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4 Introduction

4.1 Supply Chain Vulnerability

Supply chain management organises and directs the flow of information, products and services through networks of customers and suppliers (Russell and Taylor, 2019). Supply chain management controls the supply chain to meet the needs of the business (Lambert and Cooper, 2000). Without a reliable supply chain, the business cannot supply its customers reliably (Croxton *et al.*, 2001).

As supply chains stretch over long distances and multiple locations throughout the world, uncertainty and risk increase, and lean supply chains cannot provide enough slack to support supply chain disruptions (Rivera *et al.*, 2007). Innovative companies engage in formal risk management to cope with supply chain uncertainty; the first step in implementing risk management is understanding supply chain risks and vulnerability (Berger, Sorensen and Rasmussen, 2010).

Supply chain vulnerability is the weaknesses and threats present in the supply chain (Peck, 2006). Supply chain risk management is required to understand and anticipate supply chain disruptions, including the likelihood and possible impact (Finch, 2004). Supply chain disruptions can be categorised as; operational, economic, marketplace, political, or natural. As many supply chains are global, disruptions can be caused by impacts that are far removed from the customer (Storey, Emberson and Reade, 2005)

Supply chain resilience is the speed and capability to recover from supply chain disruptions (Pettit, Fiksel and Croxton, 2010). The business should be flexible and adaptable to unavoidable supply chain disruptions and remove sources of vulnerability when possible (Scholten and Schilder, 2015).

4.2 Dow Silicones Supply Chain

Dow Silicones is a subsidiary of the Dow Chemical manufacturing company. Dow Silicones comprises three pillar production sites that manufacture silicone-based products; Barry UK, Carrollton USA, and Zhangjiagang China. The primary raw material for silicone products is silicon metal. Silicon metal is mined and processed in a refinery before being shipped to one of the Dow Silicones sites.

Silicon metal is purchased and shipped in 20ft sea containers containing 23 tonnes of metal. The Barry site consumes 6,700 tonnes of silica every month, requiring 9-10 containers a day to meet current site production rates.

All three silicon manufacturing sites purchase silicon from the same suppliers. A feedstocks team manages the silica supply for all three sites to balance the cost of raw materials, supply duration and supply reliability evenly amongst all three sites; this optimises the supply chain model based upon profit rather than geographical convenience.

Dows silicon suppliers are based in Brazil, China and Europe. Brazil has four sites that supply silicon; Dow owns two, and two are third party suppliers. The China supplier is a third party company; Europe has three silicon suppliers based in Norway, France and Spain. The Carrollton site also has a third party supplier in Canada; the other two Dow Silicones sites do not use this supply.

Silicone is an abundant raw material and can be found almost anywhere on earth; however, silicon mines and refineries are often located to utilise low-cost labour and energy. Therefore, they are predominately located in East Asia and South America. Table 1 illustrates the silicon suppliers currently used by the Barry site and how the first quarter (Q1) supply for the site is currently distributed between suppliers.

Table 1- Dow Silicon Barry Site Current Supplier List

Supplier	Supplying site	Source Country	Normal Port of Entry	Q1 2022 Supplier Split
Dow	Chabang	Brazil	Tilbury/Southampton	5%
Dow	Breu Branco	Brazil	Tilbury/Southampton	12%
Dalian	-	China	Southampton	0%
Elkem	-	Norway	Tilbury	5%
Liasa	-	Brazil	Tilbury	68% combined
Minas Ligas	-	Brazil	Tilbury	
Rima	-	Brazil	Tilbury	
FerroglobeFP	-	France	Portbury	5%
Ferroatlantica	-	Spain	Portbury	5%

In Q1 2022, most of the Barry sites silicon supply is from the four Brazilian suppliers. The metal is transported from the manufacturing site to the port in Rio de Janeiro. The material is shipped to Antwerp by the Mediterranean Shipping Company (MSC). MSC's specialist route is Rio de Janeiro to Antwerp, and they have been the largest container shipping company globally since 2021. Multiple shipping companies transport the product to Tilbury from Antwerp, this is a regular shipping route, and the carrier is chosen based on the next available shipment. Once in the UK, the Barry site has more control of the supply chain and final transportation method. Typically, the material is transported from Tilbury by train to Barry Docks; there are currently two trains a week. The material is stored at Barry Docks, and individual containers are driven to the site (<1 mile) and fed into the process. The last leg of the process from Tilbury is managed and completed by Associated British Ports (ABP), who have had a longstanding contract with the Barry site. This supply chain takes two months (on average) from door-to-door.

If necessary, the Barry site can expedite material from Tilbury in less than 24 hours; currently, it costs £1,000 per container. The material is expedited by road; this has become possible since Brexit, previously EU regulation limited the weight for road transport, preventing the containers from being transported this way.

ABP have storage facilities at Barry docks that the site utilises for silica storage. The storage facility can hold 9,000 tonnes of silica; however, the site targets an inventory level of 5,000-6,000 tonnes, around 20 days of production supply. This level has been chosen as a business decision to balance supply chain risk against capital investment, silica metal is the most expensive product in silicone manufacturing, and low working capital is a business fundamental of Dow. There are no special requirements for silica storage; it remains stored in shipping containers.

Dow employs a Just In Time (JIT) principle for inventory management to reduce unnecessary and unprofitable capital investment in inventory. This methodology works well and has been optimised by the feedstocks team; however, problems occur when actual delivery times do not meet expected delivery times. The JIT system does not contain enough buffer to adapt to unreliable raw material supply. Dow Silicones suffer from supply chain vulnerability on all three production sites. The whole supply chain is at capacity; therefore, minor delays may result in more considerable delays as alternative transport solutions are unavailable. This knock-on effect can result in extensive delays and significant financial intervention to resolve.

5 Critical Evaluation of Supply Chain Vulnerability

5.1 Supply Chain Management

Supply chain management organises and directs the flow of information, products and services through networks of customers and suppliers (Russell and Taylor, 2019). Supply chain management controls the supply chain to meet the needs of the business (Lambert and Cooper, 2000). Businesses have varying demands for their supply chain; these include cost targets, environmental requirements, speed of delivery, ability to transport a variety of product sizes and weights, as well as potentially hazardous products; however, all businesses have a unified requirement for the supply chain to deliver the goods on time (Werner, 2013). Without a reliable supply chain, the business cannot supply its customers reliably (Croxtan *et al.*, 2001).

If a business suffers from poor supply chain reliability, it will negatively affect the customers. Consequences of poor customer supply include loss of reputation, loss of repeat business, contractual penalties and product shortages (Hendricks and Singhal, 2005). In some industries, poor supply chain reliability can lead to social consequences such as food shortages, fuel shortages, building materials and other goods that are foundational to society (Institute for Government, 2021).

A survey conducted by The Economist and GEP (2021) studied the business costs of supply chain disruption. The survey was conducted in 2020 on 400 senior supply chain and procurement executives in five sectors (healthcare and pharmaceuticals, agriculture and food, consumer goods and retail, heavy industry, and energy and utilities). The respondents are based in eight countries across the US and Europe (UK, Belgium, Ireland, France, Luxembourg, Germany, and the Netherlands). Figure 1 illustrates the impacts that have been seen as a consequence of supply chain disruption (% of respondents).

