ADBI Working Paper Series

THE SURPRISING DEVELOPMENTS OF DIGITAL SUPPLY CHAINS TO RAISE RESILIENCE IN THE FACE OF DISRUPTIONS

Carlos Cordon

No. 1383
May 2023

Asian Development Bank Institute

Carlos Cordon is a professor of strategy and supply chain management at the Institute for Management Development, Lausanne, Switzerland.

Suggested citation:

Cordon, C. 2023. The Surprising Developments of Digital Supply Chains to Raise Resilience in the Face of Disruptions. ADBI Working Paper 1383. Tokyo: Asian Development Bank Institute. Available: https://doi.org/10.56506/KPJD9061

Please contact the authors for information about this paper.

Email: carlos.cordon@imd.org

Asian Development Bank Institute
Kasumigaseki Building, 8th Floor
3-2-5 Kasumigaseki, Chiyoda-ku
Tokyo 100-6008, Japan

Tel: +81-3-3593-5500
Fax: +81-3-3593-5571
URL: www.adbi.org
E-mail: info@adbi.org

Abstract

We describe the need for resilience in supply chains given the recent stream of disruptions that the world has experienced. Based on recent events, we identify different types of disruptions that have challenged the resilience of supply chains. Subsequently, we describe the different digital tools used in supply chains and their success or failure in increasing the resilience of supply chains. We conclude that some digital solutions help to increase resilience, while others have almost no effect, namely systems integration, artificial intelligence (AI), and simulation. We propose a classification of how to relate the type of disruption to the effective digital tool. We finish by proposing a framework for future research to validate digital solutions that increase reliability. We also conclude that some tools, including 3D printing and blockchain, might have a role in the future in increasing the resilience of supply chains, but that today there is no evidence of a positive effect.

Keywords: supply chain, digital, resilience, disruptions, Industry 4.0

JEL Classification: M11

Contents

1. INTRODUCTION

In recent years, supply chains have been facing constant disruptions of a magnitude unparalleled in history, from COVID-19 to the Russian invasion of Ukraine, that have exposed the great fragility of our supply chains. Consumers have been facing a series of stockouts in the last few years, from the panic buying of toilet paper at the beginning of the COVID-19 pandemic, to delays in getting new cars from manufacturers, to recently finding out that sunflower oil was not widely available due to the Russian invasion of Ukraine.

Consequently, there is a big emphasis on how to increase the resilience of supply chains, both from governments and companies. Scholars and executives (Buatois and Cordon 2020) have even suggested that company boards should stress-test the resilience of their supply chains similarly to the stress test of financial institutions in the aftermath of the financial crisis of 2008. Very recently, governments around the world (from the Biden administration to the European Union) have passed legislation aimed at increasing the resilience of the supply chains in different "strategic" sectors like food, pharmaceuticals, and micro-electronics. Thus, there is widespread effort to make our supply chains more resilient in the face of "waves" of disruptions.

In a parallel way, during the last few years, the digitalization of supply chains has been praised as a solution to many of the challenges facing different industries. In the early 2010s, many executives, consultants, academics, and governments expected the digitalization of supply chains to deliver billions in savings and to increase the value they created. A prime example was the initiative by the German government regarding Industry 4.0, whose objective was to help German companies to implement digital technologies to attain the benefits derived from those advanced tools.

During the 2010s, initiatives to push the digitalization of both factories and the complete supply chain proliferated, like the example of lighthouses where companies would use one factory as an example of how digitalization might help to increase value and productivity. Some of these initiatives delivered on the promise of savings and more value created. Quite a few created acceptable returns and many others failed to provide almost any benefit (Büyüközkan and Göçer 2018). Interestingly enough, many research papers and consultants claimed that around 70% of those "digital transformations" failed to deliver the expected results.

While many of these digital initiatives were originally driven towards lowering the costs or "creating a competitive advantage by transforming" the industry, the recent wave of disruptions has changed dramatically the context and even the purpose of supply chains. In a stable context, the main objective of supply chain executives was to minimize cost for a given level of service and a given quality level. In a context of very high instability, the objective is not to minimize cost but to maximize availability and fast service, to profit from the scarcity of products.

Such a fundamental change in the objective of supply chains has pushed the emergence of some digital solutions that provide unexpected benefits for resilience, while the initiatives focusing on lower costs in a stable environment have lost momentum. For example, relatively straightforward digital communication tools have proven to be very useful in managing disruptions, while sophisticated tools like the IOT for digital twins of machines are not being pursued strongly because many of their benefits are not so relevant in a very unstable environment.

Additionally, the recent drive towards sustainability has made the situation more complex, leading to many companies looking for digital solutions to manage such complexity. For example, because of the huge demands for reporting, many global companies are developing and adopting digital solutions because it is simply impossible to fulfill the reporting requirements in a nondigital way. In a recent case study about the global company Henkel (Wellian and Cordon 2022), it is described how challenging it is to obtain the required information about the consumption of energy by its customers using their detergents, as they have millions of consumers. The only accurate way of tracking the consumption patterns of millions of consumers is by using digital technologies.

In this paper we explore how digital developments in supply chains are having a positive effect on resilience and why some digital initiatives have failed to deliver any benefit. Specifically: (1) we explore how management for resilience is fundamentally different from managing for low cost; (2) we explore the development of a framework to try to understand the logic behind the impact of digital tools on resilience; and (3) we conduct a discussion on what could be the future evolution of digitalization of supply chains and its impact on resilience.

Spieske and Birkel (2021) have performed an extensive literature research on papers examining the effect of digital technologies on resilience, but logically their data are based on papers published mainly before 2021, so most of them do not consider the events of COVID-19 and the Ukrainian war. They conclude that only big data analytics seem to help to increase the reliability of supply chains. Given the recent events of such an unprecedented magnitude, we base our research on very recently published cases and on conversations in forums with practitioners. Thus, in the paper some hypotheses are proposed, but there are not yet enough data and experience to build a database and test propositions. Our objective is to provide a taxonomy that could be the basis for future empirical research.

2. THE OBJECTIVE OF A SUPPLY CHAIN: RESILIENCE VS. COST MINIMIZATION

2.1 Focus on Cost Minimization

During the last few decades companies and researchers have focused most of their objectives and research on how to reduce cost. The objective function of supply chains was minimizing cost while providing a given service level (often in the high 90s) within a given quality level (often close to 100%).

Executives pursued strategies of factory focus and low-cost country sourcing to minimize costs. Focusing factories on the production of the biggest possible quantity of the same or similar products makes it possible to obtain economies of scale and follow the learning curve as fast as possible. We have seen over the last few decades a constant reorganization of supply chains by closing factories to focus on the biggest ones and rationalizing warehousing and transportation to reach economies of scope. In the same vein, companies have followed a very strong policy of offshoring, looking for locations with lower costs, availability of labor, and regulations whose fulfillment requires lower costs.

