and flows of a supply chain, so that they work seamlessly towards the achievement of the economic goals of the company. Lummus and Vokurka (1999, p. 2) also state that “a key point [in supply chain management] is that the entire process must be viewed as one system. Any inefficiencies incurred across the supply chain (suppliers, manufacturing plants, warehouses, customers, etc.) must be assessed to determine the true capabilities of the process.”.

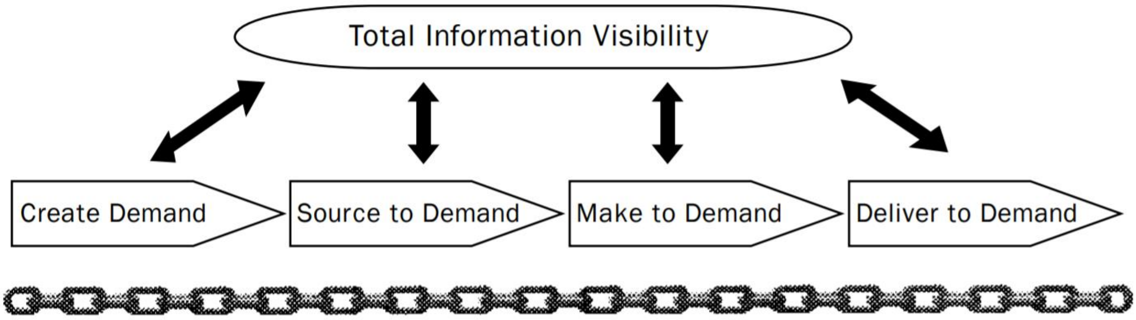


Figure 2 - Total integration required within the supply chain (Lummus & Vokurka, 1999)

One very predominant aspect is the involvement of multiple companies and industries working together in a synchronized way to manage all activities necessary for the chain to function properly, this is called an end-to-end supply chain. So, in order to manage the supply chain, it is important to coordinate suppliers, customers, and any external providers of services across different channels. Managers from one company usually take an interest in the performance of other companies, working together to ensure the entire chain works successfully for the benefit of all parties (Lummus & Vokurka, 1999).

Because of the many relationships, interactions, and points between the processes inside supply chains and between actors across different supply chains, one glitch on one side of the chain quickly transforms into increasingly large inaccuracies by the time it reaches the other end. This is known as the "bullwhip" effect. The distortions can travel both upstream and downstream the chain. The main causes of this are: (Lee, et al., 1997)

- Demand signal processing: there is information asymmetry between retailers and upstream suppliers, causing the suppliers to assume demand based on the retailer's behavior.
- Rationing game: during shortages, suppliers will ration the number of units available to order from each retailer, but this will cause retailers to order in excess in fear of running out of supplies.
- Order batching: companies prefer periodically placing larger orders fewer times.
- Price variations: agents will replenish stock when prices are low and delay placing orders for as long as possible when prices are high.

One technicality that is often mistaken is the distinction between supply chains and supply networks. Slack et al. (2016) define supply networks as "all the operations that are linked together to provide products and services to end customers. In large supply networks there can be many hundreds of supply chains of linked operations passing through a single operation".

The phase of supply chain management that concerns warehousing all goods, be that raw materials, components, or finished products, and transporting them from one node in the chain to another is called logistics. It is of fundamental importance to the integrity of the supply chain, being the factor that determines if final customers are able to receive products in time or not. Logistics management includes inventory management, transportation, and fleet management. (Zijm, et al., 2019)

According to Barbara Gaudenzi & Antonio Borghesi (2006), in order to be working effectively and bring added value, supply chains must be focused on two main objectives:

- Value offered to final customers and assurance of their satisfaction. Companies should concentrate their effort on clients when designing supply chains, in order to maximize the value offered and its perception. Therefore, it is crucial to understand which elements contribute to the creation and the increase of perceived value.
- Reactivity. Supply chains must be designed in a way that allows both a quick flow of processes that generates final products in a short amount of time and fast adaptation to possible changes and disruptions.

Additionally, Slack et al. (2016) define 5 different performance objectives for supply networks. Three of these – quality, speed, and flexibility – are analogous to the objectives already mentioned. The novel two are:

- Dependability: being able to reduce uncertainty inside the chain to avoid inefficiencies and complications.
- Cost: aiming at reducing transaction costs such as inventories, transportation between activities, the cost of locating suppliers, and making agreements.

1.3 Closed-loop supply chains

Given the importance of sustainability, and its recent increased awareness, it is worth dwelling on one particular aspect of supply chains. Additionally, the importance of focusing on this matter will be highlighted in section 3.2.7, where increasing circularity is proposed as a strategy for increasing the resilience of supply chains.

The scope of the supply chain has been recently broadened to also encompass the handling of returns: products that are shipped back to a previous point in the chain because of defects or because they remain unsold. The handling of these flows gives rise to the so-called closed-loop supply chains, where often the objective is to upcycle materials or parts of the products, leading to cost savings and more environmentally friendly practices. (Zijm, et al., 2019)

Closed-loop supply chains are composed of two stages: the forward chain, where the initial production and distribution is carried out, and the reverse chain, where the products are retrieved and upcycled. This flow is also referred to as reverse logistics.

Van der Laan (2019) outlines five different aspects to consider when analyzing a closed-loop supply chain:

- How the product is made: the materials, and how these materials are combined, determine how easy or difficult it is to separate and recycle them. For example, products entirely made of one type of plastic can easily be melted down and made into something new.

- The cause for return, which is linked to the condition in which the item is. It could be sent back because of defects, because it was never sold or because it reached the end of its intended period of use. Better conditions doubtlessly imply more options to recover value out of the product. For example, a smartphone returned because of a cracked screen can be put back into the chain with a simple replacement of the frontal glass. Differently, a car returned under a scrapping policy can probably only be scavenged for raw materials to recycle.
- The driver for the recovery, which impacts how the network is structured and what its aim is. The main drivers are legislation, corporate social responsibility, and economics.
- The way in which the main processes of the chain (acquisition, recovery, and remarketing) are organized, and which is the focus of the organizational effort.
- The actors involved in this last phase of the supply chain. In particular, the distinction is made depending on who is the agent performing the recovery: if it is the original manufacturer, then the chain is a *closed* closed-loop supply chain, while if a third party not originally involved is taking on this responsibility it is an *open* closed-loop supply chain.

These factors determine the type of configuration the closing flow of the supply chain will assume. However, it is specified that warranty returns and similar are not covered in these scenarios.

- When legislation is the main driver, the activities are usually carried out by third parties monitored by governmental institutions. One example is the scrapping of vehicles.

- When recovering materials to recycle is profitable, companies will often undertake only specialized recycling due to the high investments required by the facilities needed.
- When it is possible to create a value-added network that is profitable, this will be done by either a third party or by the brand owner itself. In the latter case, the manufacturer has the advantage of deep knowledge of the product design and of being integrated into the distribution infrastructure to facilitate collection. The best example of this is ink cartridge refurbishing.
- When the goods can be used again with little to no repairs or intervention, a collection and distribution network will form.
- When manufacturers are obligated to take back products, because of customer protection laws and warranty, these returns are highly valuable since the products are often almost brand new and can be resold after a light refurbishment.

To evaluate if a reverse logistics network is feasible and profitable, and decide which strategy to follow to best take advantage of it, companies must consider the different values that can be obtained with it. These are:

- Value derived from cheaper sourcing of materials and avoiding fees for waste disposal and environmental impact.
- Value from positive image gained by communicating recovery initiatives.
- Value from higher customer satisfaction due to increased services and products offered.

- Value from the information collected while inspecting the products returned, which can help improve both the products and the recovery process.

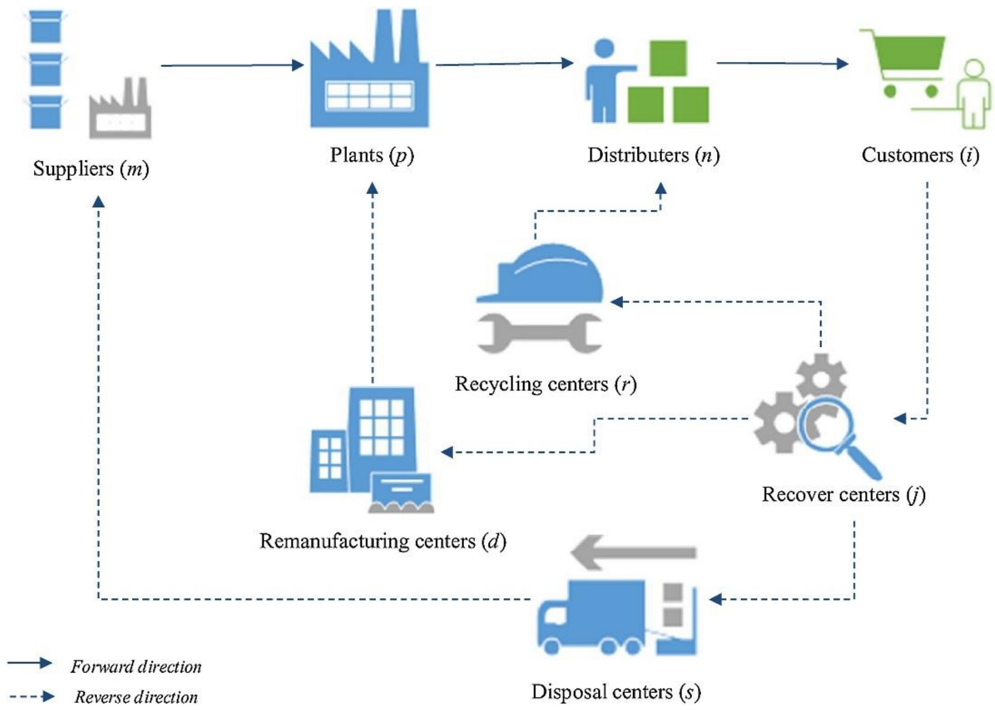


Figure 3 - Simplified graphical representation of a closed-loop supply chain (Fathollahi-Fard, et al., 2018)

1.4 Strategic Inventory Positioning

Another fundamental matter when discussing the structure and activities of supply chains is strategic inventory positioning. Since section 3.2.4 will examine the increase of stock and warehouse inventory as a strategy to prevent or mitigate possible disruptions to the continuity of business, it would be worth formalizing how strategic inventory positioning operates and how it can be beneficial for companies in aiding the pursuit of resilience.

Once orders are placed, items such as raw materials, components, and finished products have to be stored while waiting for the next step. This accumulation is called inventory. Material inventories can represent an important source of frozen capital, therefore lowering inventory can free up financial assets now available for other activities. However, minimizing it excessively can lead to issues of order fulfillment and halting of flows. This issue will be discussed further in the next pages.

There are five main reasons to keep an inventory:

- To minimize the impact of unexpected interruptions in supply or demand (buffer inventory). This point will be discussed further later when examining the impacts of the Covid-19 pandemic.
- To allow companies to produce different items using the same machinery (cycle inventory).
- To manage the intrinsic asynchrony of supply chains (de-coupling inventory).
- To handle planned fluctuations in demand or supply (anticipation inventory).
- To cope with delays in the transportation of materials and components (pipeline inventory).

Since processes rarely work in a synchronized way, inventories are necessary between many points along a supply chain due to its uneven flow. “If there is a difference between the timing or the rate of supply and demand at any point in a process or network, then accumulations will occur. [...] If an operation or process can match supply and demand rates, it will also succeed in reducing its inventory levels." (Slack, et al., 2016)

This perspective explains the need for inventories, however even if they are not strictly required because the supply chain is especially efficient and synchronized, placing an inventory can still be a strategically advantageous choice because it achieves what is called decoupling (as listed in the third bullet point above), defined as "Creating independence between supply and use of material. Commonly denotes providing inventory between operations so that fluctuations in the production rate of the supplying operation do not constrain production or use rates of the next operation" (Ptak & Smith, 2016). The points in the chain chosen for the decoupling inventories manage to decrease the negative impacts of disruptions by breaking the bullwhip effect, previously explained, therefore mitigating variability.

"The selection of these points is a strategic decision that impacts the performance of the supply-demand network in many regards: service, working capital, expedite-related expenses, cash flow, and ultimately return on investment" (Ptak & Smith, 2016). Therefore, where to position inventories is an important strategic decision. The authors consider six factors when determining the best possible position for purchased, manufactured, and finished goods:

- Customer time tolerance: how much customers are willing to wait to receive the service or good they requested before looking for an alternative source.
- Market potential lead time: a lead time that would allow the company to achieve more sales or charge a higher price.

- Sales order visibility horizon: how much awareness there is regarding future orders, and therefore demand.
- External variability: the potential swings in demand and supply. It is usually classified as high, medium, or low.
- Inventory leverage and flexibility: key points that contribute the most to reducing lead time.
- Critical operation protection: some areas deeply influence the quality or performance of the entire chain, and therefore must be safeguarded.

These factors are analyzed on a case-to-case basis to determine which ones have the most impact and therefore should be prioritized.

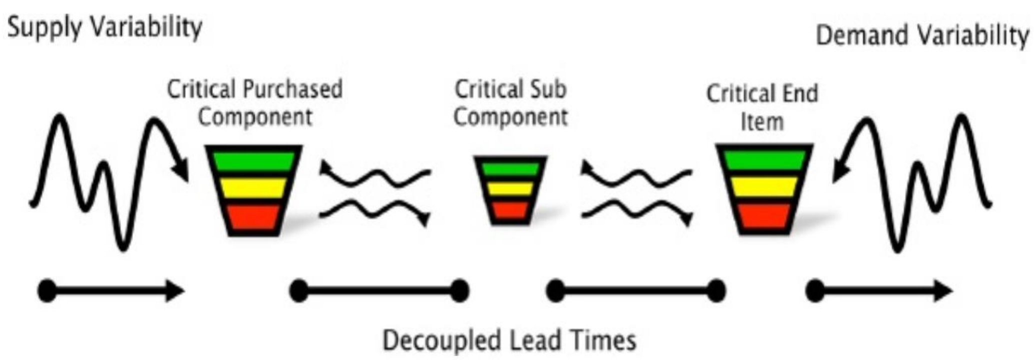


Figure 4 - Benefits of decoupling points in reducing variability (Ptak & Smith, 2016)

Different considerations are relevant for strategic positioning regarding distribution, where a balance must be sought between meeting market demands quickly and maintaining access to the financial investments that an inventory would require.

In a distribution network, the most significant source of instability is demand variability, therefore the best solution would be to place warehouses at a hub near the sourcing facility. Here volatility is lower because of the smoothing effect that happens on variability when multiple events are aggregated. The amount of smoothing can be computed mathematically through the coefficient of variance formula.

Ptak & Smith argue that “the best place in a distribution network to mitigate and manage demand variability is at a point of aggregation where there is less inherent relative volatility. Yet this mathematical fact seems to be lost on the people and organizations running the vast majority of distribution networks. Many distribution networks are designed and managed in a way that prohibits them from taking advantage of this concept.”

Many reasons to explain this apparent lack of rationality are presented:

- Shipping larger quantities of materials when organizing a shipment to facilities down the chain increases the efficiency of transportation. However, this leads to an oversupply of points down the chain while leaving the main hub understocked.
- The performance of sourcing facilities is often measured on unit costs. Bigger batches improve these metrics.
- The assumption that placing inventory closer to the point of consumption offers the most benefits is often present within organizations.
- Sometimes this downstream distribution of stock is not due to the input of the sourcing warehouse but rather of regional facilities overordering in an effort to avoid a perceived scarcity.