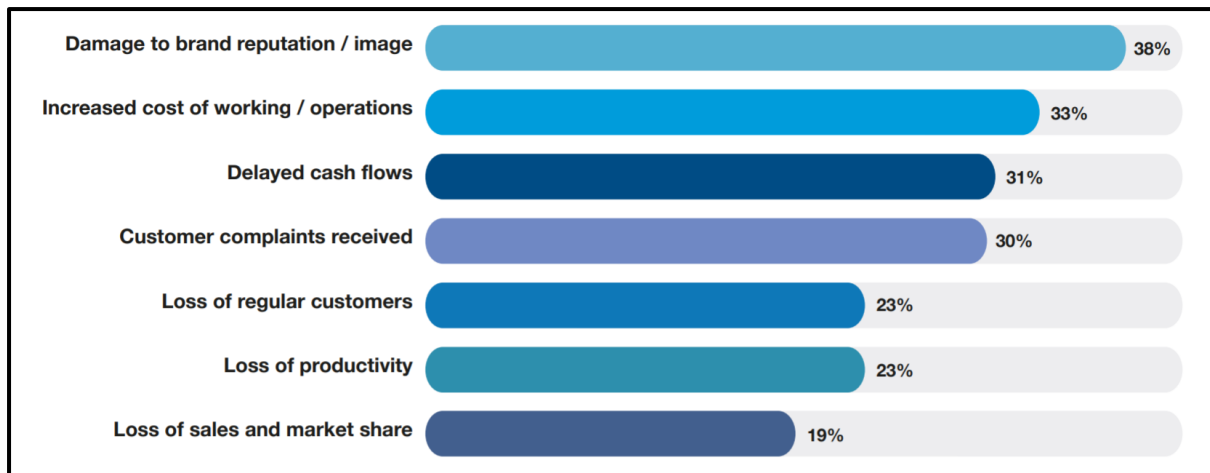


Figure 1- Consequences of Supply Chain Disruptions since 2019 (Piatek, 2021)

Poor supply chain reliability can be compensated for through holding large volumes of stock (Tomlin, 2006). Holding large amounts of inventory absorbs business capital and reduces cash flow (Callioni *et al.*, 2005). Reduced cash flow may force the business to require loans that accrue interest (Lev and Weiss, 1990). Reduced cash flow may also prevent the business from taking advantage of opportunities that require capital investment (Jones and Tuzel, 2013). Stockpiling also causes storage issues; appropriate storage needs to be found for extra inventory. Storage space costs money to purchase or rent and upkeep costs such as heating, lighting and manning (Hughes, 1984). If existing floor space is consumed through stockpiling existing products, this can prevent the business from supplying new products to customers due to storage capacity issues (Sepehri, 2011). External and internal factors can affect the value of the stockpiled inventory. The value of a product may change whilst it is in storage; this provides risk to the business; stockpiling inventory differs from inventory investment as the decision was not made based on the probability of the stock's value rising (Hartman and Dror, 1996). Internal factors that devalue the stock can be caused by reducing the cost of the stock if product sales and consumption is lower than predicted (Park, 1982). Inventory can become obsolescent when in storage; this can cause a dramatic reduction in value, as well as technical obsolete, stock can also suffer from changing trends reducing desirability, and products expiring (Lee and Billington, 1992).

Increasing inventory will never resolve the issues of poor supply chain reliability; it can only buffer downstream to customers (Lee, 2002). Appropriate management systems should be put in place to ensure supply chain reliability (Thomas, 2002).

Supply chain management has become more prominent and essential to business since the globalisation of supply chains, centralised distribution centres, outsourced suppliers and fluctuations in supply and demand (Waters, 2011). As businesses have become more efficient and implemented systems such as Just In Time and Lean, the need for supply chain reliability has increased (Phil, 2018).

Lean manufacturing identifies inventory as one of the nine forms of waste; lean is a continuous improvement methodology, lean manufacturing intends to eliminate all forms of waste from the process (Wilson, 2015). A lean process should increase throughput, reduce operating expenses, reduce lead times, decrease inventories, and improve supply chain responsiveness (Feld, 2000). Just In Time (JIT) is a fundamental principle of lean manufacturing (Benton Jr, 2010).

JIT emphasises stocking low but essential inventory; the principle is based upon receiving inventory at the same rate at which it is consumed; therefore, it is always available but never overstocked (Smith, 2019). Safety stock is not accounted for with JIT; supply and demand fluctuations can easily result in zero stock occurrences that can stop production or leave customers with extended waiting times (Jordan, 1988). JIT inventory management can provide the following benefits:

- Reduced wastage
- Improved efficiency
- Increased productivity
- Optimised production
- Reduced costs
- Improved quality

(Epps, 1995)

5.2 Supply Chain Vulnerability

As supply chains stretch over long distances and multiple locations throughout the world, uncertainty and risk increase, lean supply chains cannot provide enough slack to support supply chain disruptions (Rivera *et al.*, 2007). Innovative companies engage in formal risk management to manage supply chain uncertainty; the first step in implementing risk management is understanding the supply chain risks and vulnerabilities (Berger, Sorensen and Rasmussen, 2010).

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5.2.1 Operational Vulnerability

Operational vulnerability is the flaws in how the business has built its supply chain (Peck, 2006). Disjointed workflows and management systems are self-inflicted vulnerability and include:

- Poor supplier choices
- An overcomplex supply chain
- Poor control of the supply chain
- Outsourcing
- Poor contractual agreements
- Single sourcing
- Focus on efficiency rather than effectiveness
- Decreased vertical integration
- Just In Time (JIT) initiatives

(Burkhardt, 2021)

Further operational vulnerability can be caused by an inability to predict product demand accurately and forecast the correct amount of materials from suppliers for future orders (Brockhoff and Rao, 1993). Poor demand prediction can cause the bullwhip effect through the entire supply chain with the error magnified at each stage; this may result in a situation of feast and famine of inventory supply, illustrated in Figure 2.

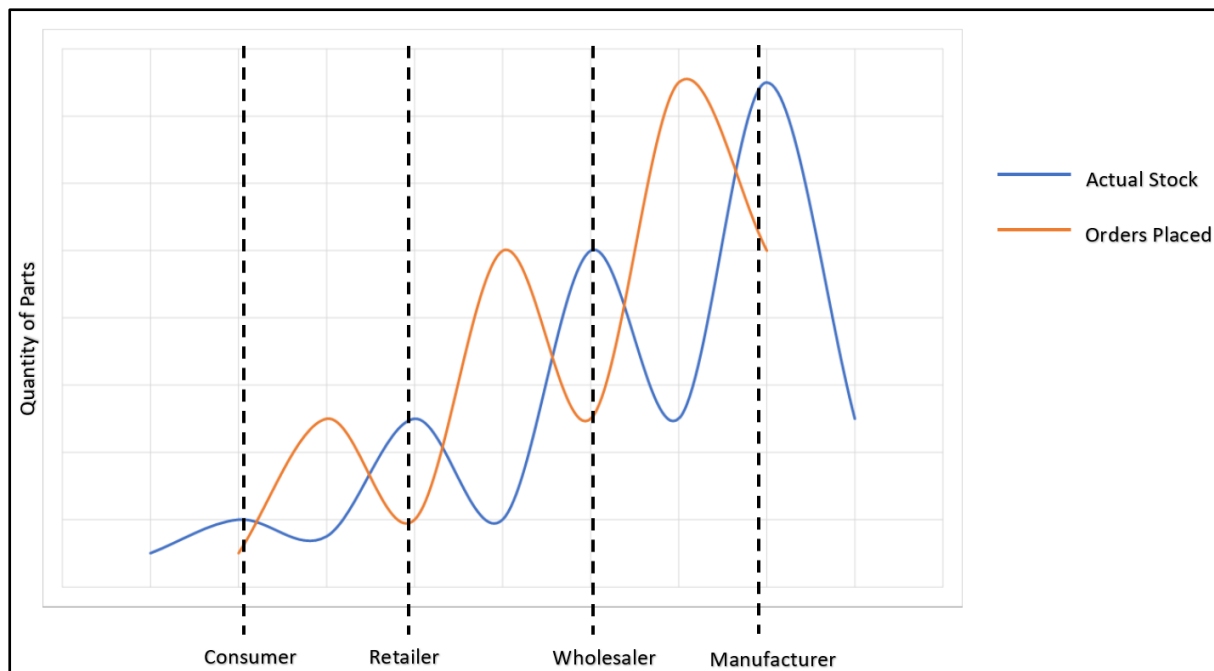


Figure 2- The Bullwhip Effect (Bray and Mendelson, 2012)

Shipping delays are a significant contributor to operational vulnerability and are often outside the business control (Miller, 1971). Shipping delays can occur in any part of the door to door delivery of products and have many causes (Lambert, 1992).