Researchers have developed models and frameworks to understand how to minimize costs and how to make decisions about sourcing locations (Daehy et al. 2019), outsourcing (Heikkila and Cordon 2002), and offshoring. In the field of operations, there are many academic papers on improving algorithms to minimize costs in different production settings. There are also quite a lot of models and empirical research about outsourcing and offshoring, ranging from competencies in outsourcing to how to develop a partnership with offshoring partners.

This drive to minimize costs is reflected in how the different digital initiatives in supply chains were focused and evaluated by companies before 2020. As an illustration, in the case of Faurecia (Kumar et al. 2019), the company evaluated the different technologies used in the digital transformation almost exclusively on cost savings.

While it could be argued that there are some notable examples of both executives and academics developing initiatives to increase agility and, therefore, resilience, they remain exactly that, notable exceptions: for example, the case of Philip Morris International (PMI) receiving a prize from the Gartner organization because of the development of their Digichain, a very agile digital supply chain that provides the flexibility needed to support their changing business model from cigarettes to electronic heating devices (Wellian and Cordon 2020). In that case, they reduced the time to volume from four months to seven days.

Similarly, academics have developed models and theoretical research about the potential benefits in terms of flexibility of using digital supply chains, but still most of the efforts have been about cost minimization. It should be noted that given the tradition in academic research about the effects of flexibility and time-based competition, there are quite a few models that could prove very useful in helping practitioners to understand the flexibility of trade-offs with respect to cost minimization.

2.2 The Emergence of Resilience

Because of the disruptions faced over the last few years due to COVID-19, a lack of availability of truck drivers, the Suez Canal blockage, the Russian invasion of Ukraine, and so on, consumers have experienced shortages and companies have not been able to deliver the levels of service they have been used to. These dramatic changes have made visible the fragility of supply chains in such a very uncertain environment.

Being able to cope with these disruptions in a supply chain is what many people would define as resilience. An accepted definition of supply chain resilience would be “the adaptive capability of the supply chain to prepare for unexpected events, respond to disruptions, and recover from them by maintaining continuity of operations at the desired level of connectedness and control over structure and function” (Ponomarov and Holcomb 2009). Another definition is provided by Ponis et al. (2012) through a systematic review of the literature, in which they define supply chain resilience as “the ability to proactively plan and design the supply chain network for anticipating unexpected disruptive (negative) events, respond adaptively to disruptions while maintaining control over structure and function and transcending to a post-event robust state of operations, if possible, more favorable than the one prior to the event, thus gaining competitive advantage.” These definitions do not distinguish between the type or severity of unexpected events or disruptions.

The level of disruptions since the COVID-19 surge has been of a much higher level than before and, we argue, we need to understand how those disruptions have affected our supply chains and what would be an appropriate definition of resilience under those circumstances. We are going to review a few of the different types of disruption and infer what would be an appropriate definition of resilience for those circumstances.

2.2.1 Temporary Disruptions

The first substantial type of shortage globally happened in the spring of 2020 with the surge of COVID-19 infections and the consequences of the containment measures. News of shortages of toilet paper was controversial because consumers were buying large quantities of the product in anticipation. The news was particularly noticeable because arguably the consumption of toilet paper is a very stable one, and the surge of COVID-19 shouldn't have any impact on its consumption.

This first wave created an initial dilemma in the management of the supply chain: should toilet paper manufacturers expect a long-term increase in the consumption of toilet paper or is it just a temporary increase in demand. It was obvious that it was a temporary increase, so manufacturers raised the production volumes in the short term as much as they could, but they didn't plan for any additional long-term capacity. This happened with quite a few consumer products in different continents (e.g., soap, canned ravioli). In this case, many experts would qualify resilience as the capacity of the supply chain to adapt to that temporary surge of demand and maintain the level of service as it was before the disruption.

2.2.2 Huge Demand Increase

The second type of shortage was the lack of many of the healthcare materials needed for personal protection and for taking care of COVID-19 patients. The challenge here was that the demand increased manyfold for products like masks for personal protection and ventilator machines to help patients to breathe. The logical reaction was to multiply capacity in manufacturing and throughout the supply chain to be able to cover the needs.

In this case, the definition of resilience becomes more problematic. Some experts would suggest that being able to deliver under such an increase in demand goes way beyond resilience; some estimates indicate that the demand for masks was 12 times the capacity of the main producer, the People's Republic of China (PRC) (OECD 2020).

By contrast, the increase in the demand for ventilators was around 300% and the demand had returned to normal by the end of 2020 (GlobalData Healthcare 2021). In the case of ventilators, it could be argued that a resilient supply chain should have been able to cope with the increase in demand to later resume its normal operation. Nevertheless, the dramatic situation of patients not being taken care of led to many different types of companies in different industries trying to produce those ventilator machines.

While it could be argued that no supply chain could ever manage this kind of huge increase in demand, some proponents of digital technologies like 3D print claim that in the future technology could be able to cope with such situations.

2.2.3 Structural Supply Chain Fragility

A surprising third type of shortage has been the lack of capacity of car companies to cover the demand. Different estimates indicate that car production was reduced by around 11.3 million in 2021 (Statista 2022) because of a shortage of semiconductors. The situation of the car industry deserves further elaboration to create an appropriate understanding of what resilience would mean in this supply chain.

Before the pandemic, quite a few experts in the automotive industry expected car sales to stabilize and peak around 2020 due to consumer trends (sustainability, new generation, uberization, etc.). Many car companies reacted accordingly, planning for a reduction in capacity over the years. Thus, the supply chain of the car industry was designed for a stable or slowly declining demand.

When the coronavirus outbreak started to have a global impact, many car companies were forced to close their factories and they also planned for a very substantial reduction in consumer demand. On 17 March 2020, Volkswagen, the world's biggest car maker, suspended production at factories across Europe (Reuters, 17 March 2020). The expectation was that consumers would stop buying cars, the world would enter an economic recession and that, consequently, demand in the long term was going to be way below the plans before the pandemic.

Car companies warned their suppliers that they would not accept further deliveries because production had been stopped, and that the expectation was a much lower demand going forward. In turn, the suppliers to the car companies went to their own suppliers, the semiconductor manufacturers, and canceled their orders. The reaction of the semiconductor manufacturers was to reduce the production of microchips for the automotive industry and, when possible, to move their production capacity to consumer electronics (which by that time was seeing an increase in demand as consumers were buying a lot of products for the home). Also, semiconductor manufacturers traditionally had a much higher profitability in consumer electronics than in automotive semiconductors.