- If the sourcing unit does not have a high storing capacity, the stock must necessarily be relocated to downstream facilities.

These arguments often lead companies towards two situations. The first one is when stock is not held at the main hub, which leads to cross shipments between local facilities because there is a divergence between amounts needed and amounts detained. It could also cause missed sales and lessen the benefits mentioned above.

Alternatively, the main facility could be able to carry enough stock, but it is simply not located strategically. As suggested before, the best position according to Ptak and Smith (2016) is as close to the main sourcing unit as possible to maximize availability while keeping lead times short and to avoid cross-shipments between entities. Additionally, this strategy minimizes the bullwhip effect, allows more efficient consumption of resources, and simplifies production scheduling.

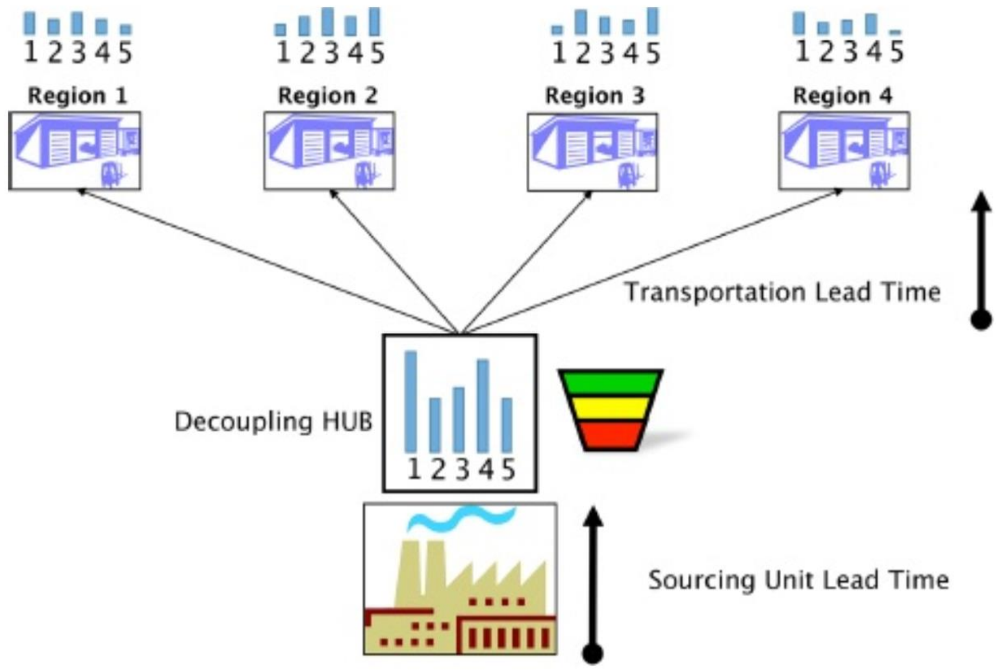


Figure 5 - Decoupled distribution network (Ptak & Smith, 2016)

However, this strategy is not always feasible for every company because of constraints related to space, network structure, or others. Often the distribution centers are several, making the above model inapplicable. In this case, one solution could be converting one of the regional facilities to a hub, creating the so-called “hub-and-spoke” model. The facility chosen for conversion should be the one with the highest volume of business, the closest to necessities like suppliers and means of transportation, or the one with the largest space available. In the case of an international company, multiple regional hubs can be designated, each covering one geographical area.

Additional advantages that come with this strategy are further decreasing external variability, better space and freight utilization, and improved capacity to meet large orders.

One final hybrid configuration is presented. Ptak and Smith (2016) argue that this model is appropriate in the case of space scarcity at a sourcing unit since it avoids the need for a full hub at that point. Additionally, "it focuses on decoupling the variability between the sourcing unit and the distribution network associated with slow-moving items [...] since their minimum quantity requirements in relation to their usage rates often create significant imbalance in the network and scheduling difficulties for the plant." (Ptak & Smith, 2016, p. 101)

2 The Covid-19 pandemic and supply chains

The current chapter will provide an account of how the Covid-19 pandemic started and its impact on the economy and specifically on supply chains, in order to provide an understanding of the consequences that such a disruption implies.

2.1 The outbreak

On December 31st, 2019, news from the World Health Organization started spreading regarding an unusually high number of pneumonia cases in Wuhan, eastern China, caused by an unknown virus. Appearing to have started from animals in the seafood market of the city, promptly shut down, the disease quickly spread, with symptoms consisting mainly of fever, a dry cough, shortness of breath, and fatigue, but presenting more severe manifestations requiring hospitalization in weaker patients (Reynolds & Weiss, 2020).

On January 9th the first victim of the virus died of respiratory failure. Despite the quarantine put over the areas initially involved, the virus reached across borders and overseas in a matter of weeks, leading many countries to close borders, put areas on lockdown and initiate emergency measures (CNN Editorial Research, 2021). On March 11th, the WHO declared Covid-19 a pandemic, which, as of August 2021, counts more than 200 million cases worldwide and more than 4 million deaths (Worldometer, 2021).

Focusing on the economic impacts of the pandemic, experts at Washington University have initially estimated an impact of over $300 billion on the global supply chain, with effects that could last for over two years (Miller, 2020).

Financial markets were not safe from the negative effects of the pandemic, seeing the sharpest falls since the economic crisis of 2008 (Carrick, 2020).

One of the hardest-hit industries was tourism due to local restrictions, closures, and especially travel bans. “The decades-long travel boom has made us more globally connected than ever before. But with no end in sight, the coronavirus has made the industry both a vector for – and unfortunate poster child of – this historic event.” (Turner, 2020)

Another sector heavily impacted globally was retail. With reduced opening hours, lockdowns preventing people from physically going to stores, and government decrees, retailers saw a great loss of income, which they were only partly able to offset thanks to an increased focus on online operations. For example, during January, February, and March 2020, European and UK retail stores saw a decrease in customer visits of respectively 10.63%, 8.89%, and 41.43% when compared to the same months of 2019 (Santos, 2020).

Additionally, the pandemic had a heavy impact on global poverty, with assessments claiming an increment of 97 million people in poverty caused by the pandemic during 2020, a figure that is lower than initial estimates but still remains a historically unprecedented increase. Even if poverty rates resume the declining trend observed before the pandemic, millions of people will live in poverty for many years to come due to the initial impact of Covid-19. (Mahler, et al., 2021)

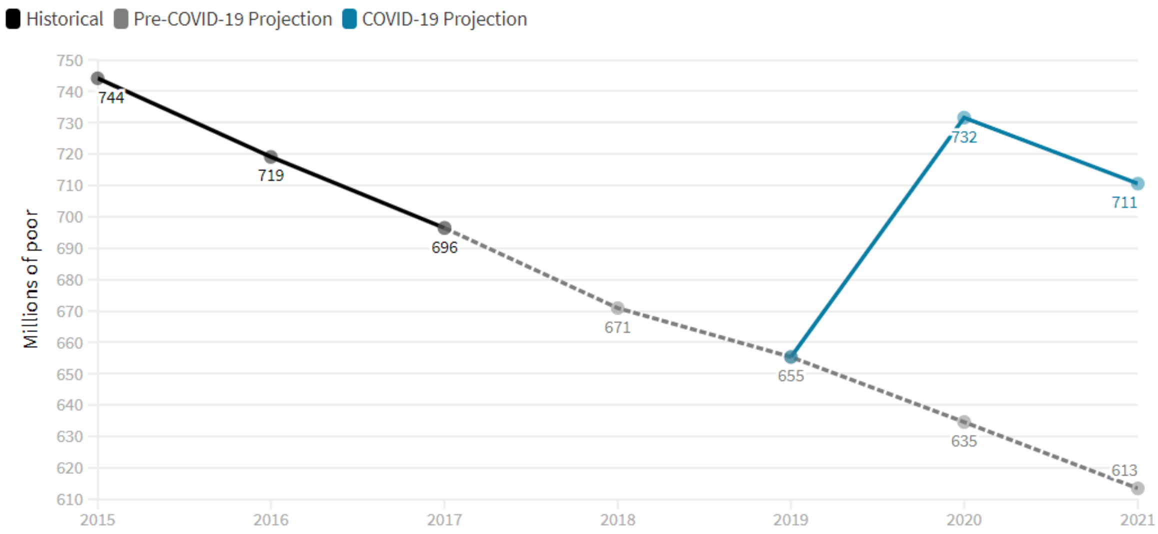


Figure 6 - Extreme poverty in 2015-2021, measured as the number of people living on less than $1.90 per day (Mahler, et al., 2021)

The sanitary emergency caused by the Coronavirus can be classified as a crisis for many reasons, according to the definition offered in their research by Chowdhury and Quaddus (2016, pp. 710-711):

- "Organizational crisis is low probable but creates high impact." Even though the likelihood of a pandemic happening has increased in the last decades (Yeung, 2019), this event can still be considered improbable. Its effects, however, are of large scale: as of November 2020, the total cost of the Covid-19 pandemic has been estimated to be between $8-$16 trillion (Financial Express, 2020).
- "It threatens viability of the organization." As will be discussed more extensively in the next section, the Coronavirus severely impacted many companies, sometimes even putting their survival at risk.
- "Stakeholders perceive crisis as personally and socially threatening." The change in consumption patterns right after the pandemic first hit proves

the public feared a high influence on their everyday life (Ernst and Young, 2020).

- "Cause, effect and means of resolution of crisis are ambiguous and may shatter individual's beliefs, values, and basic assumptions." This was demonstrated by the inability of many companies to effectively respond to the emergency, either because of lack of planning or inadequacy of the plans already formed (ISM, 2020).
- "Decision-making during crisis is constrained by time and cognitive limitations." The rapid pace of the pandemic along with its unpredictability caused uncertainty about outcomes that ensued after actions were taken, influencing the decision-making process (Gunessee & Subramanian, 2020).

2.2 Impacts on supply chains

There are four main reasons, presented by Wilson (2020), why Covid-19 had a bigger impact on supply chain compared to other disruptions like natural disasters, restrictions, political unrest, and fluctuations in the economy:

- Geographic scope. Differently from extreme weather phenomena like hurricanes, this pandemic had, and continues to have to this day, a global reach, affecting countries and companies all around the world. This also implies reluctance in sharing aid, supplies, and manpower, as usually happens with regional events, because those elements will probably be already needed locally.

- Industrial scope. Very often, in the case of disruptions in supply chains, only a specific industry, or a few, is involved. For example, Hurricane Harvey in 2017 had high negative impacts on refineries located on the Gulf Coast. However, the ones in the rest of the USA were able to make up the shortfall since they were not affected. The current pandemic has affected almost every industry and company. Additionally, to the scarcity of raw materials, many other essential items like sanitary supplies and even food have seen shortages. Service providers, factories, and many other activities that imply close human contact like people transport have been forced to halt their business.
- Demand shame. Since manufacturers did not anticipate Covid-19 happening, they continued production as usual, particularly of costly goods, reassured by the belief that high-end buyers would hardly alter their consumption patterns even in the event of a slow year. However, as a result of the pandemic, many companies have found themselves with large volumes of high-value stock which they are unable to sell, leading to frozen assets. Indeed, many responsible buyers are currently avoiding expensive investments like cars. Additionally, for some luxury brands halting business during such events represents a matter of public image: after the tsunami of 2011 in Japan, Luis Vuitton closed all the stores in the country, stating that "It just did not look right to be open and selling luxury handbags when thousands of Japanese had just lost their homes" (Wilson, 2020).
- Duration. Logically, most of the disruptions mentioned earlier, like weather events, have a short-term scope and their consequences can be

overcome or at least partly dealt with within a few months. However, pandemics last much longer because they naturally present relapses and spikes. For instance, the Spanish Flu took almost two years to fade.

In their research, P. Chowdhury et al. (2021) offer a summary of the impacts of the COVID-19 pandemic on supply chains classified by area, which will be used here as a framework to later analyze each impact further, integrating relevant literature.

Table 1 - List of impacts of the COVID-19 pandemic on supply chains (Chowdhury, et al., 2021)

Impacted area	**Specific impact**
Demand management	Demand spikes for essential products Shortage of essential products Loss of security with respect to essential items Failure of on-time delivery Declining demand for non-essential products Ambiguity or difficulty in forecasting
Supply management	Shortage of material supply/supply-side shock/supply disruption
Production management	Production disruption and backlog Reduced production capacity Unavailability of workforce Obsolescence and impairment of machinery and capital assets

Transportation and logistics management	Delays in transportation and distribution Lack of international transportation/trade Loss/lack of physical distribution channels Shift of distribution and logistics pattern (offline to online or blended)
Relationship management	Reduced social interaction Information ambiguity Lack of supplier engagement/opportunistic behavior
Supply chain-wide impact (causing impacts in internal, upstream, and downstream operations)	Ripple effect on all the operations involved in supply chains Supply chain collapse Closure of facilities, including both companies' production facilities and the facilities of supply chain partners such as suppliers and distributors
Financial management	Reduced supply chain financial performance (e.g., loss/reduction of financial stability) Reduced cash inflow
Sustainability management	Lack of focus on social and environmental sustainability practices/disruption of sustainability initiatives Threats to the health and safety of the workforce

	Contraction of the development of green and low-carbon energy sources Increase in waste Increase in recyclable materials

2.2.1 Demand Management

- *Demand spikes for essential products*
- *Shortage of essential products*
- *Loss of security with respect to essential items*
- *Failure of on-time delivery*
- *Declining demand for non-essential products*
- *Ambiguity or difficulty in forecasting*

Following the Covid-19 outbreak, demand for many products greatly transformed. Essential items like food and medical supplies quickly became scarce because of panic buying, fueled by mass hysterics and the media's sensationalism, leading manufacturers to intensify production (Bagshaw & Powell, 2020). On the other hand, nonessential items like leisure products or goods requiring considerable investments, like cars or large appliances, saw a drastic drop in sales, due to shifted priorities and lower disposable income caused by a sudden rise in unemployment. (Zhu, et al., 2020)

According to an Ernst and Young survey (2020), more than two-fifths of participants believed that their shopping habits would change drastically due to the pandemic, with almost a third admitting to spending less overall, mainly as a result of lower employment rates. The study divided people into four categories, visible in the figure below: "cut deep" which represents people hit hardest by the pandemic who are spending less, "stay calm, carry on" factoring those who are continuing to spend as normal, "save and stockpile" which includes pessimists worried about their families, and "hibernate and spend" who are well-positioned to deal with negative effects and who are increasing expenses. However, even amidst this divergence of behavior, the study found that all categories decreased consumption of non-essential items, as illustrated in the graphic below. These demands alterations undoubtedly caused complications across the management of supply chains.