The March 2021 Suez Canal obstruction and significant backlog is a shipping delay that heavily affected Dow Silicones Barry site. At the time the site was importing 50% of its silicon supply from Chinese suppliers, the shipping route utilises the Suez Canal. Due to the short notice of the delay, Dow was unable to import extra material from other suppliers; this raw material shortage resulted in lost production for the site.

A further shipping delay to affect the Dow Silicones Barry site in February 2022 is a broken lock gate at Portbury. Currently, 10% of the silicon metal is shipped through Portbury, which cannot receive shipments; the shipping company has arranged diversion and offloading at Liverpool docks; however, Dow must arrange specialist pick up at additional costs and duration.

UK shipping delays have increased since 2020 due to Brexit; there are various reasons why Brexit has impacted supply times to the UK; however, they can be summarised as a lack of clarity from the government to allow the business to adapt to changes in import legalisation (Braakman, 2017).

Documentation is one of the most consistent causes of shipping delays into the UK (Notteboom, 2006). The complexity of documentation required to import and export from the UK since Brexit has caused an increase in shipping delays (Bows *et al.*, 2012). Documentation related to Brexit has caused shipping delays for Dow Silicones Barry; all raw material imports transit through the EU to the UK; however, import duty only must be paid on the value of raw material processed and sold back into the EU. The value of the import that is processed and then sold outside the EU is not subject to import duty. Due to the large volume of raw material constantly imported, it is essential to get the import duty correct as variation could cost the business a large sum of money or result in tax evasion.

Labour constraints have been a contributing factor for shipping delays. Labour shortages are prominent throughout the transport chain; warehouses, drivers, dockworkers, rail workers, and shipping lines (Nagurney, 2021).

5.2.2 Economic and Marketplace Vulnerability

Economic and marketplace vulnerability can arise from the business's economic strength; this can be caused by changes in the marketplace or in the business itself. One major cause of marketplace vulnerability is the cost of commodities such as energy and fuel (Butner, 2010). Fuel is one of the most significant overheads in the supply chain, and volatile fuel prices can force logistics companies to increase prices or incur losses (Brown and Thies, 2009). This change in profitability can cause delays in shipping or force businesses to close (Rodrigues *et al.*, 2008).

An increase in demand for shipping is another cause of economic and marketplace vulnerability. Demand for shipping has been increasing steadily for ten years; however, a massive spike in demand occurred in January 2021 caused by the Covid 19 pandemic, limited alternatives to shipping freight, port closures in China, changes to shipping regulations, global equipment imbalances and driver shortages (Krantz *et al.*, 2022). It has not been possible for the shipping industry to increase its capacity to match the increase in demand; therefore, availability decreases, and prices rise following demand (Corbett and Winebrake, 2008). Figure 3 illustrates the increase in shipping costs since 2019.

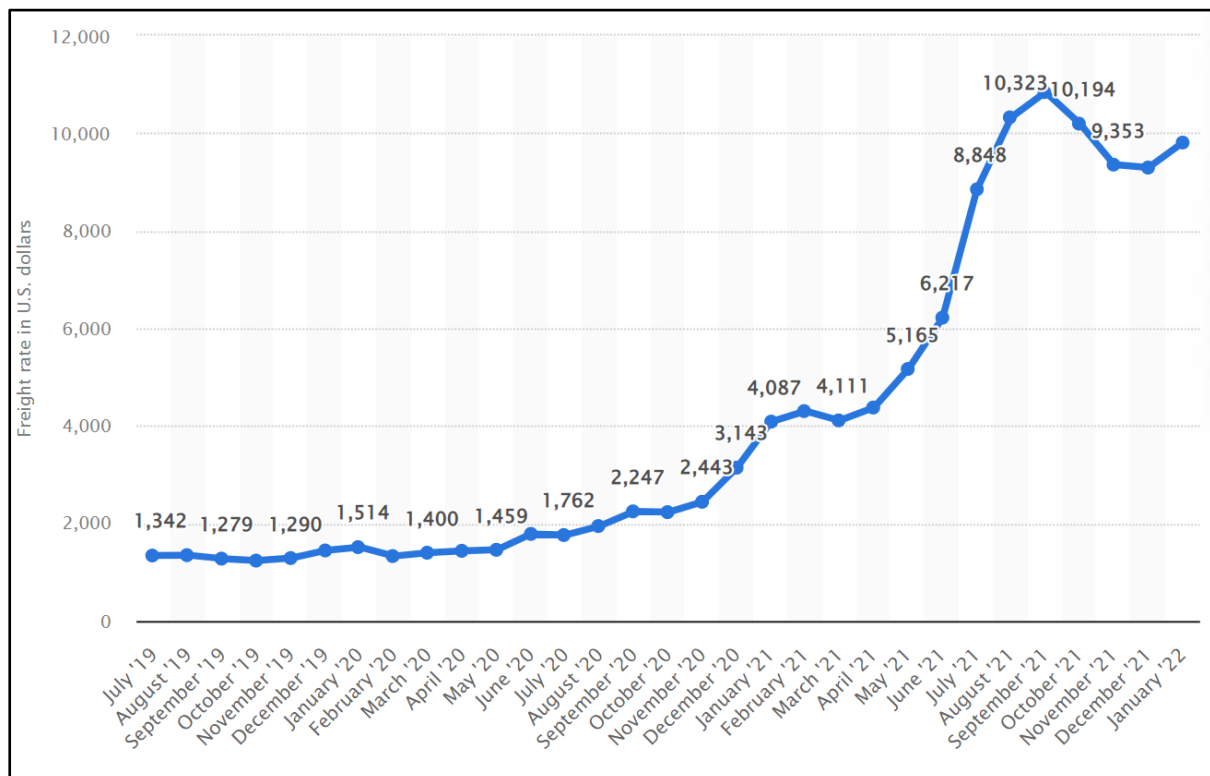


Figure 3 - Cost of Freight Services (Freight Weight Index USD) (Statista, 2022)

The Dow Silicones Barry site has been directly affected by the increase in shipping demand due to the shipping services operating at capacity. Therefore, if any delays are causing the shipment to miss its scheduled slot for onward travel, it now takes over a week before another available shipping

method can be used; prior to 2020, it was typically possible to find a shipping alternative within 48 hours.

Cyberattack is another form of economic vulnerability in the supply chain. Supply chains are a target for cyberattacks due to large volumes of customer assets, predominantly customer data, including Personally Identifiable Information (PII) data and intellectual property (European Union Agency for Cybersecurity (ENISA), 2021). Supply chain cyberattacks are increasing in prominence as they allow criminals to target large numbers of customers simultaneously, resulting in a widely propagated impact (Warren and Hutchinson, 2000). This produces a cascading effect causing widespread damage affecting businesses and their customers all at once (Khan and Estay, 2015).