While this was very much the case through the spring and summer of 2020, the demand for cars surprisingly started to increase in the autumn of 2020. GM (General Motors) reported a 4.8% increase in US sales in the fourth quarter of 2020, Toyota reported a 9.4% increase, and Volkswagen a 10.8% increase (Reuters, 5 January 2021). Some experts indicated that some consumers were reluctant to take public transport because of the risks of contagion and that the economic measures by governments providing subsidies for consumers helped to avoid a recession. When car companies went back to their suppliers, who in turn went to the semiconductor manufacturers with an increase in demand after having almost stooped the whole supply chain, the capacity was not there. On top of that, the industry is undergoing a massive change to electric vehicles, which require many more semiconductors.

Some experts argue that the automotive supply chain executives created their own fragility by (1) having a supply chain in which semiconductor manufacturers captured a very low part of the total value created, (2) reacting brutally when the disruption started, basically turning their back on suppliers, and (3) completely mispredicting the evolution of the market (both in terms of demand volumes and types of cars) (McKinsey 2021).

In these types of cases where the industry developments by its different organizations have created a structural fragility, resilience could be the capacity of the supply chain to adapt to disruption and changes in demand. However, it is not clear whether recovery means going back to the previous situation, because in the case of the automotive industry, the demand going forward from 2022 is very different from the one before.

The obvious example is the huge demand for electric cars, as this is very different from the one experienced before the pandemic.

Finally, in the case of the car industry, it is also fair to question whether the lack of resilience has been detrimental for the industry or just for the consumer. An anecdotal illustration is presented in Table 1, which shows the quantity of cars sold by three leading companies in 2021 in comparison to those sold in 2019. (We chose GM, FORD, and VW (Volkswagen) because they are leading companies, and the period is the same.)

Table 1: Comparison of Global Sales of Cars in 2021 Vs. 2019 by Three Leading Companies (Car Figures in Millions; Revenue and Profit Figures in Billions of US Dollars)

Company	Cars Sold 2021	Cars Sold 2019	Revenue 2021	Revenue 2019	Profits 2021	Profits 2019
GM	6.29 M	7.72 M	127 B	137 B	10 B	6.7 B
FORD	3.90 M	5.50 M	136 B	156 B	18 B	6.4 B
VW	8.90 M	11 M	250 B	253 B	20 B	19.3 B

Source: Created by the author.

As can be seen in Table 1, in 2021, these three leading companies sold 21% (5.1 million) fewer cars than in 2019 and had 48% higher profits in 2021 than in 2019. Thus, even though their supply chain was not resilient enough to adapt to the increase in demand and the shortage of semiconductors, their business had record profits.

2.2.4 Disruption of Transport Services and Basic Infrastructure

A fourth type of disruption is the disruption of transport and basic infrastructure. In 2020, it had already become very difficult to ship products around the world. The closure of borders and the confinement imposed to stop the pandemic meant that many transport and basic infrastructure services were no longer available.

Governments were very conscious of the consequences of confinement restrictions and allowed strictly necessary transport and basic infrastructure to continue working. However, while companies believed that once those restrictions had been relaxed those services would go back to normal, that didn't happen. Prices of containers skyrocketed, as well as transport costs, and there were bottlenecks in global supply lines. On 5 July 2021, the *Wall Street Journal* reported that the average price worldwide to ship a 40-foot container had more than quadrupled in one year to $8,399 on 1 July 2021 (WSJ, 5 July 2021).

Over the last two years, the Suez Canal became blocked, and shipping ports experienced huge traffic jams, strikes, and even paralysis at times because there were not enough truck drivers to transport all the unloaded containers. Finally, the zero-tolerance policy for COVID-19 in the PRC meant that some of the busiest ports in the world would be stopped for several days or weeks because just one coronavirus case had occurred.

In the case of disruptions, many supply chains simply became blocked and the challenge was to find alternatives, i.e., air transport or suppliers in different continents. Resilience in this case would be being able to adapt and find a response that would allow the supply of the product or the service to continue.

2.2.5 Disruption of Local or Nearby Services or Infrastructure

The fifth type of disruption is the one that we have used for decades when defining resilience, that of a specific service or infrastructure being disrupted – for example, when there are strikes or local disruptions that affect a part of the supply chain. An anecdotal example is the lack of truck drivers in the UK (United Kingdom) to transport gas from the depo to the gas stations.

These types of disruptions happen relatively often, are considered at a global level to be of low impact, and are the ones for which companies have business continuity plans and risk plans. The typical way of managing and preparing for these disruptions is a risk management framework that traditionally includes steps like: identifying the risk, analyzing, prioritizing, minimizing, and monitoring.

Many organizations have well-elaborated plans based on those methodologies that have proven effective with this type of disruption. The challenge is that the disruptions listed above were way beyond the risks these organizations considered. For example, almost no organization included in their business continuity plans the possibility of a global pandemic. Thus, when COVID-19 happened at a global level, those business continuity plans were of very limited use.

For this type of disruption, a localized disruption, the traditional definition of resilience is very appropriate: “the adaptive capability of the supply chain to prepare for unexpected events, respond to disruptions, and recover from them by maintaining continuity of operations at the desired level of connectedness and control over structure and function.”

2.2.6 Global Shortage of Products and Materials

The last type of disruption is the global shortage of products and materials, as has happened with the Russian invasion of Ukraine, with the world experiencing shortages of sunflower oil, cereals, and many other items. While this kind of disruption was eventually considered by military organizations, it should be said that most businesses didn’t even have in their risk plans the possibility that such an event might happen.

It should be noted that many experts consider the Russian invasion of Ukraine to be the event triggering a lot of the resilience supply chain plans by governments and companies. For example, at the start of the war, governments in countries like Egypt were very concerned that basic food would not be available in sufficient quantities for their population (Barnes 2022).

Also, for many European companies, it meant that the country risk in the east of Europe was not zero, as many have considered for years, and their supply chains were heavily affected. As an anecdotal illustration, Skoda car production was heavily affected by the war and was forced to move its sourcing of cable harnesses to the Czech Republic. This would be a typical example of managing a disruption and increasing the resilience of the supply chain, finding and developing a new supplier in a short time.

Another type of reaction by suppliers, particularly in the food industry, reacting to the shortage of sunflower oil, has been to change the composition of their products (what they call “flexible recipe”) to adapt to available ingredients. It should be said that this goes against the traditional way of working for many global companies who try to “standardize” products to obtain economies of scale.

Using the stated definition of resilience, we could say that the reaction of a company like Skoda, as explained above, can be classified neatly into that definition of a more resilient supply chain that could adapt to disruptions. Similarly, the idea of a flexible recipe for food companies would fit very well into that definition.