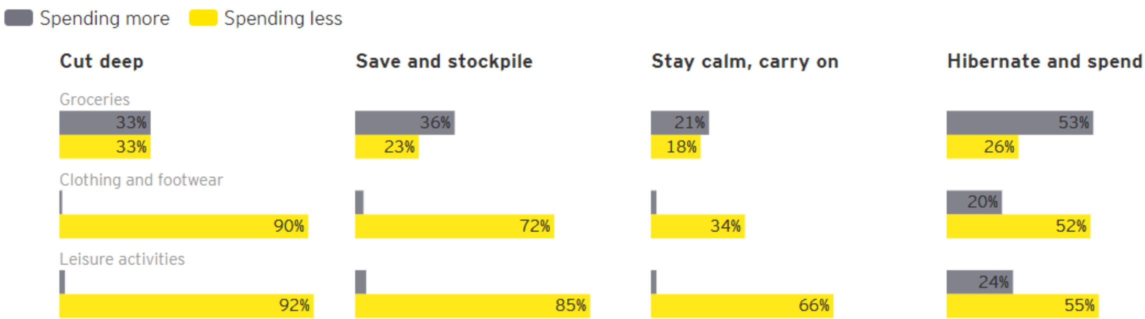


Figure 7 - Covid-19 impact on spending habits by segment (Ernst and Young, 2020)

2.2.2 Supply management

- *Shortage of material supply/supply-side shock/supply disruption*

Production and shipment of raw materials and components to be assembled halted worldwide since borders and factories closed to contain the infection, disrupting the production chain even in regions not yet affected or affected less severely. (Zhu, et al., 2020)

Indeed, "in South Korea, automakers have shut down plants due to a lack of component parts from China, implying that there are no alternative suppliers ready to fill the gap" (Lierow, et al., 2020).

A whitepaper by GS1 US (2021) points out the two main implications that the shortage of raw materials has entailed:

- High dependency on a few suppliers concentrated in limited geographical areas.
- Asymmetry between the production that happens off-shore and the one in factories closer to the final point-of-sale, implying increased difficulties in predicting the availability of products to be sold, longer lead times, and challenges during planning.

Impacts related to material shortages and unavailability of parts inevitably compromise the integrity of the entire supply chain because of the aforementioned ripple effect, therefore they will be better discussed in section 2.2.6.

2.2.3 Production management

- *Production disruption and backlog*
- *Reduced production capacity*
- *Unavailability of workforce*
- *Obsolescence and impairment of machinery and capital assets*

As found by a study by the Institute of Supply Management, Chinese manufacturing facilities were operating with 56% of staff, causing significant reductions in production capacity (ISM, 2020).

The closing of borders has decreased the number of migrant workers and hindered the flow of commuters. One of the industries most affected by this is agriculture, which heavily relies on seasonal job force. This matter raises worries regarding possible food scarcity and the impacts of the entire food production system, especially after the initial plans for the growth of locally sourced labor did not deliver: “Despite much political noise around filling vacancies with workers who lost their jobs in other sectors, only 150 workers started harvesting jobs in UK agriculture as part of a scheme for which initially 50,000 UK workers had signed up” (Trautrims, et al., 2020, p. 4). This unavailability of workforce put stress on companies who experienced surges in demand or that have to hire new workforce to fill in positions that are vacant due to layoffs needed at the beginning of the pandemic, preventing them from running thorough selection processes to assess skills and adequate qualifications because of the pressure to keep up with the fast-paced nature of changes caused by the pandemic.

Additionally, the sudden and unplanned decrease in production resulted in the obsolescence of materials and machinery before their usefulness was fully exhausted, leading to a loss of utility and efficiency (Dente & Hashimoto, 2020).

2.2.4 Transportation and logistics management

- *Delays in transportation and distribution*
- *Lack of international transportation/trade*
- *Loss/lack of physical distribution channels*
- *Shift of distribution and logistics pattern (offline to online or blended)*

Since travel restrictions took effect in almost every country, fewer commercial flights and trains were circulating. In addition to a decline in tourism, which undoubtedly caused direct economic losses, this factor also implies reduced opportunities to transport cargo, which previously could be loaded alongside luggage in the aircraft hold. Moreover, transport trucks were limited by closed borders on land and increased safety measures, leading to delays along the entire process of transport, especially during customs clearance due to reduced personnel and increased regards towards potential sources of spread of the infection. Each of these elements contributed to increased costs and lower efficiency in the transportation of finished goods. (Zhu, et al., 2020)

This impact is particularly significant because, as noted by Rahman et al. (2021, p. 1), the shipping sector accounts for 90% of global trade and can be considered the "artery of international supply chains". Indeed, the authors also highlight that, due to the pandemic, the volume of cargo transported dropped by 13% in mid-April 2020, and forecasts announced a 32% reduction in the following months.

Forecasts produced in February 2020 anticipated a reduction in global shipping at U.S. ports of 12.9% year over year in February 2020 and of 9.5% in March 2020 (Lierow, et al., 2020).

Additionally, a survey conducted by the ISM (2020) highlights that during the spring of 2020 62% of participants reported delays in receiving materials from China, 48% were facing issues when moving goods inside the Chinese borders and 46% experienced slower loading operations in Chinese ports.

An industry particularly affected by the decrease in passenger flights is the pharmaceutical industry. As reported by The Washington Post Sunday (Duncan, 2020), by March 2020 the cost for airfreight increased from a few dollars per kilogram to $15, even though the shipping rates for pharmaceuticals did not increase disproportionately when compared to other cargo. This event highlighted the high dependency of the USA's pharmaceutical companies on foreign drugs, particularly from China and India, especially after their request to the Food and Drug Administration to prompt airlines to prioritize medical supplies and international flights that transport them.

According to van Hoek (2020), globalization caused the lengthening of the logistic pipeline, introducing additional risks of delays in the delivery process and increasing dependency on remote sources. This mechanism undoubtedly concurred in aggravating the impacts of the Covid-19 pandemic.

2.2.5 Relationship management

- *Reduced social interaction*
- *Information ambiguity*
- *Lack of supplier engagement/opportunistic behavior*

The sudden obstacle to smooth communication between actors involved in a supply chain resulted in the incompleteness of the information shared, increasing the ambiguity (already present even under normal circumstances due to intrinsic complexities) under which decisions had to be made. Gunessee and Subramanian (2020, p. 4) summarize several declinations of this phenomenon based on the research available in operational management literature:

- Performance ambiguity, which leads to difficulties in evaluating the efficiency of operations and therefore in deciding how to allocate resources.
- Information ambiguity, inducing issues in interpreting the data available and make decisions based on that.
- Causal ambiguity, strategically very important, which concerns the uncertainty on the connections between outcomes and which events caused them. “[It] could manifest itself in the supply chain context where an organization is unable to determine how it has achieved a competitive advantage as a result of some purchasing activity, or it could be a lack of understanding of the linkages between inputs and outputs as related to a supplier’s knowledge.” (Gunessee & Subramanian, 2020, p. 5)
- Extreme ambiguity, related to the lack of awareness regarding possible future scenarios.

- Role ambiguity, meaning uncertainty on what is an actor's position in the supply chain hierarchy, which are their powers, and which are their obligations.
- Relational ambiguity, which leads to a lack of understanding of how two businesses are interconnected
- Processing time ambiguity, leading to incapacity to accurately plan.
- Uncertainty about probabilities, which might lead decision-makers to gravitate towards choices with more certain outcomes and avoid ambiguous ones.

Studies have shown that "decisionmakers benefit from trust, effective communication and information exchange, and close relationships. [...] Strategically formulated social and environmental practices that are based on long-term relationships and commitments – rather than mere tick-box compliance exercises – can significantly increase organizational resilience" (Trautrims, et al., 2020, p. 5).

GS1 US (2021) defines three main issues caused by a lack of visibility and traceability inside supply chains which creates information ambiguity and makes companies vulnerable to opportunistic behavior:

- Failure to recognize signs that indicated an imminent shift in demand patterns
- Inability to respond to these shifts efficiently and effectively, for example with changes in production. This inability could be caused by shortages of raw materials or external constraints like new restrictions.

- Inadequacy in reallocating goods towards locations in higher need of them.

A factor contributing to this issue is the lack of a monitoring system, currently suffered by 44% of companies, which would allow them to address the fluctuations in demand, supply, as well as promptly address challenges that may arise. “A solid traceability system contributes confidence and trust to organizations in the supply chain. Traceability helps ensure that companies can confirm exactly where their products are in their life cycle and reduce the risk of bad actors taking advantage of supply chain blind spots.” (GS1 US, 2021, p. 5).

2.2.6 Supply chain-wide impact (causing impacts in internal, upstream, and downstream operations)

- *Ripple effect on all the operations involved in supply chains*
- *Supply chain collapse*
- *Closure of facilities, including both companies’ production facilities and the facilities of supply chain partners such as suppliers and distributors*

Depending on a single source for any level of operation, from sourcing raw materials to human labor, constitutes a great risk of disruption for supply chains. When countries started to go on lockdown at the beginning of March 2020, the world’s largest 1,000 companies were deeply affected, as highlighted in a study by the risk management company Resilinc (Linton & Vakil, 2020) and visible in the figure below, as they possessed more than 12,000 factories, warehouses, and other operations located in areas where activities where almost entirely stopped to prevent the spread of infection.

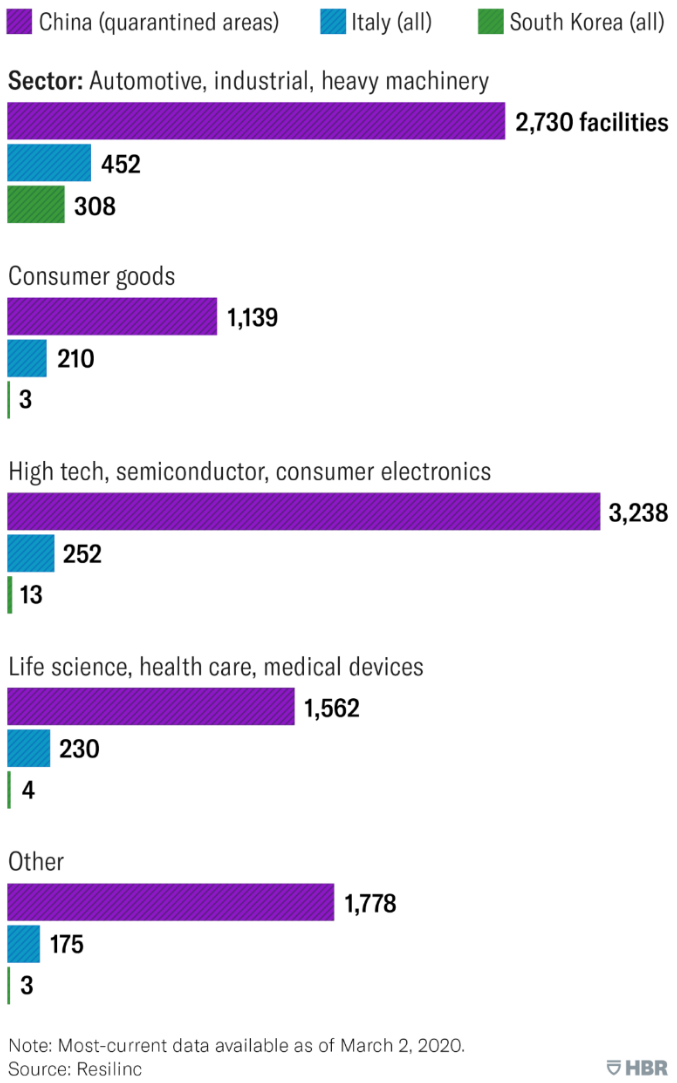


Figure 8 - Dependence on quarantined areas (Linton & Vakil, 2020)

As reported by the Harvard Business Review (Haren & Simchi-Levi, 2020), "mounting pressure to reduce supply chain costs motivated companies to pursue strategies such as lean manufacturing, offshoring, and outsourcing. Such cost-cutting measures mean that when there is a supply-chain disruption, manufacturing will stop quickly because of a lack of parts". Indeed, following the efforts of the Chinese government to contain the transmission by quarantining almost half of the population, many companies that relied solely on Chinese manufacturers for sourcing components had to suspend production in some plants due to the inability to find parts. As notable examples, Fiat Chrysler Automobiles and Hyundai are mentioned.

Often, however, this issue proves particularly insidious when the disruption involves second-level suppliers upstream, not the suppliers the company has direct contact with, giving firms a false sense of security. This concern can be explained using as an example the medical shortage faced by North America. Long before the threat of the Covid-19 pandemic, the US Food and Drug Administration carried out routine checks on their first-tier equipment providers to assess the risk of shortages, finding them acceptable. However, they failed to realize that those providers were sourcing raw materials from a narrow portfolio of suppliers located in limited regions of India and China, pinpointing the problem in an area of the supply chain that was further upstream than what the FDA was focusing on. (Zhu, et al., 2020) As additional confirmation, a study by the Institute for Supply Management found that the suppliers of 600 US companies were operating at 50% capacity, leading to delays in the delivery of final products (Ivanov & Das, 2020).

This issue represented a weak link in the chain and consequently a great risk. Indeed, “disrupted global supply chains have had the biggest impact on operations and the global economy in general” (Trautrims, et al., 2020, p. 3).

2.2.7 Financial management

- *Reduced supply chain financial performance (e.g., loss/reduction of financial stability)*
- *Reduced cash inflow*

As a consequence of the negative impacts on production, during February 2020 companies on average were forced to reduce their revenue targets by 5.6%, with the hardest-hit companies going down as far as 15% (ISM, 2020). Just one month later, the figures significantly worsened reaching 22% (ISM World, 2020).

Some industries, like airline transport, have seen such considerable losses to have forced companies to ask for governmental bailouts in order to keep the business running and avoid leaving thousands of workers without employment (Hakovirta & Denuwara, 2020).

The reduction of liquidity has been particularly challenging for SMEs. At the beginning of the pandemic, 60% of Chinese SMEs reported availability of cash sufficient for only two months' worth of fixed costs. Similarly, in the USA small business have on average enough cash flow to last only 27 days. This factor constitutes a great vulnerability for SMEs, placing many at risk of permanent closure. (Albaz, et al., 2020)

2.2.8 Sustainability management

- *Lack of focus on social and environmental sustainability practices/disruption of sustainability initiatives*
- *Threats to the health and safety of the workforce*
- *Contraction of the development of green and low-carbon energy sources*
- *Increase in waste*
- *Increase in recyclable materials*

The Covid-19 crisis has also impacted the attitude of firms towards sustainability, both economic and environmental.

The pandemic brought companies to increase their focus on "employee health and wellbeing, helping employees to cope up with remote working conditions [and] skill improvements." (Sharmaa, et al., 2020, pp. 4-5). However, the presence of other studies stating that Coronavirus may have worsened the likelihood of exploitative conditions for workers in prone environments (Trautrims, et al., 2020) raises the question of whether the previously mentioned focus is just of performative nature, in order to improve the public image of companies in these uncertain times, or if there are indeed two opposite trends happening.

A study by the Economic Policy Institute (GS1 US, 2021) attests that 55 million essential workers employed in 12 different industries are not equipped with adequate protective devices, despite engaging in activities like food preparation or tasks that are heavily based on human contact like retail customer services. However, according to the RSM (Goel, 2021), "70% or more of manufacturers took measures like asking sick workers to stay home, increasing the cleaning of workplace surfaces, and encouraging workers to avoid face-to-face meetings”.