5.2.3 Political Vulnerability

Changing political climates can have a significant effect on supply chain vulnerability. Political vulnerability comes in many forms but is driven by decisions, legislation and political agendas; often, these causes do not have long term effects as businesses can adapt to changes, it is the uncertainty and lack of clarity when changes are made that cause the most disruption (Hosnavi *et al.*, 2019). Political vulnerability occurs as changes to standards and regulations, Brexit, Environmental regulations, US-China trade war, terrorism, industrial action and piracy (Wieland, 2021).

Standards and regulations are constantly changing; the more extensive and global the supply chain, the more potential for regulatory change that will affect the supply chain (Wagner and Bode, 2006). Brexit is an example of a political decision that has changed various standards and regulations that affect supply chains between the EU and the UK (Roscoe *et al.*, 2020). The HMRC (2019) estimate £7.5 billion of additional costs in administration for UK businesses annually due to Brexit.

Brexit was an uncertainty that Dow Silicones Barry site planned for; additional inventory was built before January 2020 to ensure that any unpredictable supply delays could be absorbed without impacting the customer. The original business decision was to deplete the extra inventory in Q1 of 2020 as it was thought delays related to Brexit would plateau and a more predictable supply could be returned; in practice, the extra inventory was necessary until Q3 2020.

Environmental regulations constrain the supply chain; environmental corporate social responsibility has increased with public and government awareness and expectations for all businesses to take responsibility for their carbon footprint resulting in environmental legislation (Lioui and Sharma, 2012).

One example of environmental regulations that have affected the supply chain was the 2020 sulphur directive. This directive required maritime transport to reduce the sulphur content of marine fuels to 0.5% (down from 3.5%) (Donner and Johansson, 2018). Due to this directive, shipping costs have increased, fuel costs have increased, there has been a shift to road transport, and a closure of multiple shipping routes and ports (Wang, Corbett and Winebrake, 2007).

One environmental regulation that has affected the supply of silicon to the Dow Barry site is the Chinese government's energy mandate in Q3 and Q4 of 2021. The 'dual control' policy limited the energy use in Chinese silicon mines and refineries; this reduced the quantity and increased the cost of silicon metal to Dow. As a result, the Barry site reduced its supply from 30% to 0% from China in Q4 2021. This supplier change has applied additional strain on the Brazilian supply chain and resulted in increased reliance on more dependable European suppliers.

US-China trade war is another political vulnerability in the supply chain. In March 2018, the Trump administration set tariffs and trade barriers upon China, with China imposing import tariffs on American goods in March 2018; both parties implemented further increases on specific goods throughout 2018 and 2019 (Itakura, 2020). Figure 4 illustrates the difference in tariffs that China has with the US compared with the rest of the world. The increased import and export costs between China and the US made many suppliers un-financially viable, and supply chains had to be sought elsewhere (Evans, 2019).

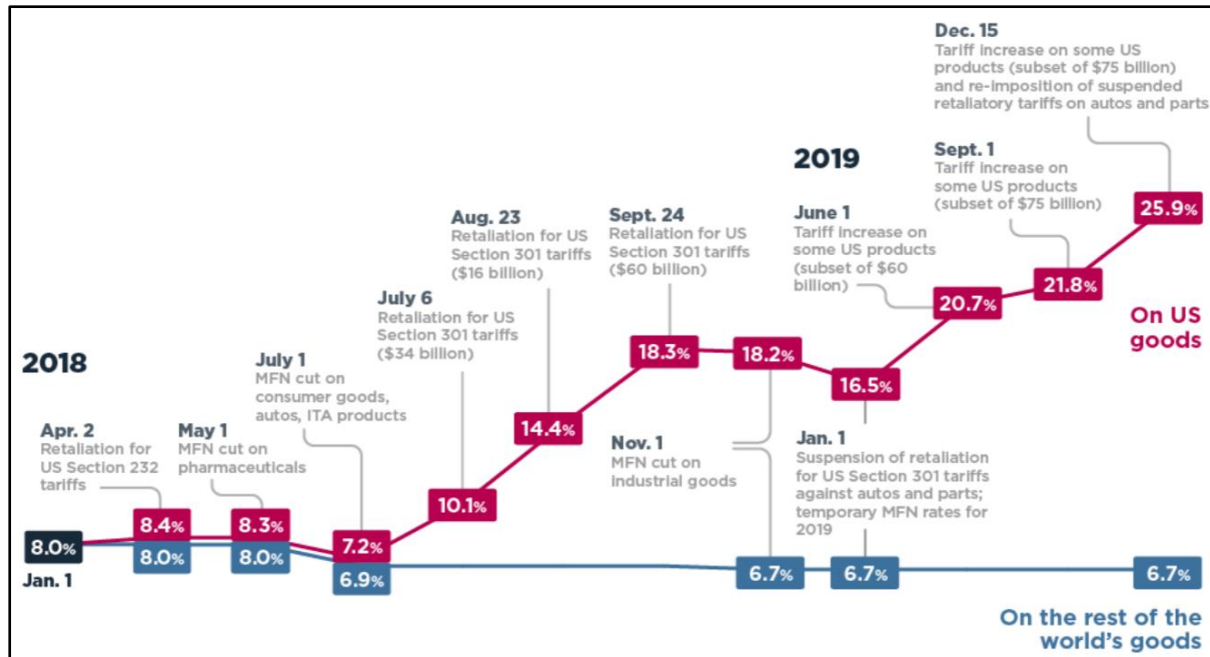


Figure 4 - Chinas Increasing Tariff Rate for the US Compared with Rest of the World (Bown, 2019)

Terrorism is another form of political vulnerability that affects suppliers. There are substantial costs to supply chains when acts of terrorism occur (Rahman and Findlay, 2003). Many manufacturing countries and shipping routes are considered to have significant terrorist threats; these include India, Thailand and the Suez Canal (Cook, 2008). Terrorist attacks can often be the most disruptive factor to the supply chain as they can occur with little to no warning (Wagner and Bode, 2006).

Industrial action is a form of political vulnerability caused by workers and unions inside the supply chain rather than external bodies. Labour disputes, overtime bans and strikes will affect any business that relies on transportation or manufacturing (Svensson, 2000).

Modern maritime piracy is a political vulnerability that affects supply chains. Risks from modern maritime piracy include stolen or damaged cargo, shipwrecks, port sabotage, danger to employees lives, and ransom (Min, 2011). Table 2 details the location and frequency of actual and attempted acts of piracy.