On the other hand, it could be said that no supply chain would ever be able to support a disruption of that magnitude. The amount of sunflower oil in the global market taken out by the Russian invasion of Ukraine was more than 50% (Strubenhoff 2022). Thus, a company consuming a lot of sunflower oil can't cope with this magnitude of disruption.

2.3 The Dilemma of Lost Revenues Vs. Cost Savings

The main reason for organizations to focus on increasing the resilience of their supply chains is that the disruptions create losses of potential revenues because of the lack of product. It also creates potential long-term losses of market share, as customers might be forced to try competitors' products and they might keep buying them after the disruption has finished. Finally, some companies are very concerned about the damage to the brand and reputation of their companies because of the failure in servicing customers.

There were plenty of examples during the pandemic of companies losing sales because they had chosen in the past to source products from low-cost locations that couldn't deliver due to the restrictions in manufacturing and trade. Some governments' organizations, like the Danish Ministry of Industry, even conducted studies about how to help companies to find nearshoring alternatives to avoid losing production and sales.[1]

The main challenge of potential lost revenues vs. cost savings is clearly expressed in the agility vs. efficiency matrix developed by Fisher (Fisher 1997) in the 1990s and presented in Figure 1. In that classification the author proposes that a more efficient supply chain for a differentiated product is not the right choice because the potential lost profit due to the lack of availability would be higher than the savings obtained by reducing the production cost. Logically, the ideal would be to be the most cost-efficient producer of a highly differentiated product, but the logic is that the more efficient a supply chain is, the less capacity to change volume it has and, therefore, the less capability to react and the higher the probability of lacking supply if the demand increases.

In practice, it is not at all obvious how to make those trade-offs, because cost savings are very precise while potential sales lost are perceived as very hypothetical. The calculation of how much a company is going to save by going to a low-cost location is often relatively easy to calculate and it appears in the accounting books as a positive deviation with extreme accuracy (it might be wrong, but it is very accurate). On the other hand, the sales lost because of a lack of capability to supply are very inaccurate because companies usually do not know how much more sales they would have got if they had the supply. For example, a retailer might not know how many sales were lost because the shelf was empty; it can only calculate the out-of-stock incidences at the retail level. (It might be different for digital retailers because they might calculate how many customers were looking for the product but couldn't buy it because of the lack of availability.)

[1] This author was asked by a Danish Ministry of Trade department to help with the development of a framework to make nearshoring decisions.

Figure 1: Matching Supply Chains with Products (Fisher 1997)

Because of this situation, many companies have found themselves in a supply chain situation over the last few decades where they had focused so much on efficiency that they had the wrong supply chain for an appropriate balance of loss revenues vs. cost savings. Finally, the instability of global supply chains has made many supply chains much less agile than before. For example, while sourcing from the PRC was, for many companies, quite flexible thanks to the responsiveness of Chinese suppliers, the reality of the transport situation has made those supply chains lose much of their agility.

In short, global supply chains have lost a lot of agility, capability to adapt, and, therefore, resilience. Thus, companies and governments are looking very strongly (some experts would even say desperately) to increase the reliability of global supply chains.

3. DIGITALIZATION: A TAXONOMY OF SUCCESS AND FAILURES

Given that our objective is to look at the developments in supply chain digitalization to improve resilience, we are going to use standard and convenient definitions of digitalization. We are not going to try to clarify the debate on defining what digitalization is in supply chains as there is a considerable amount of debate among scholars and executives about what is part of digitalization and what is not part of it.

A widely accepted definition is that of Industry 4.0, which includes the following technologies:

- Augmented reality
- System integration
- Cloud computing
- Big data and analytics
- IIOT (Industrial Internet of Things)
- Additive manufacturing (3D printing)

- Cybersecurity
- Autonomous robots
- Simulation

Since that taxonomy was proposed more than 10 years ago, several other technologies have emerged that could be added to that list. The two that we propose to include are artificial intelligence and blockchains, the first because of its wide use and the second because of the number of proposals concerning its potential utilization. We group artificial intelligence (AI) with big data and analytics, because AI requires big data and it could be argued that it is a further development of analytics from a practical point of view.

As we discussed previously, there have been successes and failures in the use of these digital initiatives in supply chains. We review below the successes and failures of those initiatives from the perspective of the supply chain resilience against the disruptions that have occurred in the last few years.

Given that the phenomenon is very recent, it is not yet possible to conduct empirical research about the usefulness of the technologies discussed; we just provide anecdotal examples based on how companies have used them. In some cases, there are very recent case studies that provide support for those claims, but it is obvious that future research should be conducted to test empirically to what extent the proposed effects on resilience are widely applicable in different industries and to different types of disruptions.

3.1 Augmented Reality

Augmented reality in the industrial setting has been a surprisingly useful digital initiative for very specific tasks like maintenance and training. At the same time, it has been a dismal failure, for the moment, for the consumer market, and its usefulness in increasing resilience is, for the moment, limited.

A widely publicized introduction of augmented reality was the Google Glass product introduced in a beta stage by Google. It was developed by Google with the ambition of becoming a widely adopted consumer product. However, it never became a mass production success, and the company basically discontinued the product and abandoned the market.

A very similar development has been happening very recently with the apparent popularity of the metaverse, which often includes the use of augmented reality together with blockchain technology. The company that used to be called Facebook changed its name to Meta to symbolize its commitment to that development with its augmented reality product, Oculus. It could be said that the jury is still out in assessing whether those developments would revolutionize the Internet or if it would experience limited adoption.

On the industrial side, augmented reality has been relatively widely adopted for training and maintenance. It could be said that while the adoption has been positive and with profitable business cases, it can’t be claimed that it has created a revolution.

Companies are finding it very useful to conduct training for operators on how to operate machines. The main advantage is that operators find it easier and quicker to learn. They are also finding that it makes maintenance tasks easier because of the way the maintenance operators are guided on how to proceed and the easy access and view of a representation of the machine being maintained.

With respect to its usefulness for resilience, it should be said that its impact has been relatively limited. Some companies explain that they can do maintenance remotely, and therefore the disruptions caused by machine failures are solved in a shorter time frame.

3.2 System Integration

By system integration is typically understood the automated linkage between different systems and the ability to share data transparently across different systems. Using this definition, applications like control tower would be part of the system integration class.

These applications allow companies to understand where products are produced, where materials are sourced and stored, where components are in the supply chain, and how the product reaches the distribution and the customer. There are different scopes and definitions of control tower, but at its root most of them allow parts of that visibility.

In one anecdotal example, a medical device company used a digital technology called "process mining" to extract the data from the ERP (Enterprise Resource Planning) system and to be able to follow in real time the procurement situation and foresee potential supply problems during the pandemic. Specifically, it was able to extract in real time all the purchase orders from the ERP, visualize their manufacturing orders, and identify which products were potentially affected by potential delays in deliveries of those purchase orders. It should be noted that process mining is not designed for that purpose but that the company used the ability to integrate systems to visualize the information.