Additionally, many projects aimed at advancing green initiatives, like implementing renewable energy sources, will be suspended because of a lack of funding and more pressing priorities. For example, Morgan Stanley planned to decrease the installation of US solar photovoltaics by 48%, 28%, and 17% respectively in the last three quarters of 2020. Furthermore, the disruptions in supply chains have affected the production of components necessary for these implementations: “Many parts for large-scale renewable projects come entirely or partially from China, other parts of Asia, or the United States. These are specialized supply chains with few ready substitutes. The COVID-19 outbreak has already slowed Chinese production of solar panels and materials, delaying projects in countries including India and Australia. Manufacturing disruptions in China could contribute to a significant one- or two-year dip in renewable additions.” (Fox-Penner, 2020)

Regarding waste, the sudden surge in the use of single-use items - like surgical masks, gloves, hospital supplies, etc., - has undoubtedly increased the pressure on waste management operations. Similarly, those industries characterized by perishable items which saw a drop in demand had to face the degradation of their material stock and its subsequent disposal. (Dente & Hashimoto, 2020)

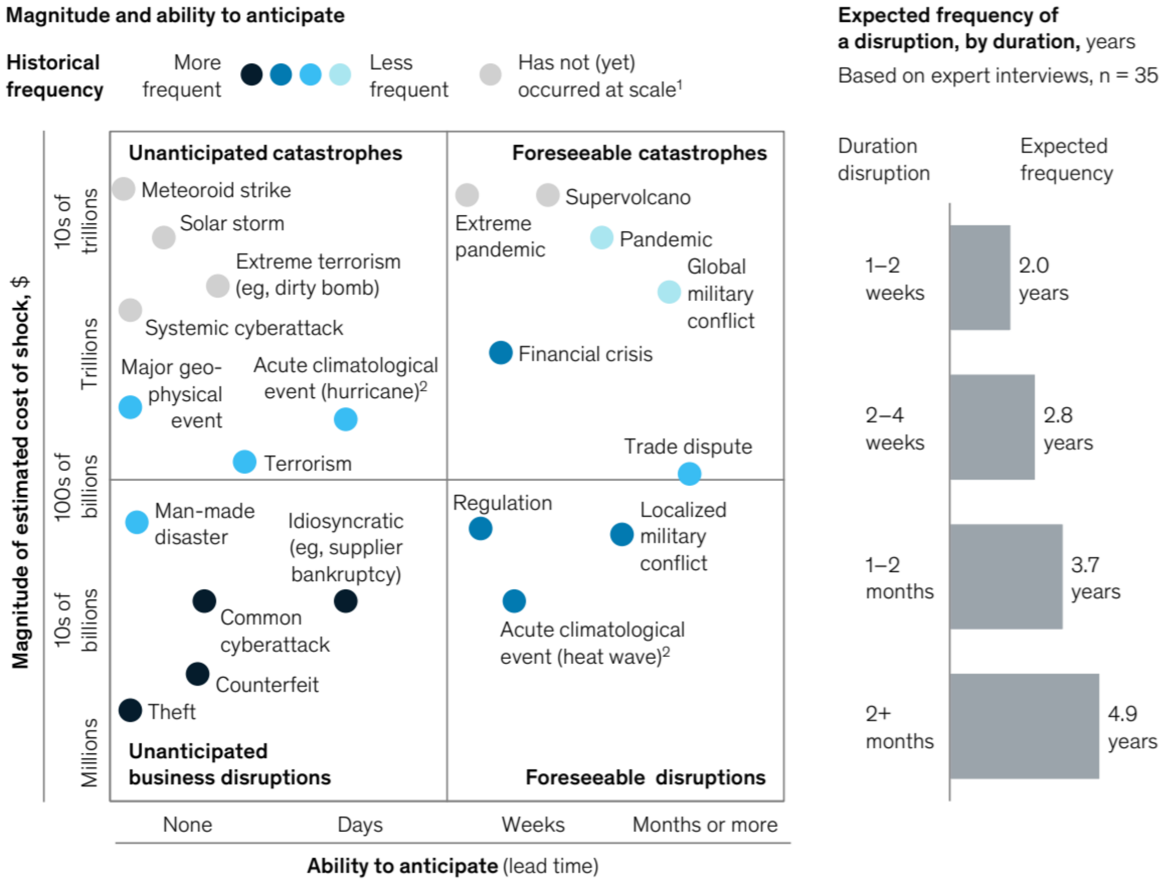
3 Building resilience

The current chapter will offer insights on why increasing the resilience of companies is a fundamental practice and how that can be done, by firstly formalizing the process of risk management and later investigating some strategies that can be implemented to increase the resilience of companies.

According to the same study by the Institute for Supply Management mentioned previously (ISM, 2020), as of the beginning of March 2020 almost 45% of the companies surveyed had not prepared a resilience plan in case of disruptions in their supply chain. Among these, 23% have reported disruptions in their operations as of spring 2020. However, in a survey conducted in May 2020, 93% of the supply chain executives interviewed declared intention to increase resilience through concrete plans, with 44% of those being willing to do so even at the expense of short-term savings (Lund, et al., 2020).

“Given the increasing frequency and intensity of natural disasters as well as the continuous stream of anthropogenic catastrophes, the riskiest thing a company can do is to have no contingency plan” (Fahimnia & Jabbarzadeh, 2016, p. 307).

According to experts at McKinsey Global Institute (Lund, et al., 2020) supply chain disruptions that last more than a month can now be expected to happen on average every 3.7 years, implying major consequences for companies. Additionally, 80% of global trade involves countries with declining political stability, increasing the risk of shocks to supply chains. Based on probabilities, companies can expect these shocks to cause on average a loss of 45% of one year’s EBITDA over the course of a decade.



1. Shocks that have not occurred either at scale (eg, extreme terrorism, systemic cyberattack, solar storm) or in modern times (eg, meteoroid strike, supervolcano).
2. Based on experience to date; frequency and/or severity of events could increase over time.

Figure 9 - Magnitude, lead time, and frequency of disruptions (Lund, et al., 2020)

All of the elements mentioned above serve as evidence to prove the importance of adopting strategies to increase business resilience.

Additionally, it's useful to mention that McKinsey and Company (Alicke & Strigel, 2020) highlights the different instances in which either proactive or reactive responses to supply chain risks are more appropriate, depending on the type of disruptions at hand. Therefore, the authors indicate reactive strategies as most appropriate for risks that are hard to anticipate, in order to respond to the disruption after this has happened. On the other hand, if the ability to anticipate the risk is fair, it is worth adopting a more proactive approach.

It should be noted that the graph in Figures 9 and 10 present the same measure in the axes, but these are reversed.

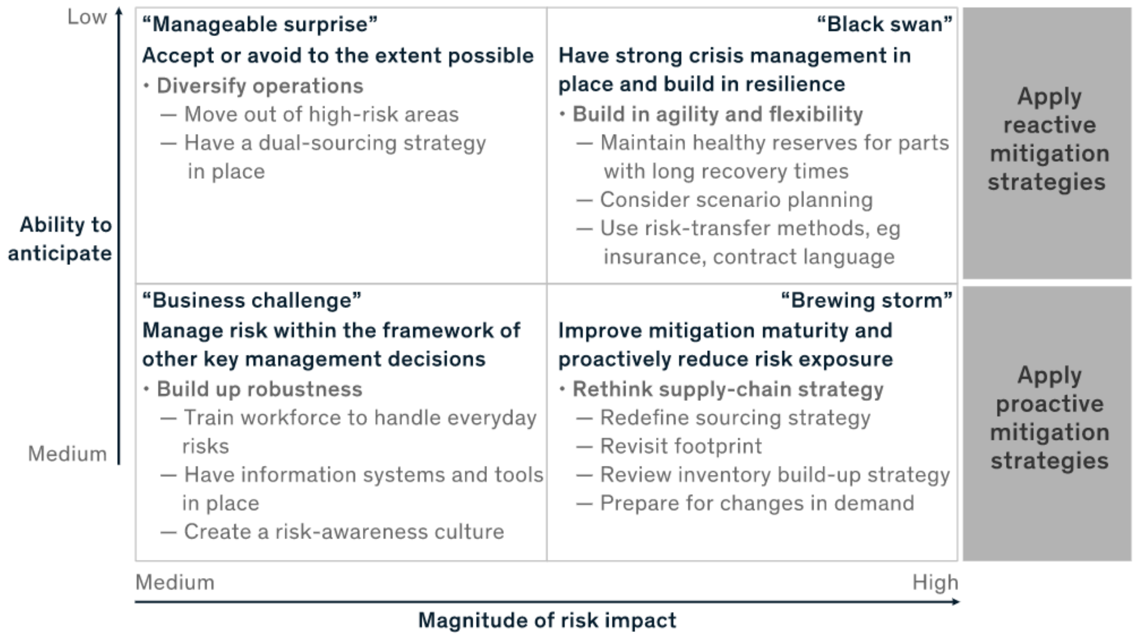


Figure 10 - Most appropriate set of response strategies depending on the type of disruption (Alicke & Strigel, 2020)

3.1 Risk management

Since section 3.2 will be dedicated to reviewing practical resilience strategies, which are none other than applications of risk management to avoid or decrease future repercussions should a disruption like Covid-19 happen again, it would be helpful to firstly formalize what exactly risk management is and what process it follows.

According to van Hoek (2020, p. 2) "existing supply chain resilience literature would categorize panic buying as a demand risk, and the closure of supplying factories and warehouses as a typical supply risk". It is clear that risk exists at various levels of the supply chain, and risk assessment is subject to the opinion of those who are assessing since each individual will have his or her own opinion about what may constitute a risk.

Barbara Gaudenzi and Antonio Borghesi (2006, p. 1) quote professor Martin Christopher when defining supply chain risk as “any risk to the information, material and product flow from original suppliers to the delivery of the final product”. Generic risk management should aim to protect companies by identifying unfavorable situations that could constitute a risk and then stopping the negative events or reduce the consequences that could be detrimental for a business while helping the recovery process after the crisis has passed (Slack, et al., 2016). Risk management applied to supply chains, on the other hand, is considered a supporting process to aid the achievement of predefined goals.

Risk management consists of four main activities, explained more broadly in the next sections:

- Assessment of potential failures
- Prevention
- Mitigation, which is minimizing the negative consequences
- Recovering from failures when they do occur

3.1.1 Assessment

The first and most critical phase in the risk management process is to assess activities in order to find potential sources of risk. Often this stage is what determines the severity of the consequences since failure to detect a low risk could prove to be more detrimental than a great risk that the company prepared for. “Whatever approach to risk is taken, it can only be effective if the organizational culture that it is set in fully supports a ‘risk-aware’ attitude”

(Slack, et al., 2016, p. 619). In the relevant literature, possible events with negative consequences are defined as “failures”. Slack et al. (2016) provide a checklist of potential causes of failure to analyze when beginning the risk management process:

- failures of supply: fast progress and changes in products, together with market fragmentation, have determined an elastic demand. Additionally, the shift towards lean inventories and supply chain efficiency, as discussed before, has caused companies to be highly dependent on their outsourced activities.
- internal failures such as those deriving from human, organizational and technological sources: these can be determined by human mistakes, either voluntary or involuntary, poorly designed organizational structure or processes, or faults in the facilities caused by lack of maintenance or external undermining.
- failures deriving from the design of products and services: often companies are pressured to meet a fast time-to-market performance at the expense of accuracy in the design process.
- failures deriving from customer failures: client misuse could cause the performance of products to be perceived inaccurately, therefore companies should take on the responsibility to educate customers and provide easy-to-use products.
- general environmental (or institutional) failures: this category includes political disruptions and natural disasters. Unquestionably, Covid-19 falls in this category. Slack et al. (2016, p. 622) argue that “this source of potential failure has risen to near the top of many firms’ agenda due to a

series of major events over recent years. As operations become increasingly integrated (and increasingly dependent on integrated technologies such as information technologies), businesses are more aware of the critical events and malfunctions that have the potential to interrupt normal business activity and even stop the entire company".

However, sometimes sources of failure are difficult to identify. For this reason, it is valuable to analyze previous disruptions and their root causes to build a learning set for future reference. This post-failure analysis includes the following activities:

- accident investigation: an examination of large-scale events carried out by experts, which is important to carry out accurately since there is a low number of cases to analyze due to their low frequency.
- failure traceability: the act of ensuring that all failures can be traced and linked to the processes they went through. This helps recall entire batches of products or analyze the chain that produced and handled a certain good to find the element at fault.
- complaint analysis: gaining feedback from customer complaints in order to find faults and how they are perceived by final consumers.
- fault-tree analysis: a logic map built starting from a failure to examine possible causes, other consequences not yet detected, and ways to improve goods and services.

After determining possible causes of risk, managers should estimate the likelihood of a failure occurring. These estimates can be objective or subjective. (Slack, et al., 2016).

Objective estimates are computed using historical performance based on data collected, they can be measured using failure rates – how often a failure occurs; reliability – the chances of a failure occurring; or availability – the amount of available useful operating time left after taking account of failures. Subjective estimates are more convoluted and unreliable since they are based solely on the judgment of the individual (or team) making the estimate, who is not perfectly rational by nature and who could have a different attitude towards risk than the company. When objective estimates are unattainable, subjective estimates, although not ideal, are preferable to no estimates at all.

The next stage is to assign priorities to risks in order to decide which to tackle first with preventative and corrective actions. The approach described by Slack et al. (2016) is failure mode and effect analysis (FMEA), used to "identify the factors that are critical to various types of failure as a means of identifying failures before they happen". It assigns a risk priority number calculated based on the answers to three key questions:

- What is the likelihood that failure will occur?
- What would the consequence of the failure be?
- How likely is such a failure to be detected before it affects the customer?

A very similar approach for assessing risk priorities by assigning numerical values, the "Probability-Impact Matrix", is explained by Dumbravă & Iacob (2013). Often adopted in project management and emergency management, it consists in evaluating risks based on two variables, the likelihood of it happening and the impact it would have in case it happened. Many variations of this method exist; however, the general process is building a matrix based on the two variables, either with quantitative or qualitative values. In the case of quantitative values, the two are multiplied to find the final risk score. Usually, the matrix table is labeled with colors or letters to represent how critical the risks are and therefore the priority with which managers should tackle those issues. An example of the probability-impact matrix is provided in the figure below.

LIKELIHOOD ↓ / SEVERITY →	ACCEPTABLE – 1 – LITTLE TO NO EFFECT ON EVENT	TOLERABLE – 3 – EFFECTS ARE FELT, BUT NOT CRITICAL TO OUTCOME	UNDESIRABLE – 5 – SERIOUS IMPACT TO THE COURSE OF ACTION AND OUTCOME	INTOLERABLE – 7 – COULD RESULT IN DISASTER
IMPROBABLE – 1 – RISK IS UNLIKELY TO OCCUR	LOW – 1 –	MEDIUM – 3 –	MEDIUM – 5 –	HIGH – 7 –
POSSIBLE – 2 – RISK WILL LIKELY OCCUR	LOW – 2 –	MEDIUM – 6 –	HIGH – 10 –	EXTREME – 14 –
PROBABLE – 3 – RISK WILL OCCUR	MEDIUM – 3 –	HIGH – 9 –	EXTREME – 15 –	EXTREME – 21 –

RISK RATING KEY	LOW 1 – 2 OK TO PROCEED	MEDIUM 3 – 6 TAKE MITIGATION EFFORTS	HIGH 7 – 13 SEEK SUPPORT	EXTREME 14 – 21 PLACE EVENT ON HOLD

Figure 11 - Probability-impact matrix for risk assessment, with rating key (author's elaboration, template by Smartsheet)

3.1.2 Prevention

Once the causes of failures with the highest priority have been established, prevention methods can be implemented to avoid the occurrence of negative consequences.