Table 2 - Locations of Actual and Attempted Acts of Modern Maritime Piracy (ICC International Maritime Bureau, 2020)

	Location	2016	2017	2018	2019	2020
S E ASIA	Indonesia	49	43	36	25	26
	Malaysia	7	7	11	11	4
	Philippines	10	22	10	5	8
	Singapore Straits	2	4	3	12	23
	Thailand					1
EAST ASIA	China	7	2	3	3	
	Vietnam	9	2	4	2	4
INDIAN SUB	Bangladesh	3	11	12		4
CONTINENT	India	14	4	6	4	6
SOUTH AMERICA	Brazil			4	2	7
	Colombia	4	6	1	3	1
	Dominican Republic				1	
	Ecuador		2	4	3	5
	Guyana	2	1	2		
	Haiti	4	1	3	2	5
	Mexico	1			1	4
	Panama				1	
	Peru	11	2	4	10	8
	Venezuela	5	12	11	6	
AFRICA	Algeria				1	
	Angola	2	1			6
	Benin	1		5	3	11
	Cameroon			7	6	
	Dem. Republic of Congo	2		1	1	
	Dem. Rep. of Sao Tome & Principe		1		1	
	Equatorial Guinea				2	3
	Gabon				1	2
	Ghana	3	1	10	3	9
	Guinea	3	2	3	2	5
	Gulf of Aden*	1	3	1		
	Ivory Coast	1	1	1	1	3
	Kenya	2	1		1	
	Liberia				2	2
	Morocco	1			2	
	Mozambique	1	2	2	3	4
	Nigeria	36	33	48	35	35
	Red Sea*		1			
	Sao Tome and Principe					2
	Senegal		1			
	Sierra Leone		4		1	
	Somalia*	1	5	2		
	South Africa	1				
	The Congo	6	1	6	3	3
	Togo	1		1	3	3
REST OF	Iraq					1
WORLD	Oman		1			
	Yemen	1	3			
Total at year end		191	180	201	162	195

5.2.4 Natural Vulnerability

Natural supply chain vulnerabilities are external to human influence and cannot be controlled by any part of the supply chain. Examples of natural vulnerabilities include the Covid 19 pandemic, natural disasters and bad weather (Peck, 2005)

The Covid 19 pandemic has had an extreme effect on global supply chains that have never been seen before (Garnett, Doherty and Heron, 2020). At the start of the Covid 19 pandemic, Chinese lockdowns on cities, factories, and ports caused knock-on effects throughout global supply chains (Miller *et al.*, 2021). As the pandemic spread, further countries enforced lockdowns restricting travel and movement across cities and borders, resulting in further supply chain disruption (Schattelman, Woodhouse and Terino, 2020). As the pandemic continued, labour shortages became a prominent

issue for supply chains; many businesses suffered as employees could not work due to exposure to Covid and necessary isolation periods (Fonseca and Azevedo, 2020). The labour shortage was particularly impactful on the supply chain when large numbers of factory workers and drivers were in self-isolation (Sharma, Gupta and Jha, 2020). With countries in lockdown and many people staying at home, a surge in online shopping was seen, applying increased demand on supply chains and logistics companies (Koch, Frommeyer and Schewe, 2020).

Figure 5 illustrates the impacts seen from Covid-19 upon supply chains. The graph details the magnitude of each effect. The survey was completed by Statista and included 173 business managers/leaders from various industries.

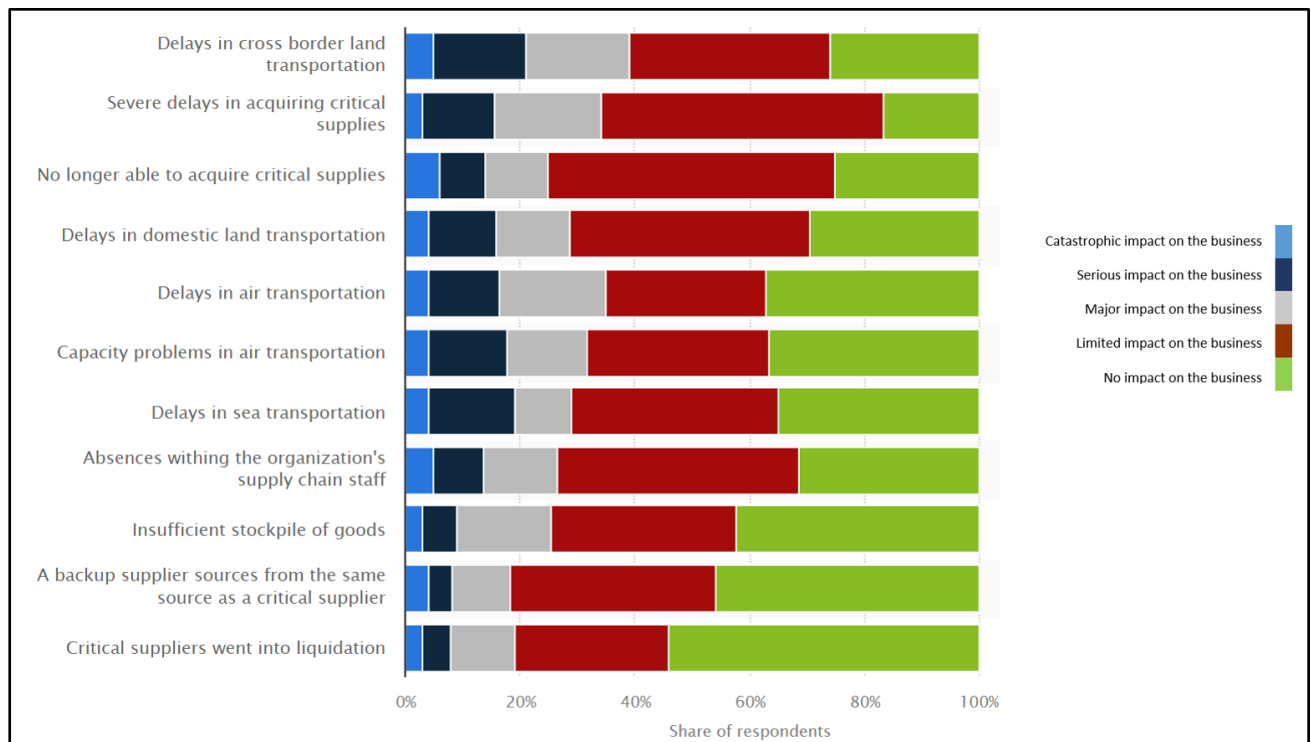


Figure 5 - Impacts of Covid-19 on the Supply Chain (Mazareanu, 2020)

Natural disasters are another case of natural vulnerability upon a supply chain. Examples of natural disasters that affect supply chains are; famine, drought, hurricanes, floods, earthquakes, volcanic activity, wildfire and tsunamis (Ergun *et al.*, 2010). Food supplies are most affected by natural disasters due to the vulnerability of crops; however, all resources are vulnerable, as well as shipping routes (Reddy, Singh and Anbumozhi, 2016). Due to climate change, natural disasters are expected to increase in frequency and intensity and become more widespread, resulting in an increased impact upon global supply chains (Burkhardt, 2021). Figure 6 illustrates the increase in losses on supply chains since 1970 due to natural disasters.