There are many examples of companies using control towers or similar applications based on system integration to be able to visualize the supply chain end to end and to improve its performance significantly. On top of those systems, many companies use other digital technologies like AI and simulation to improve even further the performance of the supply chain.

In another significant example, in November 2021, at a Summit at IMD, a group of chief supply chain officers from big multinational companies selected three initiatives that they considered worth working on together to improve their supply chains. The most selected initiative was "Connected Planning," which was defined as the ability to integrate planning systems with other systems, specifically to deal with disruptions.

While it could be argued that system integration in itself doesn't solve any problem created by disruption, it was clear for many companies that the capability to visualize the situation and understand the whole picture was key to being able to take decisions to adapt the supply chain and to make it more resilient. In our opinion, this seems to be the most useful digital initiative to increase the resilience of the supply chain. While it doesn't create resilience in itself, executives explain that it allows faster and much more informed action.

3.3 Cloud Computing

This digital technology was thought to be one that big companies would develop and profit from. For example, GE (General Electric) developed a full suite of tools based on their protocol Predix that included a cloud computing solution.

After years of evolution, it has become a widely adopted solution provided externally by big companies (Google, Amazon, Microsoft, and Oracle) that other companies use as a service. It could be compared to a utility like electricity. Thus, it is widely adopted because it has provided clear benefits of scalability, ease of use, reliability, and good cost/price trade-offs. However, it could be argued that except for the providers of cloud computing services, it has not provided any competitive advantage to any company using it.

In terms of reliability, one of the advantages of moving to cloud computing is the increase in the reliability of digital services. However, no significant impact on the reliability of the supply chain itself was anecdotally reported by any company.

3.4 Big Data, Analytics, and Artificial Intelligence

These technologies have been widely adopted by companies in their supply chains in many different applications and in combination with other digital technologies. They have provided substantial benefits and some companies claim that they have provided clear advantages over their competitors (Bag et al. 2021; Papadopoulos et al. 2017).

Of particular relevance is the area of forecasting and predictive analytics. In the area of forecasting, many companies have found that by using big data and AI to create better forecasts of demand, significant improvements in accuracy and, consequently, in the overall performance of the supply chain have been achieved.

It was very interesting that at the outbreak of the pandemic, many experts doubted the use of AI for forecasting given that the situation was so different, and that the historical data reflected past trends but certainly not the dynamics created by the pandemic. Quite a few companies followed closely the comparison of the accuracy of AI systems vs. the forecast done by human experts to assess their efficacy and when to reconnect them. The conclusion was that AI didn't do worse than the human experts (Henkel IMD-7-2420 2022) in the first weeks of the pandemic and that after a few weeks the AI system was already providing superior predictions to the human experts.

A similar example is the use of big data and AI for predictive maintenance. By accumulating and analyzing a lot of data it is possible to predict when would be the best time to carry out the maintenance of machines and how to minimize the downtime due to interruptions. Many manufacturers are applying these tools to minimize maintenance operations, maximize availability, and reduce stoppages due to machine failure. Some companies have even been able to increase production when confronted with external disruptions by assessing the probability of failure vs. the opportunity cost of keeping production running.

We could claim that there is ample anecdotal evidence that big data, analytics, and artificial intelligence have proven very useful in increasing the resilience of the supply chain and, in some case, even provided a competitive advantage to the companies using them.

3.5 Industrial Internet of Things (IIOT)

The IIOT is relatively rarely used in isolation, but rather to capture data and to take actions at the local level. Many uses of this technology are a way of providing data to AI, real-time updates to control towers, and to apply changes in machine control systems based on the analysis of predictive maintenance, for example (Al-Talib et al. 2020; Chen et al. 2022).

A typical example of the IIOT is using this technology to control the energy consumption in different parts of the supply chain and taking action to minimize the waste and excess consumption. It could be thought of as an industrial application and version of the popular Nest device sold by Google to create an intelligent house with respect to heating and cooling.

Thus, despite having been adopted relatively widely, very few organizations would claim that it provides a competitive advantage or that it helps significantly to increase supply chain resilience. However, as mentioned before, it could be claimed that without its utilization, the benefits of other technologies like system integration or AI could, in some specific cases, be severely diminished.

3.6 Additive Manufacturing (3D Printing)

Additive manufacturing or 3D printing is a technology that has existed for decades but that was thought to reach maturity with the other technologies of Industry 4.0, and it was expected to deliver substantial benefits. At the beginning of the early 2010s, there were even expectations that it would replace mass manufacturing and enable mass customization of products. Even today, many experts would claim that in the near future 3D printing will replace mass production in quite a few industries.

The fact is that additive manufacturing today has found several markets where it provides substantial advantages (Naghshineh and Carvalho 2022). It is a clear winning proposition in several healthcare applications like hearing aids and prostheses for knees where the value of creating a product customized for the anatomy of a specific person is very high. The technology has also been very useful in the massive creation of art products (printed in plastic) and of toys.

In the industrial setting it is has found a clear application in the development of prototypes for products, in the production of temporary spare parts, and in the creation of tools to help to increase productivity in line set-ups (Henkel IMD-7-2420, 2022). Attempts were made during the early breakout of the pandemic to manufacture ventilator machines for breathing to help to increase production volumes, but the results were quite disappointing.

With respect to supply chain resilience, we can conclude that so far it has not proven to provide any increase in resilience. However, many proponents would claim that with the improvement in material technologies for printing we could see a much more positive impact on resilience.

3.7 Cybersecurity

It is not obvious how to classify cybersecurity with respect to supply chain resilience. It could be easily claimed that cybersecurity is a fundamental part of resilience because it prevents major disruptions due to cyberattacks. It could also be reasoned that apart from cyberattacks, which are a very specific kind of disruption, cybersecurity has no impact on the resilience of the supply chain.

The occurrence of a cyberattack is certainly a potential major disruption in a supply chain (Roege et al. 2017). It is not only a potential threat but a reality of increasing proportions as many cybersecurity company reports continuously remind us. An unfortunate memorable example was the attack on the shipping company Maersk that forced several of their ports to stop operations for several days. It was without doubt a major disruption. Since then, the company has increased very substantially its level of cybersecurity to enhance the resilience of the supply chain.

It is also the case that in the current Ukrainian conflict, cyberattacks have been used as a weapon with the objective of disrupting the supply chains of the opposing forces. It is even the case that hacker groups have tried independently to harm the communications and supply chains of the opposing forces.

It could also be argued that these are very specific attacks that focus not only on supply chains but also on disrupting whole organizations, and that, therefore, they are not specific to supply chains. While there is merit in this argument, we believe that it should be included in the supply chain resilience considerations.