Three main approaches are used (Slack, et al., 2016):

- Redundancy: having backup systems or components in case a process or part of it fails. For example, companies that need to provide fast services, like hospitals, have staff on call in case people on the current shift have setbacks or more personnel are required.
- Fail-safeing: implementing systems or devices to prevent human mistakes.
- Maintenance: taking care of facilities and resources to enhance safety, increase reliability, provide higher quality, lower operating costs, ensure a longer life span, and achieve higher end value.

3.1.3 Mitigation

When the occurrence of a shock cannot be avoided, therefore making prevention methods not sufficient, mitigation can help to minimize the negative effects of the adverse event. This step is essentially about minimizing exposure to shocks.

Several actions for mitigation exist (Slack, et al., 2016):

- Mitigation planning: ensuring that all possible outcomes have been met with an action plan.
- Economic mitigation: taking on insurance or hedging against failures.
- Spatial containment: stopping the spread to other physical parts of the facilities.
- Temporal containment: containing the spread of the effects of a failure over time.

- Loss reduction: taking deliberate action to implement systems that do not directly mitigate the failure but can reduce its negative effects.
- Substitution: comparable to the concept of redundancy mentioned before, however, it does not always imply excess resources, it could merely involve having backup plans in case the current one is deemed inapplicable due to new circumstances.

An important element that aids in the mitigation process is the presence of an emergency operations center (EOC). The presence of these departments is usually limited to the corporate or business unit level, however, companies could greatly benefit from their implementation to a deeper extent. These centers could provide "predetermined action plans for communication and coordination, designated roles for functional representatives, protocols for communications and decision making, and emergency action plans that involve customers and suppliers". (Rice, 2020)

3.1.4 Recovery

After the failure has occurred, companies can engage in actions to recover and benefit from the knowledge gained by the experience. The systematic approach is aimed at "discovering what has happened to cause failure, acting to inform, contain and follow up the consequences of failure, learning to find the root cause of the failure and preventing it from taking place again, and planning to avoid the failure occurring in the future." (Slack, et al., 2016, p. 668).

In the subject matter of supply chains, and specifically their readjustment after the impacts of the Covid-19 pandemic, the recovery process would necessitate a revision of its structure. Changes in the flows and configurations could be necessary in order to implement contingency plans developed with data collected during the disruption. Additionally, collaboration between key actors, both in terms of restorative actions and knowledge sharing, would be fundamental elements to overcome the disruption. (Jabbour, et al., 2020)

3.2 Resilience strategies

Given the disruptions caused by Coronavirus that have been presented previously, it would be constructive to review some strategies analyzed in literature and applied by industry players that could help companies increase their resilience and therefore mitigate adverse repercussions.

The instances illustrated in the following pages are practical applications of the four steps of risk management described previously. Some sections deal with assessment strategies, therefore only implying a passive analysis of the current state of the supply chain to increase awareness and transparency. Others, on the other hand, present actual changes in the organization of activities and in the structure of the business, sparked by the know-how gained thanks to the current sanitary crisis in order to prevent future reoccurrences.

3.2.1 Assessing the supplier network structure

The structure of the network of suppliers plays an important role in the vulnerability of a supply chain and of the entire company.

For example, the interconnectivity of the network is an important factor to consider. Actors that play a central role in the ecosystem could potentially disrupt the network in a disproportional way. This is often the case of technology providers who act as a de facto common utility for the network (Lund, et al., 2020).

The ecosystem analysis should also include competitors within the industry as well as correlated industries. If a supplier providing input to two different nodes in the system suffers a breakdown, the company providing it will the least business could be sacrificed in an attempt to minimize damage to relationships with big buyers. Alternatively, a disruption limited to one industry could cause difficulties to other industries that are dependent on the first one. For example, Covid-19 caused ethanol production to decrease because of a drop in gasoline sales. This issue affected the price of the CO2 used by companies producing carbonated beverages, impacting their material costs. (Lund, et al., 2020)

This newfound need for transparency has increased the attention put on the entire chain of suppliers, focusing beyond just a firm's immediate supplier. The episode of medical shortage in North America mentioned in section 2.2.6 emphasizes the need for greater scrutiny and transparency of the complete chain of suppliers, with a proactive effort of information sharing, from initial sourcing to finished products.

Indeed, Choi et al. (2020) testify that "companies that invested in mapping their supply networks before the pandemic emerged better prepared" thanks to the increased visibility into the structure of the chain, which allowed them to benefit from the abundance of information readily available as soon as the disruption happened. This data provides insights on the suppliers, locations, components, and products most at risk, granting a head start in securing inventory and switching production between sites.

A study by McKinsey (Lund, et al., 2020) found that tier-one suppliers are often publicly disclosed, and companies manufacturing complex products, like aircrafts, have the greatest number of tier-one suppliers. However, the study found also that the entire network of suppliers expands exponentially beyond those directly in contact with the company, with a total number that is 7 to 17 times the number of tier-one suppliers, and that more than 33% of disruptions to supply chains occur beyond the second tier.

For instance, the JIT strategy (further described in section 3.2.4 “Increasing stock”) causes the resilience of the company’s production to rely solely on the resilience of its suppliers by minimizing the amount of stock. Therefore, a comprehensive analysis of the reliability of the providers should be conducted. This investigation could reveal that the companies able to grant continuity in adverse conditions are also less convenient economically, or that no agent would be able to withstand a disruption, maybe due to the nature of the industry itself, exposing the company to risk.

The figure below features the characteristics of different structures of supplier networks, highlighting in particular how they promote or hinder resilience.

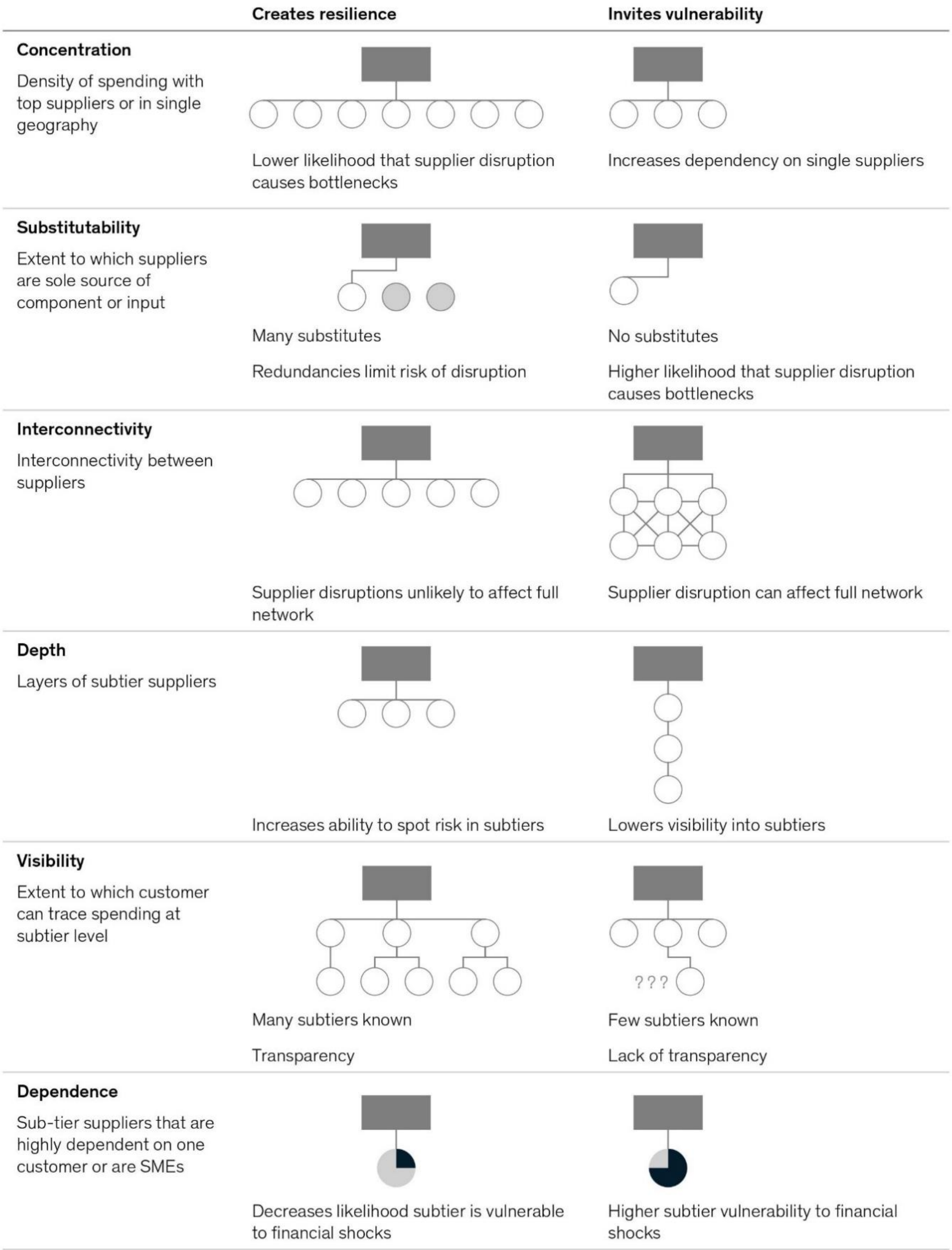


Figure 12 - Impact on resilience and vulnerability of different supplier network structures (Lund, et al., 2020)

3.2.2 Stress testing

Following the financial crisis of 2008, a “bank stress test” was introduced to determine a bank’s financial strength. This assessment consists in running what-if scenarios to check whether an institution possesses sufficient assets to endure times of economic stress. (Pritchard, 2021)

Much similarly, in order to address the risk created by low-probability high-impact events like calamities or pandemics, some economists at Harvard Business Review (Simchi-Levi & Simchi-Levi, 2020) developed a mathematical model useful to understand the risks and impacts associated with disruptions along a supply chain. The model pivots around two main concepts:

- Time to recover (TTR): “the time it would take for a particular node in the supply chain — a supplier facility, a distribution center, or a transportation hub — to be restored to full functionality after a disruption” (Simchi-Levi, et al., 2014). The values identified by this metric are based on historical data and on assessments of buyers and suppliers and can differ across nodes of the supply chain.
- Time to survive (TTS): “the maximum duration that the supply chain can match supply with demand after a facility disruption” (Simchi-Levi, 2015). This second metric was added afterwards due to the tendency of suppliers to be too optimistic about the time needed to recover from an interruption of their normal flow. Therefore, a measure to identify which suppliers’ performance is more sensitive to accuracy in TTR disclosure was needed.

The figure below is a graphical representation of this model as an example, applied to the supply chain of the American automobile manufacturer Ford.

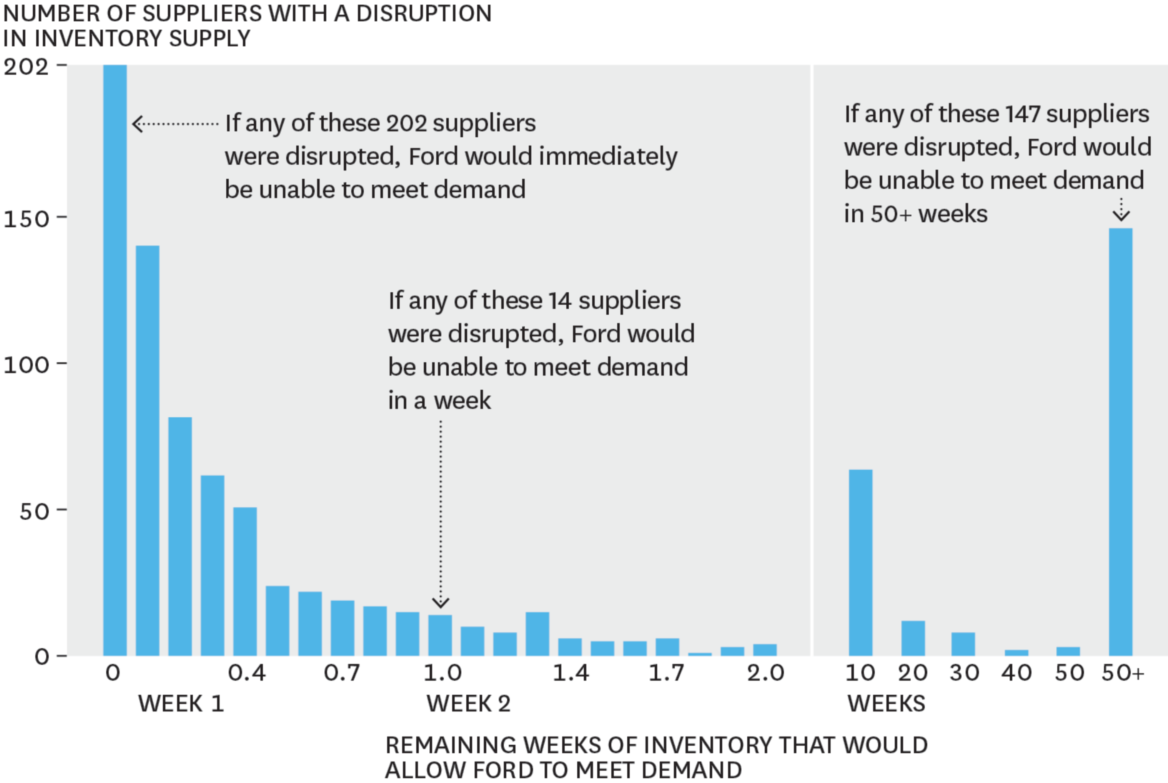


Figure 13 - Example of TTS metric applied to Ford's supply chain (Simchi-Levi, 2015)

The model aggregates the data from the two previously mentioned metrics with any additional information available (bill-of-materials, relationships between actors in the supply chain, inventory levels, etc.), offering a representation of the network of dependencies happening in the supply chain.

Broadly speaking, when the TTS of a specific activity is lower than the corresponding TTR, that node is likely to expose the firm to disruptions because it will not be able to satisfy demand with supply for the entire time needed to recover. Therefore, inventory can be strategically placed where it will cause the TTS to be greater than the TTR “and thus a disrupted node will always recover before it exceeds its ability to apply the mitigation strategies the firm has in place”. (Simchi-Levi, 2015).

More accurately, this model runs scenarios simulating a disruption in one node of the chain at a time, accounting for different levels of severity, determining which type of response would minimize the impact of the disruption on the performance of the firm.

Depending on the optimal response determined (reducing inventory, modifying production, adjusting transportation, etc.) the model offers a financial or operational performance impact (PI) for each node analyzed. This dimension can be embodied by different measures of performance, like units or revenue. The node in the chain presenting the highest loss in performance, and therefore the highest PI, is paired with a risk exposure index (REI) of 1.0, while all the other nodes are assigned values that are relatively computed from this first one, making the overall scale ranging from 0 to 1. These indexed scores allow firms to rapidly identify which activities in the supply chains are most at risk and therefore require the most attention. (Simchi-Levi, et al., 2014)

3.2.3 Diversifying sourcing

Many companies rely on China for raw materials, components, and even finished products, however during the year 2020 it has quickly come to attention that if an entire country shuts down due to a pandemic, several industries are forced to come to a halt. Diversifying to more than one supplier and choosing suppliers from different countries can stem this problem. This is called plus-one diversification, an approach that was already becoming common even before the pandemic, due to the rising cost of Chinese labor and the resulting search for more economically advantageous options. (Zhu, et al., 2020)

For instance, Foxconn, a contract manufacturer of Apple, has decided to start shifting production towards India with an investment of $1 billion to diversify its supply chain needs across multiple regions (GS1 US, 2021).