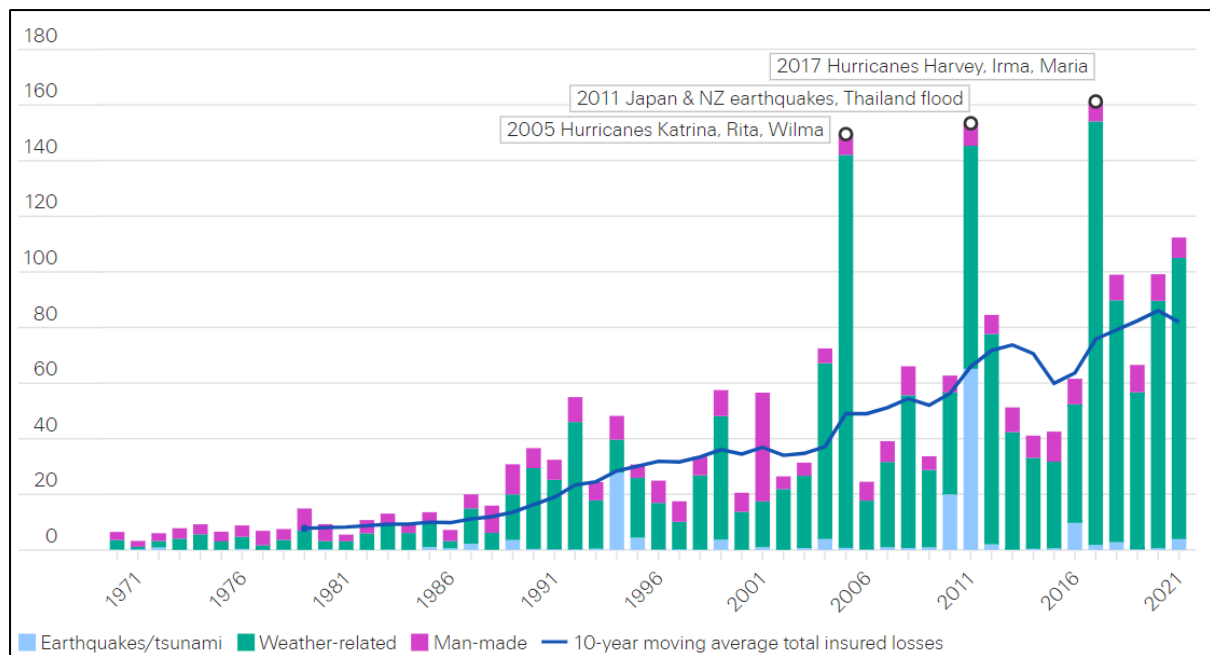


Figure 6- Insured Losses (USD) (Bevere, 2019)

Bad weather has a lesser impact on supply chains than natural disasters; however, it is highly likely to occur. Manufacturing sites are more resilient to typically adverse weather conditions; however, shipping and transportation can be vulnerable to bad weather (Miller *et al.*, 2021). Bad weather is built into the duration of shipping lanes, as seasonal bad weather is expected and accounted for in travel duration (Koza *et al.*, 2020).

6 Steps to Make the Supply Chain More Resilient

Supply chain resilience is the speed and capability of a business to recover from supply chain disruption (Pettit, Fiksel and Croxton, 2010). The business should be flexible and adaptable to unavoidable supply chain issues and completely remove sources of vulnerability when possible (Scholten and Schilder, 2015).

Once the supply chain vulnerabilities are established, steps can be taken to make the supply chain more resilient. The potential impact and frequency of the vulnerabilities should be understood to ensure an economically viable solution is found (Lambert and Cooper, 2000). In many cases understanding the supply chain and its vulnerabilities can help establish an action plan prior to impacts occurring, which will result in a more efficient response to the impact reducing downstream consequences (Hugos, 2018). Figure 7 illustrates the factors that have had a significant disruptive impact on supply chain operations, a survey conducted by The Economist and GEP (2021) including 400 senior supply-chain and procurement executives (% of polled).

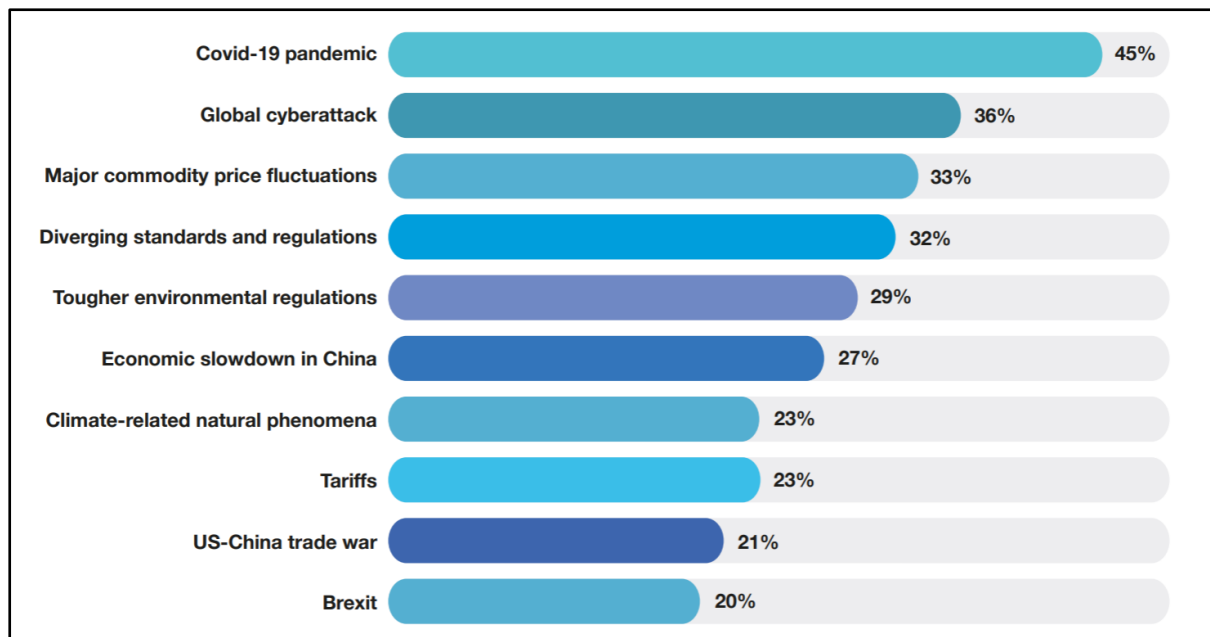


Figure 7 - Factors That Have Had Significant Impact on the Supply Chain since 2019 (Piatek, 2021)

Many decisions can be implemented that mitigate supply chain vulnerability; these include:

- Supplier selection and diversification
- Shortening supply chains
- Contract planning
- Supply chain management systems
- Insurance
- Stockpiling and redundancy planning

Where possible, cases of supply chain vulnerability should be removed entirely; however, on many occasions creating an action plan for when the vulnerability arises can be effective in limiting downstream impact; and can be the only method of preventing losses (Croxtton *et al.*, 2001).

6.1 Supplier Selection and Diversification

Supplier selection can form a basis for good supply chain resilience. Dependability on a small number of suppliers can leave a business very vulnerable to supply chain disruption (Ellram, 1991). If the sole supplier's production is disrupted, this will directly impact the business production; multiple suppliers will allow the business to disperse its risk and supply chain vulnerability (Tan, 2001). Multiple suppliers will also allow the business to manage the supply chain themselves; the business can increase/decrease volume from each supplier to balance the most economical and reliable supply chain (Blanchard, 2021).

Suppliers should be selected on several factors, the cost will always be a significant part of any supplier selection, but supply chain reliability should be valued highly within the selection process (Stadtler, 2008). When considering a new supplier, the potential supply chain vulnerabilities should be established; the operational, economic, marketplace, political, and natural vulnerabilities should be considered (Cox, 1999).

Once the supplier and supply chain vulnerabilities have been identified, collaboration with the supplier should be established to reduce the risks (Lambert and Cooper, 2000). Discussing the supply chain vulnerability with the supplier before the service is established provides a good indication of the flexibility and dynamism the supplier can provide in the event of supply disruption (Jacobs, Chase and Lummus, 2014). All aspects of the supply chain relationship should be considered, including the flow of goods, information, and money (Tayur, Ganeshan and Magazine, 2012). The supplier should be confident in predicting the time it would take to recover from a supply chain disruption as this provides vital data for the business contingency planning (Fredendall and Hill, 2000). Working with suppliers can help align organisational agendas around the areas of highest risk to the supply chain (Bechtel and Jayaram, 1997). The responsibility of the supply chain should be shared with the supplier as a reliable supply chain is mutually beneficial; however, a contract should be utilised to detail the specific responsibilities of each party (Thomas and Griffin, 1996).