The challenge with cybersecurity is that it is difficult to estimate its benefits, since it is more a prevention tool for a specific risk than a way to help the response of the supply chain.

3.8 Autonomous Robots

Autonomous robots have existed for many decades and have been used in supply chains for many years. The main, relatively recent development in this area was the creation of cobots, or collaborative robots. In contrast to the previous generation of robots that could be dangerous machines and as such were typically kept in cages, cobots will stop to make sure that they do not damage any human or animal and work alongside humans. There has also been a lot of expectation about the development of autonomous vehicles, like self-driving trucks, that were going to alleviate substantially the problem of the lack of truck drivers.

The adoption of robots continues to increase in the supply chain because of the ease of implementation and the decreased costs, and to alleviate the struggle to find operators willing to work in certain environments. A clear example of that is Amazon Robotics using its Kiva robots to reduce cost, to be able to deliver packages in a reduced time, to facilitate the work of its warehouse workers, and to reduce the cost of picking through very sophisticated use of AI, the IIOT, and systems integration. It is a clear example of those technologies combining to provide a competitive advantage to a company.

On the not-so-positive side, cobots and autonomous vehicles have not delivered at all on the expectations created. Relatively few cobots have been implemented in supply chains, and engineering experts claim that we are still many years away from self-driving vehicles (although this is not an opinion shared by leading companies like Tesla).

The fact is that autonomous robots have not, for the moment, provided any major help to increase the resilience of supply chains. Certainly, the potential of autonomous driving is high with respect to resilience, but it is not yet a reality.

3.9 Simulation

Digital simulations have been used for decades in supply chain management to design its footprint, to optimize its performance, and to respond to disruptions. The developments in recent years have mostly been about the level of granularity and realism of the simulation, the ability to run many scenarios in a very short time, and the ability to use more sophisticated algorithms to find better solutions using many more variables.

The benefits have been the ability to minimize costs, the development of business continuity plans based on different scenarios, and the ability to react in the case of disruptions by evaluating different possibilities. It is the last of these that has seen the biggest improvements with the capability of central teams to gather information in real time and to even use artificial intelligence to evaluate many options digitally and present to management the ones worth considering.

As an illustration, one of the global leaders in packaging has a center in South America where they continuously monitor and simulate different scenarios to enable them to make fast decisions in reacting to unexpected events. The benefits in the words of the chief supply chain officer of that company are “a much better and faster reaction to disruptions.”

Thus, simulation is certainly a digital initiative that provides resilience to supply chains by allowing much better and faster decisions to be made in adapting to disruptions. Also, it is worth noting that the combination of simulation and other digital technologies like artificial intelligence and system integration has provided even better results.

3.10 Blockchain for Supply Chain

The last digital initiative that we consider in this paper is blockchain for supply chains (Taqui et al. 2022; Dubey et al. 2020; Min 2019). We include it in this analysis because of the amount of news about it both from providers of solutions (i.e., companies like IBM and Accenture) and from companies promoting its use (e.g., Maersk was promoting its use for shipping e-commerce), and because of the increasing number of doctoral dissertations about its use in supply chains (this author has been asked by several doctoral students from other universities in the last year to provide input as a scholar in supply chains).

The fact is that while there are many claims about the expected use of blockchain for supply chains, its use at scale is very rare. Many companies, particularly FMCGs (Fast-Moving Consumer Goods companies), have done proofs of concept successfully, so the technology works. However, it seems that no company has scaled the solution up, mainly because they find that there are no important benefits associated with the use of the technology.

There are many debates about how in the future the technology will prove very useful for supply chains in many situations, but the fact today is that there are very few examples of successful and beneficial deployments at scale. Accordingly, today blockchain is not a digital technology that increases the resilience of a supply chain.

Finally, we summarize the effect of these technologies on supply chain resilience in Table 2. In this table a +++ sign means that the technology strongly supports supply chain resilience while a + sign indicates a minor supporting effect. It should be mentioned that some technologies, like robots and blockchain, might take time to redeem their potential, so this assessment is based on the current status of the achievements of those technologies as of today (2023).

Table 2: Effect of Digital Technologies on Supply Chain Resilience

Digital Technology Used in Supply Chain	Effect on Supply Chain Resilience
Augmented Reality	+
System Integration	+++
Cloud Computing	+
Big Data, Analytics, and Artificial Intelligence	+++
Industrial Internet of Things (IIOT)	+
Additive Manufacturing (3D Printing)	+
Cybersecurity	++
Autonomous Robots	+
Simulation	+++
Blockchain	+

4. DISCUSSION

To assess whether a digital solution has a positive impact on resilience, we can review for which kinds of disruption the digital technologies examined are able to increase resiliency or provide help to increase resiliency. In Figure 2, we list the different types of disruption that we identified in Section 4 and which digital technologies have proved to increase resilience against those types of disruption.

It is very important to emphasize that this assessment is based on the experience provided by executives and on some cases documented by scholars about the use of those digital solutions when facing disruptions over the last 2 years. We propose this classification with the objective of promoting further research to empirically validate these propositions.

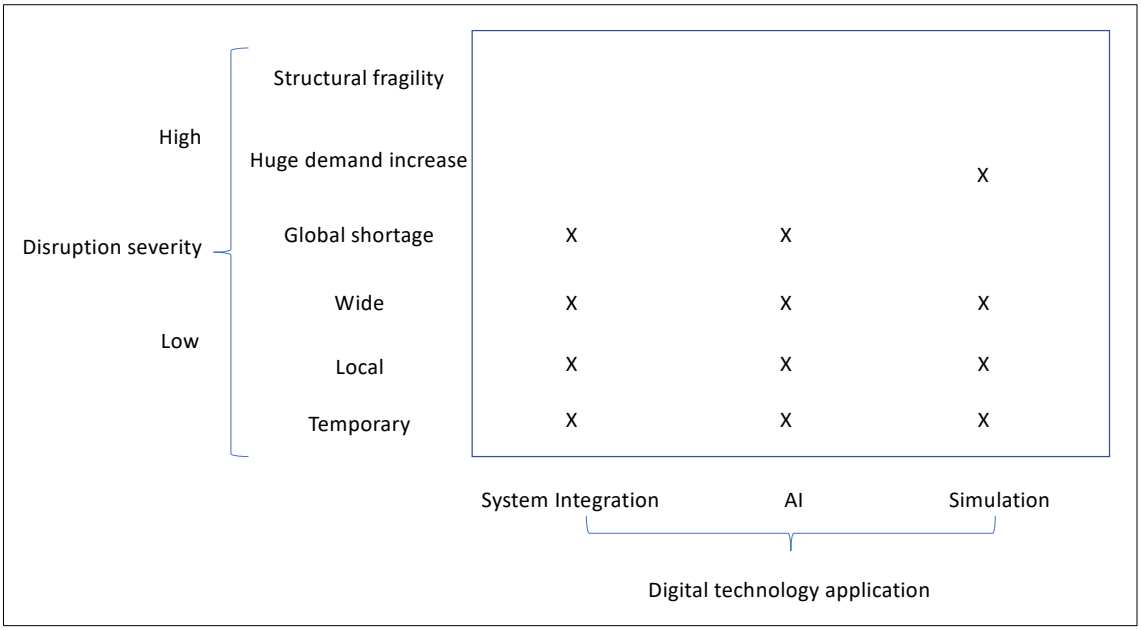
We should also note that the effect of the analysis realized leads to the conclusion that different digital solutions alone might not be the best way to proceed. In Figure 2, we present the different types of disruption identified on the vertical axis, and the digital solutions that seem effective in increasing the resilience of the supply chain when faced with those disruptions on the horizontal axis. The way to read the figure is that systems integration (x axis) increases resilience in the case of disruptions that are temporary, local, widespread, and for global shortages, while not increasing resilience significantly in the case of a huge demand increase and structural fragility.