3.2.4 Increasing stock

One very common and straightforward way to avert a shortage of supply, and therefore a disruption of business, is to increase stock. Many authors in literature, among which Chiaramonti and Maniatis (2020), argue that maintaining a sufficiently large strategic storage is critical to ensure continued business.

The practice of keeping stock in a warehouse has been abandoned in the last decades in favor of lean methodologies and the Just In Time strategy, "an integrated set of activities designed to achieve high-volume production using minimal inventories of parts that arrive exactly when they are needed" (Jacobs & Chase, 2018, p. 18). This approach has many advantages, first and foremost efficiency and cost saving, but it also leads companies to be highly reliant on their supply chain, which is often very far from the company's production site: if the delivery of materials is delayed or there is a shortage, the factory's activities inevitably get halted (Zhu, et al., 2020). The inadequacy of these strategies stems from the use of historical data to forecast production and stock needed, rarely considering the chance of major disruptions like calamities or pandemics happening (Simchi-Levi & Simchi-Levi, 2020).

Therefore, considering the consequences faced due to the Covid-19 pandemic, the JIT approach should be re-evaluated in other to weigh the undeniable positive aspects against the negative ones. Companies should analyze their specific situation, given the industry they belong to and the portfolio of products and services they offer, and question if higher cost efficiency due to no warehousing is worth the loss in resilience. A good compromise could be increasing (or establishing when not present) the buffer amount of stock in order to grant the continuity of production even in the initial phases of an event like the Covid-19 pandemic, where self-sufficiency is a crucial discriminant between losing a high share of business or retaining performance while potentially acquiring the market share lost by other less resourceful competitors.

Indeed, after the first wave of the pandemic, 47% of supply chain executives declared intention to increase the amount of inventory for critical products, and 19.6% plan on keeping more inventory overall (Finances Online, 2021).

Section 1.4 argued good reasons for maintaining an inventory and how this practice can benefit businesses. It also explained how the practice of maintaining a sufficient amount of stock can increase the independence of manufacturing operations from fluctuations in material availability.

3.2.5 Reshoring and domestic production

Even after the emergency has subsided, companies should focus on offshoring towards selected countries near the main production site in China, in order to foster easy communication and exchanges between factories while lowering their dependency and therefore risk exposition. Additionally, by moving part of the production to countries adjacent to China, other states will recognize the opportunity to compete with Chinese suppliers. This would induce legislators to produce policies that would be advantageous to companies attracted by low costs and high diversification, convincing them to externalize inside their territory. (Zhu, et al., 2020)

There would still be the negative aspect of uncertainty: since firms would be investing in unfamiliar countries, they would face an initial learning curve regarding the local culture and how to effectively manage relations with the new branch factories. Even though the risk of the entire region facing a disruption like a total lockdown still exists, the probability of it involving all the factories of a company situated in different states is remote, and either way, it would be impossible to avoid this risk – or any risk – all together. (Zhu, et al., 2020)

Moreover, several firms in the USA moved factories closer to their home country, for example in Mexico, in order to have greater influence and control on their supply. However, this may not always be possible, due to existing binding contracts or difficulty finding similar quality and expertise elsewhere. (Zhu, et al., 2020)

Another option consists in moving production in-house. Chiaramonti and Maniatis (2020), for example, argue that maintaining the availability of necessary supplies that are strategically fundamental heavily relies on the ability to maintain some level of domestic production. Although localizing can be very good for brand image by appealing to ethically conscious consumers that prefer to shop locally or consumers attracted by products made in their home country, and overall increasing the perceived value of products, it also implies much higher costs, both of labor and of materials, requiring a budget that may simply not be available, especially in the short term (Zhu, et al., 2020).

Indeed, a report by McKinsey (Lund, et al., 2020) estimates that between 16% and 26% of global production for export could potentially move to a different location in the future, shifting either to domestic production, nearshoring, or offshoring to a new nation. The main industries involved in this estimate are pharmaceuticals, petroleum, apparel, and communication equipment.

3.2.6 Technological advancements

The pandemic was also the catalyst for the increasing adoption of advanced technology and automation already in motion in recent years. “Technology and data can make supply chains more efficient, so they run more smoothly and deliver greater value to customers, partners and the company.” (Goel, 2021).

Automation

Firstly, introducing more automated machines in factories significantly reduces the need for human labor, since robots can work in unfavorable or unsafe conditions, allowing production to continue even when safety measures mandate fewer workers to be present in the workspace (Zhu, et al., 2020). Additionally, robots are quicker and more effective in carrying out certain tasks, especially when those tasks are dangerous for humans or very repetitive, for instance in industries that are recently gaining more traction like material sorting and upcycling (GS1 US, 2021).

For example, the British online grocery store Ocado, known for its e-commerce and automated warehouse technology which are already being sold to other supermarkets globally, has recently acquired two robotics companies from the US, intending to eventually create a fully automated “dark” order fulfillment center which requires no human presence (Kahn, 2020).

Internet of things

Employing new ways of monitoring processes, like the internet of things, increases efficiency and the flow of information available to higher management, favoring more informed decisions (Zhu, et al., 2020).

According to an article on Forbes (Williamson, 2020), a prediction formulated before the beginning of the pandemic was forecasting more than 5.8 billion endpoints in the Industrial Internet of Things (IIoT) ecosystem by the end of 2020. This technology can prove to be indispensable for companies to face future challenges and disruptions like this pandemic. IIoT sensor networks can provide manufacturers with the data necessary for fast decision-making.

Additionally, thanks to the data offered and the intelligence to analyze it in a valuable way, it can show companies where to concentrate the resource that may be subject to shortages at that moment. Moreover, inventory management systems based on IIoT can potentially reduce inventory levels by as far as 36%. Lastly, since the IIoT ecosystem provides real-time data on supply and especially demand, it offers valuable insights and predictive analytics that are helpful to avoid ripples of the bullwhip effect to cause drawbacks in supply chains. (Williamson, 2020)

Digital twin

One factor that can help companies achieve higher resiliency against disruptions is increasing the visibility during the entire life cycle of a product. This can be done by applying a “persistent identity” to materials, components, and products through a technological tool called “the digital twin”, a technological tool strictly intertwined with the internet of things (GS1 US, 2021).

According to Kritzinger et al. (2018, pp. 1016-1017), the digital twin is "a digital informational construct about a physical system, created as an entity on its own and linked with the physical system in question. [It] should optimally include all information concerning the system asset that could be potentially obtained from its thorough inspection in the real world". This virtual representation is characterized by synchronization between the digital and real version of the system in question through the use of data collected by smart devices, and it's capable of running many simulations using mathematical models and advanced data elaboration.

The authors offer three main areas in which the digital twin can help boost productivity and increase competitiveness:

- Production planning and control: orders can be planned according to statistical assumptions derived from data collected; decision-making can be supported by a detailed diagnosis offered by software; automation of plans and order placing.
- Maintenance: the impact of variations upstream or downstream can be easily pinpointed and assessed to avoid unwanted consequences on processes; preventive maintenance measures can be developed more easily; machine learning algorithms can help with the assessment of the conditions of machinery during the life cycle of products, allowing for more transparency and efficiency of data sharing.
- Layout planning: planning of the production systems is made easier, as well as the evaluation of the current status.

Additionally, three main benefits of applying this technology can be observed: (GS1 US, 2021)

- Ensuring product confidence and authentication
- Augmenting the repair, recycle, and reuse process with comprehensive product history
- Returning the authentic product's materials into the manufacturing process

The importance of the last two advantages mentioned has been analyzed previously in section 3.2.7 "Increasing circularity".

Online stores

Additionally, many companies invested in the creation or improvement of online stores or the presence of their products in online marketplaces to retain sales and appeal to a larger audience given the limitations to travel and mobility. However, this change often requires specialized skills, knowledge, and investments that may not be already available to companies, especially small ones, preventing them from reaping the benefits of this evolution. (Zhu, et al., 2020)

Indeed, according to statistics studies (Finances Online, 2021), during the pandemic "64% of retailers were challenged to adapt their supply chain for e-commerce".

3D printing

Furthermore, new technologies like 3D printing have allowed some companies to quickly adapt production to be able to respond to unexpected changes in demand for specific goods. This is the case of Naturepedic, a company specialized in mattresses, who thanks to 3D printing quickly switched the use of its cotton to produce face masks. (GS1 US, 2021)

3.2.7 Increasing circularity

"When faced with resource shortages, product scarcity, and limited traceability, the supply chain became susceptible to counterfeit goods, compromised quality, and delays in distribution." (Nuce, 2021). Efforts to cope with these issues, and therefore increase the resilience of the supply chain, have been found by a GS1 US (2021) whitepaper to be highly correlated to sustainability and a circular economy.

By increasing the circularity of supply chains companies can increase the productivity of infrastructures, products, and assets since their permanence inside the chain is longer and therefore their derived value higher. This will lead supply chain streams to benefit from remanufacturing new and existing supplies, allowing emerging industries, like secondhand markets and waste miners, to grow their size and importance. (GS1 US, 2021)

Closed-loop supply chains, characterized by the practice of handling returns and upcycling them, were addressed in greater detail in section 1.3.

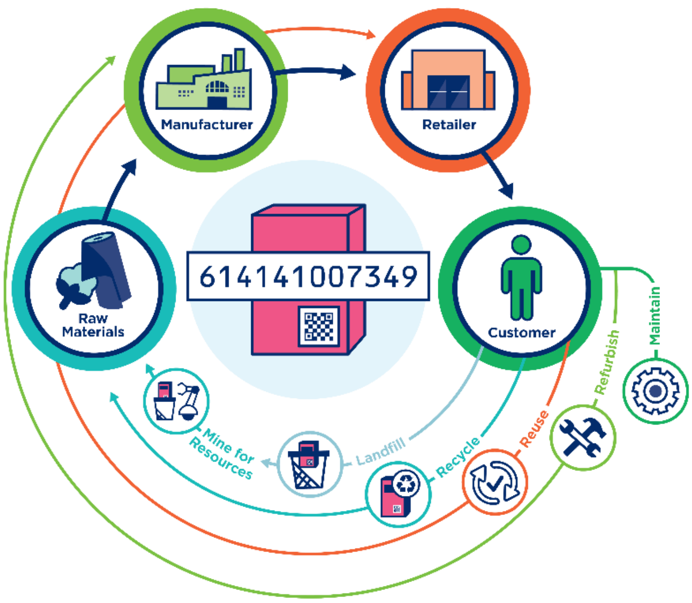


Figure 14 – Circular supply chain (GS1 US, 2021)

Additionally, consumers have shown appreciation for sustainable practices and products, leading to increased brand loyalty and higher demand, ensuring fewer fluctuations in case of disruptions when compared to products deemed more replaceable and less valued by users. (Nuce, 2021)

3.2.8 Altering production

As stated previously, in the case of disruptions, consumption habits change drastically. During an emergency, a rapid and short-term solution for companies who wish to retain their market share might be to alter the span of their product portfolio or the volume of production.

For example, in March, the Italian newspaper Il Sole 24 ORE (Carli, 2020) reported that many companies, especially from the fashion industry, converted their production chain to cover the demand for surgical face masks that skyrocketed soon after the pandemic spread. This change requires a steep level of flexibility that may be harder to obtain if employees receive highly specialized and narrow training that is difficult to expand once the need for it arises.

On the contrary, providing cross-training to most of the organization as a standard practice prepares the company for quick adaptation in time of need and facilitates brainstorming and a multidisciplinary approach among employees, which can be beneficial also outside the scope of a disruption to promote innovative ideas. (Zhu, et al., 2020)

4 Recommending resilience strategies through decision support systems

Since the previous chapter has discussed risk management and practical resilience strategies, it would be helpful to study what scenarios could occur depending on which and how many strategies a company decided to implement, in order to suggest a way to identify the best course of action. Therefore, the current chapter will be dedicated to describing an analytical method that companies could use to determine the best choices to make in order to prevent or mitigate the adverse effect of a disruption.

The basic method that will be described is able to provide maximum added value when the data used is accurate and company-specific, thus requiring unrestricted access to records and information that are hardly granted to individuals outside the organization in order to protect confidential information. The analysis here proposed, therefore, aims at presenting one methodological approach that could aid decision-makers by providing strategic suggestions and insights. Section 4.4 will offer additional observations on the potential of this tool.

4.1 Decision trees

The method analyzed in the following sections is based on decision analysis and in particular decision trees. This technique shows the elements of the decision that has to be made in a clear and straightforward way that highlights the evolution of the issue at hand through time.

This tool is composed of branches (represented by lines), which connect to each other through nodes (represented mainly by squares or circles). Each node symbolizes a point in time. If it is rendered through a square, it is called a decision node and it denotes a time when a decision has to be made. The branches spanning from it represent the options that can be chosen. If it is rendered through a circle, on the other hand, it is called a chance node (or probability node) and it embodies a time when the result of an uncertain outcome becomes known. In this instance, the branches signify the outcome possibilities and are often accompanied by the probability of that outcome happening, which have to sum up to 1. The graph proceeds from left to right indicating time passing, so branches spam from nodes that already happened (on the left) to nodes that haven't happened yet (on the right). (Winston & Albright, 2019)

In this chapter, decision trees will be used as a Decision Support System. DDSs are methodologies used to support the decision-making process using analytical tools. They are usually not completely autonomous, meaning that they are not intended to completely substitute the decision maker since they are based on a blend of factual data, business-specific knowledge, and estimates (Burstein & Holsapple, 2008). Therefore, basing on the data collected and the structure of the tree, the system will suggest a decision path as the most advantageous.

4.2 The general model

Given a generic company called Alpha, the sequence of decisions and outcomes regarding the implementation of three unspecified strategies (X, Y, and Z) can be represented with the decision tree below.

The points in time when Alpha is confronted with a decision are represented by squares, and the two possible outcomes of the choice – in this case implementing or not implementing the strategy in question – are indicated with a green or orange arrow respectively. Hence, company Alpha starts from choosing whether to implement strategy X or not, then, regardless of the outcome of the first decision, proceeds with the same process regarding strategy Y, and then similarly for Z.

It's important to note that for the purpose of this instance, the outcomes resulting from the implementation of each strategy are independent from those related to the implementation of others, meaning that the decision to carry out one plan will not influence the outcome following the implementation of the others. If, for example, the choice to implement or not strategy X was taken after the choice regarding strategy Y, the resulting situations would still cover all the possible combinations. Additionally, the implementation of strategy X does not affect the amount of mitigation arising from the implementation of another strategy or the cost that it entails, and vice versa.

The decision tree with the relative key will now be presented below.