Dow Silicones currently utilises nine silica suppliers; the business has an individual contract with each supplier and can manage the volume from each supplier independently. A feedstocks team manages the silica supply for all three sites to balance the cost of raw materials, supply duration and supply reliability evenly amongst all three sites; this optimises the supply chain model based upon profit rather than geographical convenience. Utilising nine suppliers balances risk; each individual supply chain has its vulnerabilities; however, the supply chain has been built so that if one supply chain is disrupted, the remaining suppliers can adapt to maintain an overall reliable supply.

6.2 Shortening Supply Chains

A shorter supply chain will reduce the likelihood of supply chain failures. A shorter supply chain does not necessarily mean geographically shorter but can include; fewer transportation stops, fewer modes of transport, reduced number of logistics companies responsible for transportation, and fewer countries transited through to reduce the amount of documentation required (Lummus and Vokurka, 1999). Taking measures to shorten supply chains will not reduce the impact of any supply chain risks but will reduce the likelihood; therefore, reducing the overall supply chain vulnerability (Lambert, 2008).

A geographically shorter supply chain could achieve most of the aforementioned goals; however, this is not always a practical method as the goods are not always available locally due to physical resource availability or price practicality (Power, 2005). Alternatively, the business could move closer to the supplier; this may not be possible if there is a vast range of products supplied to the business but provides a practical application in many businesses; for example, having refineries close to mines (Ivanov and Sokolov, 2009). If it is not viable to locate the business close to the supplier, it is vital to locate the business with good transport links, excellent road infrastructure, rail links, available ports and access to air freight; this can provide logistical benefits and reduce supply chain vulnerability (Kumar, 2014).

As well as a shorter supply chain, a visible and agile supply chain should be sought (Wisner, Tan and Leong, 2014). Supply chain visibility is the ability to see all stages of the supply chain from one end to another; this includes product tracking in transit (Stevens, 1990). Supply chain visibility is vital for effective management of the supply chain (Scott and Westbrook, 1991). Supply chain visibility provides supply chain agility; supply chain agility can come in many forms, but it is defined as the

ability to adapt to supply chain changes or changes in demand (Anderson, Britt and Favre, 2007).

Examples of supply chain agility are:

- Multiple suppliers available
- Methods of expediting materials
- Multiple transportation routes available
- Multiple transportation methods available
- Multiple logistics and shipping companies available

(Ross, Weston and Stephen, 2010)

Dow Silicones Barry site employs three EU silica suppliers; these suppliers incur a premium cost compared to Chinese and Brazilian suppliers; however, they have a significantly shorter delivery time and increased reliability due to geographical convenience. Due to cost implications, these suppliers are not heavily exploited; however, they are used to flatten peaks and troughs in supplies from China and Brazil to reduce supply chain instability.

In 2005 Dow purchased two silica mines and refineries in Brazil (Chabang and Breu Branco); this business decision was taken to secure reliability of silica supply and provide backwards integration of the supply chain. This takeover completely aligned the organisational models of the supplier with the business; key financial benefits were made, such as control and stability of silica price, in addition to greater control of the supply chain.

For all its shipping needs, Dow Silica employs one shipping company, Mediterranean Shipping Company; this reduces risks at ports when transferring materials between multiple shipping companies. Dow Silicones Barry site only employs Associated British Ports (ABP) for its UK logistics. ABP has a longstanding contract with the Barry site, a relationship has been built with ABP, and they can adapt to the dynamic needs of the site. ABP is responsible for collecting material from all UK docks, transportation to Barry docks, material storage, and site delivery. The use of one business for all these needs allows the Barry site to have more control over the last leg of the supply chain.

6.3 Contract Planning

Contracts should be used to reduce supply uncertainty. Long-term, medium-term, and short-term contracts should be divided equally amongst suppliers to provide a steady turnover of contracts and a balance of long-term stability with short-term agility (Christopher, 2016). Varying contract duration provides the business with a cost-effective balance of supply chain reliability and resilience (Ayers, 2000). Contracts should be utilised in all aspects of the supply chain, from suppliers to shipping and logistics companies (Patterson, Grimm and Corsi, 2003). Specifics should be included in all contracts to provide transparency and detail responsibility and penalties for not meeting particular obligations (Cooper, Lambert and Pagh, 1997). Supplier and supply chain contracts should be aligned with the needs of the business; it is the responsibility of the business to ensure the contracts meet their requirements; standard contracts will not provide flexibility and will suit the supplier's needs (Gattorna and Jones, 1998).

6.4 Supply Chain Management Systems

Supply chain management is necessary to provide dynamism and agility in all areas; the supply chain should not be relied upon to manage itself, even if robust contracts are in place (Fawcett, Ellram and Ogden, 2007). Supply chain management requires resourcing and infrastructure to succeed. A department should be established for supply chain management and suitably resourced to reflect the complexity of the supply chain; the department may require 24-hour support and the ability to communicate in multiple languages (Lancioni, Smith and Oliva, 2000). The department should learn from failures and experiences, identify the root cause of supply chain problems and implement control measures to prevent recurrence (Cooper and Ellram, 1993). The department for supply chain management should work closely with the legal department to ensure supplier contracts meet the needs of the business and provide a resilient supply chain (Tan, 2002).

Appropriate technology and operating systems are crucial to managing a supply chain effectively. Operating systems collect information from various departments and functions to allow the business to run (Monk, 2004). Operating systems typically utilise Enterprise Resource Planning (ERP) software to integrate all business functions into one complete system (Mabert, Soni and Venkataramanan, 2003). A practical method to share information across functional areas is essential for making quick and informed decisions across the supply chain (Russell and Taylor, 2019). Businesses should utilise a global ERP system that can autonomously link and communicate with all aspects of the supply chain (Jacobs, 2007). Figure 8 illustrates technologies that businesses have implemented to minimise the impacts of supply-chain disruptions; a survey conducted by The Economist and GEP (2021) included 400 senior supply-chain and procurement executives (% of polled).

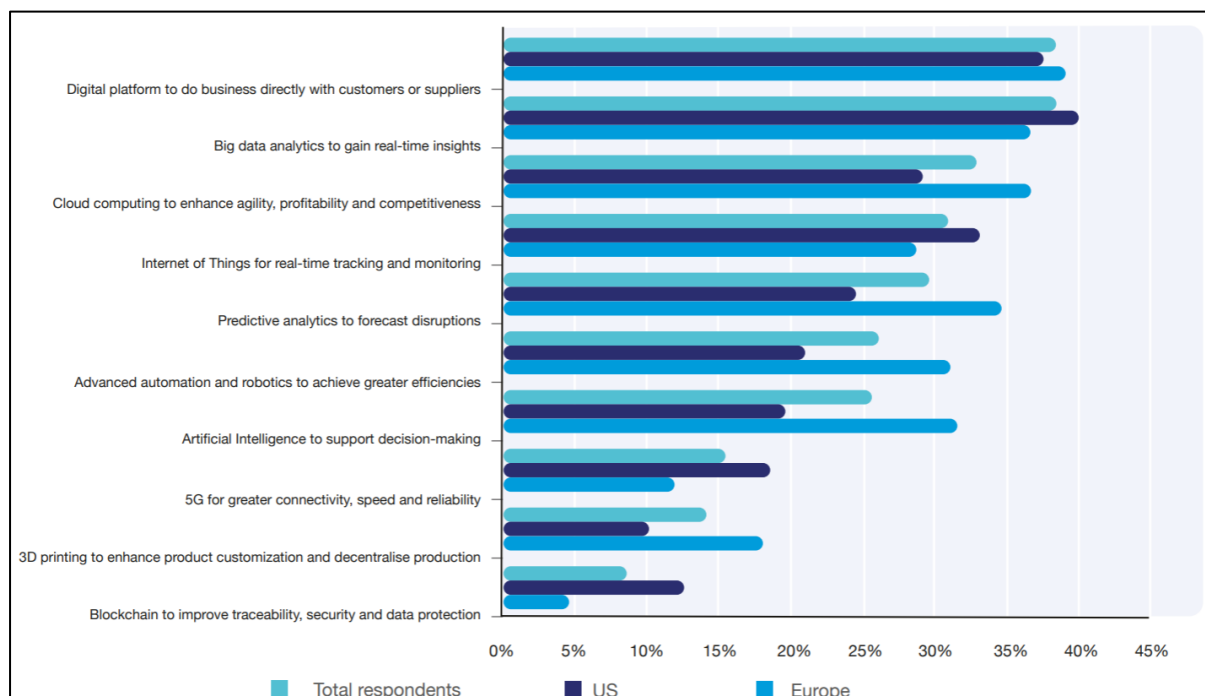


Figure 8 - Technologies Implemented by Organisations to Minimise the Impact of Supply Chain Vulnerability since 2019 (Piatek, 2021)