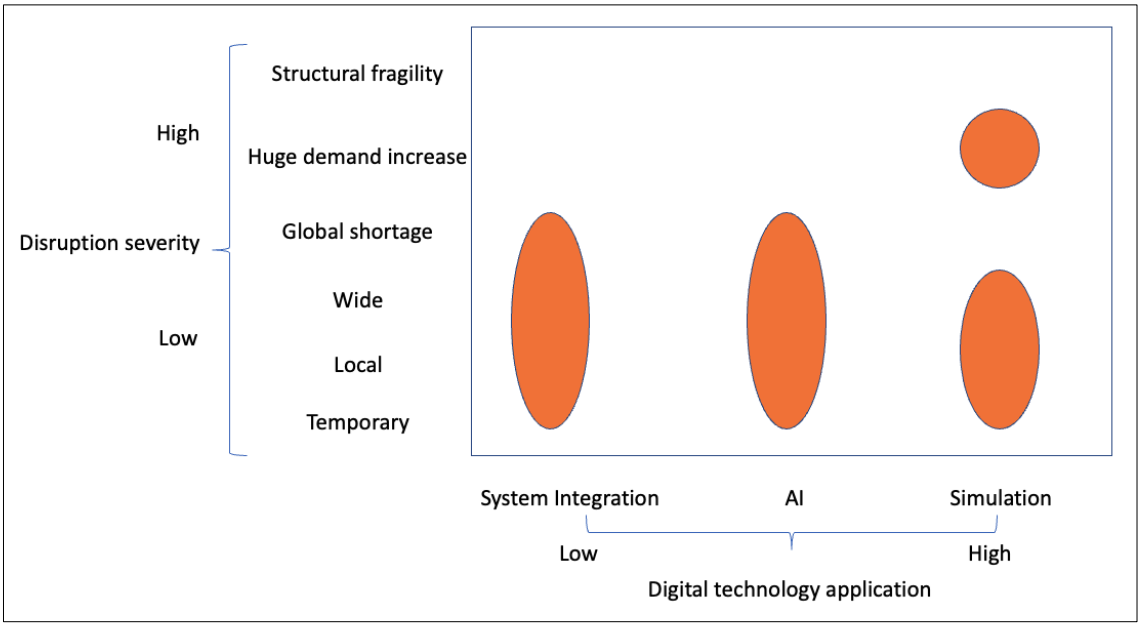
Thus, our framework leads to the conclusion that a potential hypothesis to test is that the combination of digital solutions could be superior to their individual use.

The analysis of the different types of disruption and how digital supply chains help to increase the resilience against those disruptions leads to some expected and some surprising results.

As could be expected, for major disruptions and structural challenges in supply chains, a digital supply chain is not going to have a much better resilience than a nondigital savvy one. Digital solutions might help marginally, but the disruption is so brutal that it could be argued that there are very few ways of increasing resilience.

Figure 2: Framework for Disruptions and Digital Solutions: Which Digital Solution Increases the Resilience of the Supply Chain with Respect to the Types of Disruption





Source: Created by the author.

For some substantial disruptions concerning services, infrastructure, and global shortages, companies have found that system integration, AI, and simulation help in making decisions that increase the resilience of the supply chain. The surprising factor seems to be the cumulative effect of those digital solutions. It would be a very interesting hypothesis to test that these solutions reinforce each other. It would also be very interesting to test whether there is a specific order that maximizes the value they provide.

It is also surprising that many digital solutions have very few effects on resilience. Technologies like robots, the IIOT, and augmented reality seem to have no impact on resilience. Others like 3D printing and blockchain seem to have a potential role in the future but today that potential is not realized.

Future research should test empirically whether the propositions made in this paper are validated across different industries and continents. Our suggestion is that such research should clearly identify resilience against the type of disruption, because, as we propose in our framework, different solutions apply to different aspects of resilience.

The challenge for such future research is that to measure scientifically how resilient a supply chain is against specific disruptions, it would be necessary to have multiple disruptions of that type. Hopefully, we are not going to have repeated pandemics or wars, so the research should be based on the answers from executives. Nevertheless, such research would be valid since many executives have gone over such situations in recent years.

5. CONCLUSION

The supply chains of the last two years have experienced unprecedented disruptions that have made the world try to increase its resilience fundamentally. The reality is that many supply chains have shown their fragility against disruptions, prompting companies and governments to try to act to improve the situation.

Digital supply chains have proved to be more resilient than nondigital ones, but not in all cases against all sorts of disruptions. This paper has proposed a framework to enable an understanding of which digital solutions are effective against which types of disruption based on documented examples and experiences from executives in conversation with the author.

The framework key learning is that the most effective digital tools for raising the resilience of supply chains are systems integration, AI, and simulation. Furthermore, when combined, they are even more effective. The somewhat challenging finding is that other digital technologies seem to have, at best, a marginal effect on resilience.

From the policy point of view, the fact that systems integration is one of the effective digital technologies for increasing supply chain resilience raises the hypothesis that regulators could take into consideration the need to foster the development of standards for systems to be able to integrate.

As mentioned in the introduction, governments and companies are adopting policies to increase the resilience of supply chains, particularly in the Americas and Europe. As a consequence, disruptions in global supply chains are driving global companies to find alternatives to Asia and the Pacific as the main source of manufacturing goods. Thus, digital tools that increase resilience will eventually reduce the extent to which companies are going to move manufacturing away from Asia and the Pacific. The recommendation based on this research is that Asia and the Pacific should promote the use of systems integration, AI, and simulation among companies in the region to increase the resilience of their supply chains. That would lead to global companies continuing to source from Asia and the Pacific.