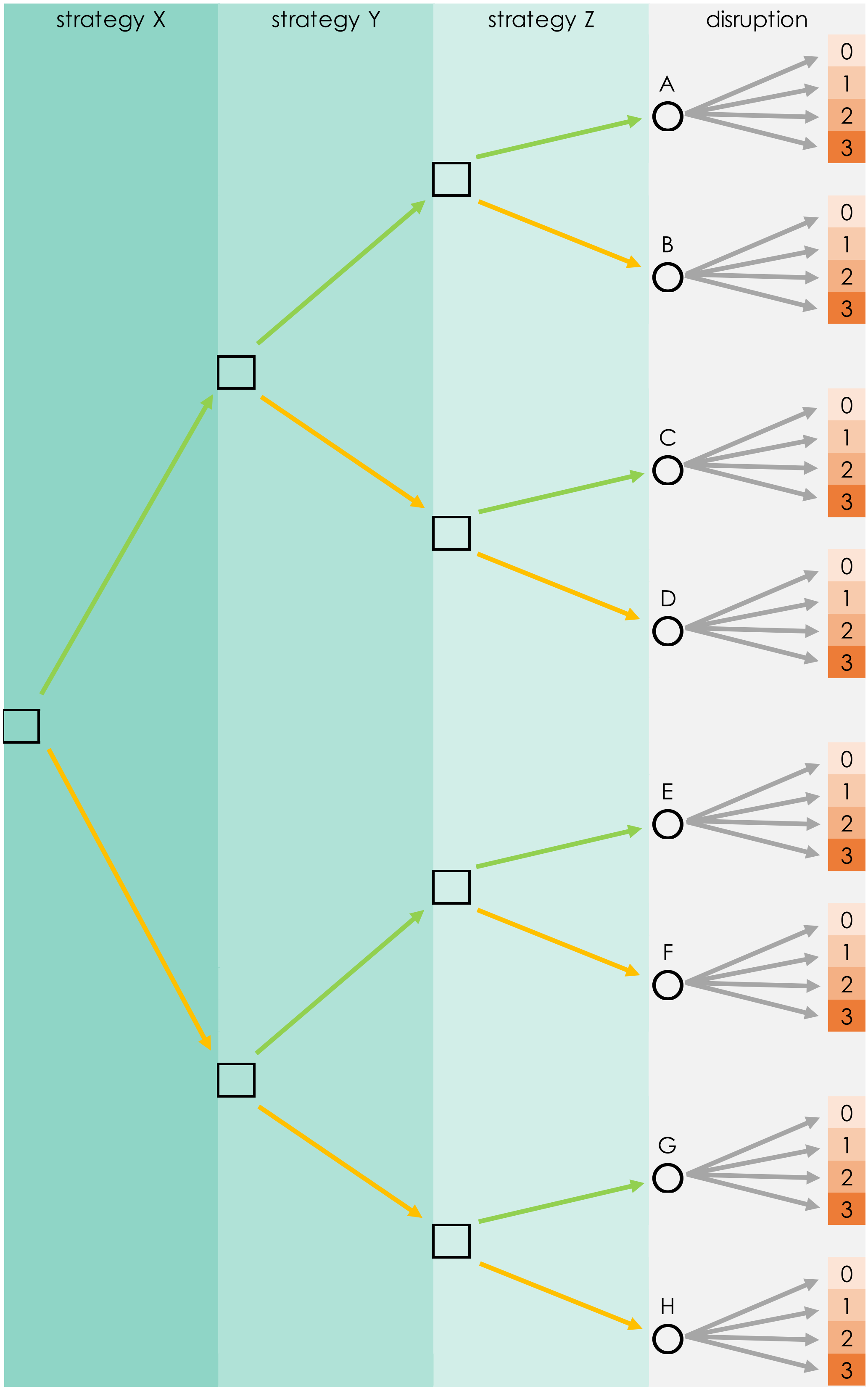


Figure 15 – Complete decision tree (author's elaboration)

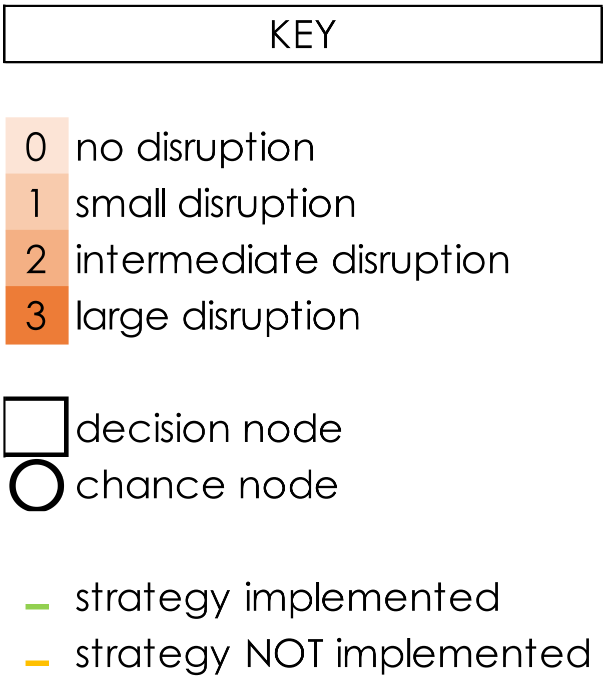


Figure 16 - Key for the decision tree (author's elaboration)

All the possible combinations of choices lead to eight different situations, represented on the right portion of the decision tree with circles and indicated by the letters A through H. They are additionally outlined for clarity in the table below, along with the combination of strategies that are implemented in each one. Therefore, for example, situation F represents the choice to implement only strategy Y but not X or Z. The last column, "σ_N", represents the set populated by the strategies that have been implemented in that situation and it will be used in formulas in the following pages.

Table 2 - Combinations of strategies implemented depending on the situation (author's elaboration)

STRATEGIES IMPLEMENTED				
SITUATION	**X**	**Y**	**Z**	σ_N
A	yes	yes	yes	X, Y, Z
B	yes	yes	no	X, Y
C	yes	no	yes	X, Z
D	yes	no	no	X
E	no	yes	yes	Y, Z
F	no	yes	no	Y
G	no	no	yes	Z
H	no	no	no	Ø

The eight situations coincide with chance nodes. The possibilities after these points are determined by probability. For this model, four outcomes have been chosen as a demonstration, and they consist of four variations of a possible disruption. The first one, 0, identifies the chance of no disruption happening (or a disruption that doesn't affect the company in question in any way), while 1, 2, and 3 represent three intensities of disruption, from weakest to strongest. The same structure of decision tree and similar results would work also considering one disruption, like the Covid-19 pandemic, and the different intensity of impacts that it could have on a company, with the relative likelihood of that impact being sustained.

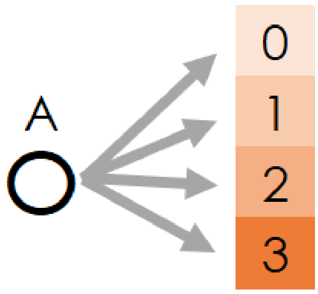


Figure 17 - Close-up of a chance node of the decision tree (author's elaboration)

The illustration will now proceed considering some simplified data, presented in the table below. For the purposes of this model, the revenue will be expressed as a value of 100 with no unit of measure in order to serve as the sole reference for all the values of impact that will be computed later.

Table 3 - Data about the company, possible disruption, and resilience strategies (author's elaboration)

DATA	
Revenue	100

Disruption	**Probability**	**Impact**
0	0,17	0%
1	0,36	6%
2	0,27	20%
3	0,20	51%

Strategy	**Cost**	**Mitigation**
X	1,30%	45%
Y	0,81%	40%
Z	1,44%	50%

Two measures are indicated for each degree of disruption. The first one, probability, indicates the likelihood of the disruption happening. These values are complex to derive due to the nature of the problem. Many factors come into play and many iterations have to be considered when trying to compute the likelihood of a supply chain disruption happening, thus explaining the difficulty of finding precise figures in literature. However, an approximation has been obtained from the study presented by Lund et al. (2020), visible in Figure 9 at the beginning of Chapter 3. The data considered for the current analysis corresponds to the three worse durations of disruption illustrated in the aforementioned study, given that it seems more constructive to consider more severe scenarios for the purposes of this study, along with being numerically more appropriate. According to the report, a disruption lasting two to four weeks can be expected to happen every 2.8 years; one with a medium duration of one to two months occurs every 3.7 years, while a prolonged disruption lasting more than two months can be expected every 4.9 years. These measures have been used as a reference for the disruptions of severity 1, 2, and 3 respectively. From these figures, the probability of occurrence can be computed, dividing 1 by the frequency. The probability of no disruption happening, corresponding to type 0, has been computed by subtracting the three probabilities from 1 to obtain the residual amount, so that all possible outcomes of the chance nodes sum up to 1, as the rules for decision trees require. The table below offers a visual account of this process. Even though this way of deriving probability from frequency is an extremely rough estimate, the high complexity of computing the likelihood of disruptions and the lack of clear figures in literature has required such an approximation.

Table 4 - Calculation of the probability of occurrence (author's elaboration)

Disruption	Frequency (years)	Calculation	Probability
1	2,8	1/2,8	0,36
2	3,7	1/3,7	0,27
3	4,9	1/4,9	0,20
0	-	1-(0,36+0,27+0,20)	0,17

The second value related to each degree of disruption, impact, represents the negative consequences that the company would have to suffer in case the disruption happened, and it's expressed as a percentage of revenue, to keep the measure relative. Unfortunately, a single source providing all the necessary estimates for this figure is nearly untraceable, therefore the specific values related to impact originate from different sources. An article relating to the effect of a six-month disruption of the retail sector (Binlot, 2020) and one related to the impact on small businesses (Arora, 2020) were used as a reference for the impact of a very heavy disruption, type 3. The remaining data for types 1 and 2 has been derived from a report by GEP (Bartels, 2021), while, reasonably, in case of no disruption the negative impacts would be none.

Regarding strategies, on the other hand, the two data presented are cost and mitigation. The first one is expressed as a percentage of revenue, and it represents the cost that the company has to incur to implement the strategy in question. The second one, mitigation, is the positive effect given by the implementation of the strategy, specifically the percentage of reduction of the negative effect caused by the disruption. In the next section, the sources for these two values will be explained in a case study using real data.

All the information presented can now be used to compute the total impact of the disruption on the company, provided visually in the table below.

Table 5 - Overall impact of the disruption differentiated by degree of severity and situations considered, after accounting for the mitigation effect of the strategies implemented (author's elaboration)

OVERALL IMPACT

SITUATION		0	1	2	3	AVERAGE
	A	3,6	4,5	6,9	12,0	6,51
	B	2,1	4,1	8,7	18,9	8,04
	C	2,7	4,4	8,2	16,8	7,68
	D	1,3	4,6	12,3	29,4	11,18
	E	2,3	4,1	8,3	17,6	7,64
	F	0,8	4,4	12,8	31,4	11,58
	G	1,4	4,4	11,4	26,9	10,42
	H	0,0	6,0	20,0	51,0	17,96

Since, as already mentioned, the revenue has been assigned a value of 100, all the values of the overall impact can be considered a cost expressed as a percent of revenue since they are normalized to it. Even with this reasoning, however, the choice of omitting percentage signs for these figures has been motivated by the pursuit of visual clarity.

To compute the values of the overall impact on the company visible in Table 5, the cost of all the strategies implemented has been summed to the negative impact determined by the specific degree of disruption corresponding to that cell. The following formula better explains the process. The key with the interpretation of all the notations can be found below.

$$T_{N,D} = \sum_{S \in \sigma_N} (C_S \times R) + (R \times I_D) \times \prod_{S \in \sigma_N} (1 - M_S)$$

Equation 1 - Formula for computing the total impact of a given situation N for a degree of disruption D (author's elaboration)

Therefore, following the formula above, these steps are performed to compute the total impact T for a determined situation N and degree of disruption D.

Firstly, the percentage cost of a strategy S is multiplied by the revenue, to reach the actual cost of the strategy. This product is done for every strategy that belongs to σ_N and is, therefore, an implemented strategy. All the products are then summed together, and the total value obtained up until now is the total cost of implementing the strategies.

Subsequently, the revenue is multiplied by the percentage impact of the degree of disruption in question, to attain the cost (or loss of revenue) suffered by the company. This measure, however, gets multiplied by another factor to account for the mitigation effect of the strategies implemented, which therefore lessens the total damage inflicted by the disruption. This factor is computed by multiplying together $(1 - M_S)$ for every strategy that is implemented in the current situation. This measure inside brackets signifies the amount of damage remaining after the mitigation, therefore the product provides the overall percentage of damage that is actually inflicted on the company after accounting for the mitigation of the strategies implemented.

The last column of Table 5, on the other hand, is a weighted average and corresponds to the value of overall impact that has been obtained by computing the matrix product of the values of the first four columns by the probabilities indicated in Table 3, as the formula below demonstrates. This provides a comprehensive view of the risk incurred by the company.

$$A_N = \sum_D (T_{N,D} \times P_D)$$

Equation 2 - Formula for computing the average effect of disruptions given the probability of them happening (author's elaboration)

Since, as demonstrated in the previous paragraphs, the values in the impact table are the sum of costs, the most convenient situation will be the one that presents the lowest value. Following this reasoning, color-coding has been added to Table 5, with shades ranging from dark green for low values to yellow for high ones, to provide an immediate and intuitive interpretation of the figures. The formula below translates this concept into mathematical language: it returns the situation N that minimizes the previously calculated average impact. It corresponds to the situation that implies the lowest cost to the firm and, therefore, to the most advantageous.

$$N^* = \underset{N}{\operatorname{argmin}} A_N$$

Equation 3 - Formula for minimizing the average impact (author's elaboration)

In this instance, the recommended situation overall is implementing all three strategies. As expected, in the first column of Table 5, where the degree of disruption considered is 0, the suggested action is not proceeding with any strategy, since it would be wasteful to invest in mitigation if no disruption happened. However, as the degrees of disruption get more severe, therefore moving towards the right in the table, the model advises more and more strongly to implement an increasing number of mitigation plans. Given the percentage of impact of the disruptions considered, this latter trend prevails, resulting in situation A to be suggested based on the average impact column.

Below, a table with the meaning of all the notations used in the formulas is presented. The numeric values of the notations used can be found in the figures and tables situated in the previous pages.

Table 6 - Key of notations used in formulas (author's elaboration)

Notation	**Meaning**
$T_{N,D}$	Overall impact for a specific situation N and a degree of disruption D
N	Situation. Values: A through H
D	Degree of disruption. Values: 0, 1, 2, 3
C_S	Cost of a strategy S, expressed as a percentage of revenue
S	Strategy. Values: X, Y, Z
R	Revenue
σ_N	Set of strategies that have been implemented in a situation N
I_D	Impact of a degree of disruption D, expressed as a percentage of revenue
M_S	Mitigation given by a strategy S, expressed as a percentage of reduction of the negative effect caused by the disruption
A_N	Average impact of the various degrees of disruption for a situation N
P_D	Probability of a disruption D happening

4.3 The model considering synergies

Let us now consider a case, following the same decision tree, where the three strategies are not generic, but specified. In particular, the following have been chosen for this example.

The first strategy consists in increasing stock, as explained in more detail in section 3.2.4. This strategy will be marked in the tables below as “stock”, and it will replace strategy X on the decision tree. The value related to its cost has been obtained from the financial data related to the Italian company Carel SPA, found in the Orbis database (Bureau van Dijk, 2021). The company specializes in control solutions for air-conditioning in the electrical and electronic manufacturing sector, therefore the choice of examining it for this study has been motivated by their heavy reliance on raw materials, which makes them the ideal candidate to identify the cost related to increasing the amount of stock to avoid shortages in the supply of materials.

In 2019, Carel had an inventory amount of €54 million, which rose to €64 million in 2020, corresponding to an increase of 15.6%. The revenue from the same years is €370 million and €400 million respectively, indicating a 7.5% increase. Since the value of the inventory grew more than what would be coherent with the growth in revenues, we can assume that the remaining inventory of 8.1%, which was not used for production, lingered as emergency stock. This amount corresponds to €5.2 million, which equates to 1.3% of the yearly revenues. A summary of this data can be found in the table below.