6.5 Insurance

Insurance is not a method to reduce the risk of supply chain vulnerability but to provide compensation and protection to downstream customers (Eggert and Hofmann, 2016). Insurance should be used alongside contractual penalties to ensure financial security for the business when supply chain disruptions occur (Nunes, Park and Paiva, 2020). Insurance payoffs can be reinvested into the business to prevent reoccurring supply chain disruption, or it can be used to expedite goods from alternative suppliers to prevent the disruption from affecting downstream customers (Sheffi and Rice Jr, 2005). Insurance payoffs may also have to be passed onto the customer as compensation to maintain customer satisfaction and retention (Hematyar and Chaharsooghi, 2014). Insurance can provide financial relief in time of supply chain crisis; however it requires long-term financial investment, insurance companies balance the risks against premium subscriptions; therefore, it may be more financially viable to prevent risks than insure for them (Heckmann, Comes and Nickel, 2015).

6.6 Stockpiling and Redundancy Planning

Supply chain vulnerability can be compensated for by holding large volumes of stock (Tomlin, 2006). Holding large amounts of inventory absorbs business capital and reduces cash flow (Callioni *et al.*, 2005). Reduced cash flow may force the business to require loans that accrue interest (Lev and Weiss, 1990). Reduced cash flow may also prevent the business from taking advantage of opportunities that require capital investment (Jones and Tuzel, 2013). Stockpiling causes storage problems; appropriate storage needs to be found for the extra inventory. Storage space costs money to purchase or rent and upkeep costs such as heating, lighting and manning (Hughes, 1984). If existing floor space is consumed through stockpiling existing products, this can prevent the business from supplying new products to customers due to storage capacity issues (Sepehri, 2011). External and internal factors can affect the value of the stockpiled inventory. The value of a product may change whilst it is in storage; this provides risk to the business (Hartman and Dror, 1996). Internal factors that devalue the stock can be caused by reducing the cost of the stock if product sales and consumption is lower than predicted (Park, 1982). Inventory can become obsolete when in storage, this can cause a dramatic reduction in value, as well as technical obsolescence, stock can also suffer from changing trends reducing desirability, and products expiring (Lee and Billington, 1992).

Increasing inventory will never resolve the issues of poor supply chain reliability; it can only buffer the effects downstream to customers (Lee, 2002). Appropriate management systems should be put in place to ensure supply chain reliability (Thomas, 2002). Stockpiling should be used to balance the risk of the supply chain, and the value of held inventory should be able to compensate for any likely but low impacting sources of supply chain vulnerability (Morstein, 2020). It is not appropriate for a business to employ stockpiling as a control measure for high impacting but low probability supply chain disasters (Russell and Taylor, 2019).

7 Recommendations

There are many potential causes of supply chain vulnerability. I recommend that all businesses assess their supply chain vulnerability and implement a formal risk management strategy. Where possible, the business should quantify theoretical losses so that investment in loss prevention is relative to the consequence. Businesses with global supply chains will naturally have more vulnerability to supply chain disruption; however, an intelligent selection of suppliers and supply routes can mitigate and eliminate potential areas for vulnerability without investment.

Shortening supply chains can be another relatively low-cost way to reduce supply chain vulnerability increase visibility and agility. Methods such as fewer transportation stops, fewer modes of transport, reduced number of logistics companies responsible for transportation, and fewer countries transited though can all reduce the likelihood of supply chain disruption.

Contracts should be used to reduce supply uncertainty. Long-term, medium-term, and short-term contracts should be divided equally amongst suppliers to provide a steady turnover of contracts and a balance of long-term stability with short-term agility. Supplier contracts should be used to align the supplier's organisation with the business needs.

Insurance is not a method to reduce the risk of supply chain vulnerability but to provide compensation and protection to downstream customers and should only be utilised where necessary to maintain customer satisfaction and retention. Stockpiling should be used to balance the risk of the supply chain, and the value of held inventory should be able to compensate for any likely but low impacting sources of supply chain vulnerability. Stockpiling should be the last resort for a business with supply chain issues, as significant capital investment prevents overall business flexibility.

In the specific case of the Dow Silicones Barry site, I recommend shipment be made directly to the UK without stop-off at Antwerp. There is currently a considerable shipping delay between the EU and the UK; this is a combined effect of Brexit, Covid and global shipping capacity. If shipping delays are incurred between the supplier and Antwerp, the delays are often multiplied as the materials await onward transport to the UK. The UK has a range of ports suitable for receiving these goods, eliminating any Brexit-related documentation delays. Shipping straight to the UK would also shorten the supply chain, eliminating stages of material handing and potential supply chain vulnerability.

Currently, the Dow Silicones Barry site only employs Associated British Ports (ABP) for its UK logistics. ABP is responsible for collecting material from all UK docks, transportation to Barry docks, material storage, and site delivery. This is a potential point of vulnerability for the Barry site; if ABP were unable to fulfil their contractual obligations or ceased trading, there would be massive production consequences for the Barry site. I recommend employing a second UK logistics company on a smaller scale that can upscale logistics operations quickly to respond to any shortfalls in ABP's service. The vulnerability of ABP's service was exposed in August 2019; a body was found in the ABP facility in Barry docks (The Guardian, 2019). Whilst police investigated the circumstances of the body; the ABP site was shut down; this resulted in an immediate seven-day shutdown for the Dow site until ABP was allowed to resume regular services.

Dow Silicones globally employs the Mediterranean Shipping Company as their sole shipping provider. Using a second shipping provider could provide more shipping routes to choose from. As one of the worlds largest cargo companies, it is unlikely that Mediterranean Shipping Company will

encounter any operational circumstances they cannot overcome; however, choosing a second shipping provider is an expense-free way to distribute risk.

During the Covid-19 pandemic, the Barry site adapted well to new working conditions, actively practising remote working a month before the UK government-enforced mandatory lockdown. The Barry site also increased inventory of silica with the expectance of supply chain issues for the impending pandemic. This, however, was a learning from the catastrophic effect Covid-19 had upon the Dow Silicones site in Zhangjiagang China (a neighbouring city to Wuhan). Chinese government-mandated lockdowns were swiftly enforced without the Zhangjiagang site properly preparing for operations once the lockdown was lifted. This resulted in long term supply chain issues as various parts of the Chinese supply chain were shut down. My recommendation includes leveraging the learnings from the Covid-19 pandemic to prepare action plans for all the Dow Silicones businesses in case of similar natural disasters and supply chain issues with global effects and short notice.

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