Table 7 - Data on inventory and revenue for Carel SPA for 2019 and 2020 (Orbis database)

CAREL SPA			
	2019 (mil. €)	**2020 (mil. €)**	**Δ%**
Revenue	370	400	+7,5%
Inventory	54	64	+15,6%

	%	**Mil. €**	**% of Rev.**
Emergency stock	8,1%	5,2	1,30%

The second strategy is diversifying sourcing, addressed in section 3.2.3. It will be referred to as “divers.” in the tables below and will take the place of strategy Y on the decision tree. The cost relating to this strategy was once again obtained by analyzing the data of the Italian company Carel, from the Orbis database (Bureau van Dijk, 2021). In 2018, Carel SPA had costs amounting to €130 million for raw materials. By diversifying sourcing, the company would not be able to benefit from some economic advantages they received from their primary supplier, like bulk discounts and lower prices reserved to long-time trade partners. We could therefore assume a yearly increase of 2% in the cost of raw materials due to this, amounting to €2.6 million and 0.81% of the yearly revenues, which can be used as a reference for the cost of this strategy. Table 8 offers a clearer understanding of this data.

Table 8 - Data on revenue and cost of raw materials for Carel SPA for 2018 (Orbis database)

CAREL SPA

	2018 (mil. €)
Revenue	320

	2018 (mil. €)	**+2% (mil. €)**	**Δ (mil. €)**	**Δ (% of Rev.)**
Cost of raw materials	130	132,6	2,6	0,81%

The third strategy is introducing automation as described in section 3.2.6, which was dedicated to discussing technological advancements. This strategy will be titled "autom." and it will substitute strategy Z on the decision tree. The cost related to its implementation has been obtained from the case of the online grocer Ocado, already mentioned in section 3.2.6 and illustrated in the article by Kahn (2020). The firm acquired in 2020 two U.S. robotics companies, for $262 million and $25 million respectively, to increase the level of automation in its warehouses. Since the value of this acquisition is of technological nature, we can estimate that the investment will have an amortization period of 4 years, which seems a reasonable measure for assets related to innovation. The article also states that the acquisitions will increase the yearly revenues of the company by $38 million, which would amount to $152 million over the period of amortization. Therefore, we can consider the net investment in technology to be the sum of the amounts paid for the acquisitions, minus the expected increase in revenues over 4 years. This value, considered yearly and as a percentage of revenue, equals 1.44%. Once again the following table clarifies the data used.

Table 9 - Financial data for Ocado (Kahn, 2020)

OCADO			
	#1 (mil. $)	**#2 (mil. $)**	**Total (mil. $)**
Acquisitions	262	25	287

Amortization period (years)	4

	Yearly (mil. $)	**Over amort. (mil. $)**
Exp. increase in revenues	38	152

	2019 (mil. $)	**Exp. 2020 (mil. $)**
Revenue	2300	2338

	Total (mil. $)	**Yearly (mil. $)**	**% of Rev. (mil. $)**
Net investment	135	33,75	1,44%

The peculiarity of choosing these strategies is that the first two, increasing stock and diversifying sourcing, belong to the same impact area, supply management. This implies that the mitigation resulting from their implementation is not independently related: adopting one will influence the amount of mitigation of the other. Therefore, the figures related to mitigation have been considered differently for the two separate strategies and then for the case in which both strategies are implemented at the same time.

Additionally, for this instance, the intensity of disruption has been considered in terms of both duration and impact on revenue. Therefore, a disruption of degree 1 will be a short interruption of business that causes small losses, while one of degree 3 will be a prolonged disturbance with heavy losses. Consequently, the amount of mitigation has now been considered variable depending on the degree of disruption in question, since the efficacy of the strategies considered varies depending on the length of the disruption that they have to mitigate.

In particular, increasing stock will be fairly effective at mitigating a short disturbance, but this effect will sharply decrease as the time length of the damage increases, since additional inventory would eventually run out and it could be difficult to replenish due to prolonged supply interruption caused by the negative event.

The same can be argued about the diversification of sourcing, despite presenting a less sharp decrease of effectiveness: having a diversified supplier portfolio would allow the company to not halt production completely due to lack of parts, but it’s unlikely that during a prolonged disturbance suppliers would be able to maintain an intensified production sufficient to compensate the loss of the suppliers who were affected by the disruption.

Implementing both will not imply much of a premium during a short disruption when compared with implementing only one of the two, since just one or the other is enough to satisfy the supply needs over a short amount of time. As the length of the disruption increases, however, having implemented both will pose a great benefit, since their combined mitigation will allow a company to grant the continuity of most of the business.

Introducing automation, on the other hand, would reasonably grant the same mitigation effect no matter the duration of the disturbance, since its benefits stem from two main reasons: firstly, automated machinery can adapt labor efforts to the needs of the company; and secondly, it can continue production when the disruption causes circumstances that would create problems for businesses that rely on human labor, such as impediments to public transportation that would hinder commuting or restrictions on assembly inside factories.

Table 10 shows all the values that will be considered for this section. Besides mitigation, which will be discussed below, the remaining data has been kept equal to the data used for the general model.

Table 10 - Data about the company, possible disruption, and specific resilience strategies (author's elaboration)

DATA

Revenue	100

Disruption	**Probability**	**Impact**
0	0,17	0%
1	0,36	6%
2	0,27	20%
3	0,20	51%

Strategy	**Cost**
stock	1,30%
divers.	0,81%
autom.	1,44%

Once costs for the strategies considered have been established, their mitigation can be discussed. Table 11 presents the amounts of mitigation expressed as percentages of reduction of the negative effect caused by the disruption, for the single strategies plus the case of both increased stock and diversification implemented at the same time, and the aggregate value for each combination of situation and degree of disruption.

Unfortunately, the search for a reference for this value has yielded no satisfactory results since the Covid-19 pandemic is still ongoing at the time of writing and, even considering other disruptions that happened in the past, finding a figure that could be universally adequate has proven to be challenging. The amount of mitigation that the strategies considered can offer against the degrees of disruption examined is extremely company-specific, therefore an accurate value would be difficult to find without considering a determined company and tailoring the entire analysis on it, asking managers and decision-makers to provide precise data. For these reasons, the numeric amounts indicated in the tables below consist of a reasonable estimate to serve as exemplification, analogously to the ones offered for the general model. As already mentioned previously, the focus of this analysis rests more on the methodological approach examined rather than the specific data used, since precise figures would need to be considered on a case-by-case basis.

Table 11 - Amount of mitigation accounting for synergies (author's elaboration)

MITIGATION WITH SINERGIES

STRATEGY	MITIGATION 0	1	2	3
stock	0%	60%	45%	30%
divers.	0%	45%	40%	35%
stock + divers.	0%	65%	75%	80%
autom.	0%	50%	50%	50%

SITUATION	AGGREGATE MITIGATION 0	1	2	3
A	0%	83%	88%	90%
B	0%	65%	75%	80%
C	0%	80%	73%	65%
D	0%	60%	45%	30%
E	0%	73%	70%	68%
F	0%	45%	40%	35%
G	0%	50%	50%	50%
H	0%	0%	0%	0%

The amounts in the aggregate mitigation table above have been derived by either plainly reproducing the value from the upper table, which shows the mitigation amounts for each strategy, or by combining two values of mitigation where applicable. For example, situation A entails the adoption of all three strategies, therefore the values used will be the one related to the row of "stock + divers." since both strategies are implemented and thus the value that considers synergies has to be used, and the one related to "autom.". These two measures are aggregated using the formula below, where M_T is the total mitigation obtained and M_1 and M_2 are the two mitigation amounts to be combined.

$$M_T = 1 - (1 - M_1) \times (1 - M_2)$$

Equation 4 - Formula to aggregate the amount of mitigation for different strategies (author's elaboration)

The data presented above can now be used to compute the total impact of the disruption on the company, presented in the table below, using the same formulas presented previously for the general model in section 4.2.

Table 12 - Overall impact of the disruption differentiated by degree of severity and situations considered, after accounting for the aggregate mitigation effect of the strategies implemented (author's elaboration)

OVERALL IMPACT

		0	1	2	3	AVERAGE
SITUATION	A	3,6	4,6	6,1	8,7	5,64
	B	2,1	4,2	7,1	12,3	6,29
	C	2,7	3,9	8,2	20,6	8,30
	D	1,3	3,7	12,3	37,0	12,42
	E	2,3	3,9	8,3	18,8	7,84
	F	0,8	4,1	12,8	34,0	12,00
	G	1,4	4,4	11,4	26,9	10,42
	H	0,0	6,0	20,0	51,0	17,96

Now an interpretation of the results obtained, analogous to the one seen in the previous section, can be performed. As observed previously, the column concerning the average impact in Table 12 highlights what the total costs associated with each situation are. The most convenient combination of strategies to implement, due to the formulas used, will be the situation presenting the lower cost. Therefore, given the data employed, the overall most convenient situation according to the model is A, i.e., implement all strategies. As seen before, the number of implementations advised increases with the impact of the disruption considered: column 0 suggests no strategies, 2 suggests only a partial implementation, while 2 and 3 will suggest a complete adoption.

4.4 Additional considerations

As stated at the beginning of this chapter, the method proposed aims at providing an exemplification of how the implementation of resilience strategies can be analytically considered to assess its feasibility and worthiness. Therefore, it should be seen as a template to be customized by companies to fit their specific needs.

For this reason, this section will now offer some considerations regarding the proposed analysis, in order to provide reflections on the assumptions utilized, insights into possible additional variables to factor in, and a more comprehensive view on the potential applications of this study.

As previously explained, the overall impact is computed by summing the cost related to each disruption multiplied by the chance of that disruption happening. However, this approach could be considered the most appropriate only for some companies. For example, firms focused mainly on short term horizons, like start-ups, could prefer focusing on strategies that mitigate only the most likely disruption, therefore choosing to ignore the risk posed by events with lower probabilities which are likely to happen with a frequency that makes them almost irrelevant to the short-term focus of the company. This means that the situation most convenient in this case according to company managers would probably not coincide with the situation derived by minimizing the last column in the overall impact table, corresponding to the average values. In this instance, the most suitable course of action could be, for example, considering only the column of the disruption of type 1, being the one with the highest probability and therefore most likely to happen in a short time horizon, and finding the best situation among those values. Other companies, on the other hand, could find it more appropriate for their strategical attitude to disregard the column of the disruption of type 1 and base their decisions only on the possible impacts caused by the more severe hazards. This could be the case if the nature of the company or the industry in which it operates already intrinsically implies a level of protection from the negative consequences of short or mild incidents.

Another interesting variable that could be added to enhance and customize the analysis is a study of the structure of the investments required to implement the strategies. The formulas used in the previous sections didn't differentiate between a fixed initial cost or a deferred payment, they simply considered the total expense related to that strategy. However, some companies might value more positively strategies that require many small investments due to their lack of liquidity, while others could prefer impacting the bottom line of the income statement all at once on the year of implementation and then going back to the ordinary level of profits in the following years.

Additionally, it could be insightful to take into consideration different degrees of implementation of the strategies. In this case, the decision tree would not present just two outcomes (implementing or not implementing) spanning from the decision nodes, but possibly others depending on how many degrees of implementation one wishes to consider. Options could be, for example, hard, soft, or no implementation, contingent on variables like intensity or exhaustiveness. In the case of increasing stock, this could mean by how much the inventory is expanded. When taking into consideration technological advancements, on the other hand, this could imply how much of the business or supply chain is equipped with the new technology. Depending on the specifics of the company considered, it could prove valuable to implement many strategies to some degree to acquire a broad, even if incomplete, protection from disruption. Alternatively, for businesses strictly intertwined in the network of the industry they work in, the best option could prove to be implementing thoroughly only sector-specific strategies and disregarding the others.

Additionally, managers could find it useful to enrich this study by performing a sensitivity analysis on key variables to investigate the impact of their change on the overall results.

For example, it could be useful to compute the minimum amount of mitigation that each strategy would have to offer in order for the implementation of that strategy to be advisable. Since this value would probably be difficult to measure with a high degree of accuracy even having unrestricted access to company records, this type of investigation could reveal how much margin of freedom the company has. For instance, if the analysis revealed that by decreasing the mitigation effects by just a few percentage points the implementation of that strategy was no longer advisable, then the company could choose to not implement it since there is a possibility of error in the input data. On the contrary, if adoption was recommended even with much lower values of mitigation, then managers could more confidently decide to proceed with that strategy.

Similarly, it could be interesting to investigate the maximum costs of the strategies that would still make their implementation the most convenient situation. This investigation could be paired with the different degrees of implementation of the strategies discussed in a previous paragraph in this section. For instance, increasing stock might not be advisable to the extent initially considered, since it implies too high of a cost. However, the sensitivity analysis could reveal that if the required investment slightly decreased, then this procedure would be advantageous. Therefore, the company could increase stock by an amount lower than initially planned to fully reap the benefits of this strategy. Additionally, if the analysis showed that a minor increase in the cost would no longer advise implementation, then decision-makers could focus efforts on ensuring that expenses stay within predicted amounts by, for example, stipulating contracts with involved actors. This supposition is especially relevant for instances with deferred payments or upkeep costs, where the likelihood of a variation in costs is higher since part of them rests in the future.

Conclusions

People innately tend to underestimate the likelihood of negative events happening, preferring to focus on the short term and ignore the distant future. Empirical evidence of this is provided by the tendency of individuals involved in business decisions to focus primarily on yearly or even quarterly results. Managers, by receiving year-end bonuses depending on their performance during this period, will be incentivized to concentrate on the short term for the sake of their own personal gain. Similarly, shareholders are interested in the returns they receive annually from the company's results. This means that both of these categories will naturally be inclined to want to avoid investments that, to protect against uncertain future events, will surely impact the company's results in the short term.

This thesis provided an overview of the significant impacts that the Covid-19 pandemic has caused to economies and businesses around the world. In particular, it demonstrated the high exposure to risks of supply chains by analyzing the many different ways in which they can be affected by disruptions, providing also practical examples and statistical data. This proved just how pervasive the effects of a seemingly small negative event can be.

Additionally, it offered an account of how companies can improve their resilience. This was done by firstly revising the ways in which risk management has been theorized, therefore attesting to the importance of this process. Secondly, it illustrated strategies gathered from literature and real-life cases which can lower the risk exposure of firms, focusing mainly on tactics based on prevention, requiring, therefore, a precautionary implementation that would safeguard the company from possible negative events in the future.

Lastly, it demonstrated how analytical tools can support the decision-making process and help understand which actions improve the resilience of businesses the most. Particularly, it firstly offered a basic illustrative analysis to present the method, using a sample approach based on decision trees. Later, it moved to a more concrete study using real-life data, considering three strategies that were described in the previous chapter. This way, the viability and usefulness of their implementation were discussed, analyzing the benefits they offered against the investment they required, to prove when their application was convenient for the company. Lastly, by providing several additional considerations and possible variables to add to the analysis, this thesis illustrated how these instruments can be tailored to the needs and attributes of specific companies, therefore proving their broad adaptability and significant value.

This study demonstrates that an increased focus must be put on the resilience of companies and in particular of supply chains, for the gain of all economies and businesses. Additional studies are required to clarify the features of possible resilience strategies, in particular on the protection they offer against different types of disruptions and on which companies could best benefit from them.

Hopefully, the events of the last two years will raise awareness on the importance of being prepared for every occurrence and on how, in this deeply interconnected world, one seemingly small occurrence can quickly spark a chain of events leading to disruptions of global scope.

References

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