This research is limited in that it is based on anecdotal evidence from practitioners and from documented academic cases. More research is needed to validate the proposed framework; in particular, the use of empirical research could validate the positive findings about technologies impacting in a positive way the resiliency of supply chains.

REFERENCES

Al-Talib, M., W. Y. Melhem, A. I. Anosike, J. A. G. Reyes, and S. P. Nadeem. 2020. Achieving Resilience in the Supply Chain by Applying IoT Technology. *Procedia Cirp*, 91: 752–757.

Bag, S., P. Dhamija, S. Luthra, and D. Huisingh. 2021. How Big Data Analytics Can Help Manufacturing Companies Strengthen Supply Chain Resilience in the Context of the COVID-19 Pandemic. *The International Journal of Logistics Management*. https://doi.org/10.1108/IJLM-02-2021-0095.

Barnes, J. 2022. War in Ukraine Threatens Access to Egypt's Staple Food: Bread. Climate Champions, March 2022. https://climatechampions.unfccc.int/in-egypt-where-a-meal-isnt-complete-without-bread-war-in-ukraine-is-threatening-the-wheat-supply-and-access-to-this-staple-food/.

Buatois E., and C. Cordon. 2020. A Post COVID-19 Outlook: The Future of the Supply Chain. IMD Tomorrows Challenges, May 2020.

Büyüközkan, G., F. Göçer. 2018. Digital Supply Chain: Literature Review and a Proposed Framework for Future Research. Computers in Industry. 97: 157–177. https://www.sciencedirect.com/science/article/abs/pii/S0166361517304487.

Chen, X., C. He, Y. Chen, and Z. Xie. 2022. Internet of Things (IoT)—Blockchain-enabled Pharmaceutical Supply Chain Resilience in the Post-pandemic Era. *Frontiers of Engineering Management.* 10: 1–14.

Daehy, Y., K. Krishnan, K. Alsaadi, and S. Alghamdi. 2019. Effective Cost Minimization Strategy and an Optimization Model of a Reliable Global Supply Chain System. *Uncertain Supply Chain Management*, 7: 381–398. 10.5267/j.uscm.2018.12.007.

Dubey, R., A. Gunasekaran, D. J. Bryde, Y. K. Dwivedi, and T. Papadopoulos. 2020. Blockchain Technology for Enhancing Swift-trust, Collaboration and Resilience within a Humanitarian Supply Chain Setting. *International Journal of Production Research*, 58(11): 3381–3398.

Fisher, M. 1997. What is the Right Supply Chain for Your Product? *Harvard Business Review*, 75: 105–116.

GlobalData Healthcare. 2021. Ventilator Market Set to Return to Pre-pandemic Levels in 2021. Medical Device Network, Jan 2022. https://www.medicaldevice-network.com/comment/ventilator-market-return-pre-pandemic-levels-in-2021/.

Heikkila, J., and C. Cordon. 2002. Outsourcing: A Core or Non-core Management Strategic Decision. *Journal of Strategic Change*, 11(4, June/July): 183–193.

Kumar, A., Y. Cantieni, M. Amici, and C. Cordon. 2019. Faurecia Digital Transformation, IMD Case Collection, IMD-7-2076, IMD-7-2077 and IMD-7-2078.

McKinsey & Co. 2021.Coping with the Auto-semiconductor Shortage: Strategies for Success. May 27.

Min, H. 2019. Blockchain Technology for Enhancing Supply Chain Resilience. *Business Horizons* 62(1): 35–45.

Naghshineh, B., and H. Carvalho. 2020. The Impact of Additive Manufacturing on Supply Chain Resilience. In *Doctoral Conference on Computing, Electrical and Industrial Systems.* Springer, Cham. pp. 214–221.

Naghshineh, B., and H. Carvalho. 2022. The Implications of Additive Manufacturing Technology Adoption for Supply Chain Resilience: A Systematic Search and Review. *International Journal of Production Economics* 247: 108387.

OECD Policy Responses to Coronavirus (COVID-19). 2020. The Face Mask Global Value Chain in the COVID-19 Outbreak: Evidence and Policy Lessons. https://www.oecd.org/coronavirus/policy-responses/the-face-mask-global-value-chain-in-the-covid-19-outbreak-evidence-and-policy-lessons-a4df866d/.

Papadopoulos, T., A. Gunasekaran, R. Dubey, N. Altay, S. J. Childe, and S. Fosso-Wamba. 2017. The Role of Big Data in Explaining Disaster Resilience in Supply Chains for Sustainability. *Journal of Cleaner Production*, 142: 1108–1118.

Ponis, S. T., and Koronis, E. 2012. Supply Chain Resilience? Definition of Concept and its Formative Elements. *The Journal of Applied Business Research* 28(5): 921–935.

Ponomarov, Serhiy Y., and Mary C. Holcomb. 2009.Understanding the Concept of Supply Chain Resilience. *The International Journal of Logistics Management* 20(1): 124–143.

Reuters, January 5, 2021. Increased New-car Demand During Pandemic has U.S. Industry Optimistic about 2021. https://www.reuters.com/business/autos-transportation/increased-new-car-demand-during-pandemic-has-us-industry-optimistic-about-2021-2021-01-05/.

Reuters, March 17, 2020. Volkswagen Suspends Production as Coronavirus Hits Sales. https://www.reuters.com/news/picture/volkswagen-suspends-production-as-corona-idUSKBN2140OF.

Roege, P. E. et al. 2017. Bridging the Gap from Cyber Security to Resilience. In *Resilience and Risk*. Dordrecht: Springer, pp. 383–414.

Spieske, A., and H. Birkel. 2021. Improving Supply Chain Resilience through Industry 4.0: A Systematic Literature Review under the Impressions of the COVID-19 Pandemic. *Computer & Industrial Engineering*, 158(2021): 107452.

Statista. 2022. Number of Vehicles Removed from Production Worldwide Due to the Semiconductor Shortage in 2021, with a Forecast for 2022 and 2023. https://www.statista.com/statistics/1288308/automotive-production-reduction-semiconductor-shortage/ (accessed 18 Oct. 2022).

Strubenhoff, H. 2022. The War in Ukraine Triggered a Global Food Shortage. Brookings. https://www.brookings.edu/blog/future-development/2022/06/14/the-war-in-ukraine-triggered-a-global-food-shortage/.

Taqui, W., I. El Hassani, A. Cherrafi, K. Zekhnini, and A. C. Benabdellah. 2022.Blockchain Technology for Supply Chain Resilience. In 2022 *14th International Colloquium of Logistics and Supply Chain Management* (LOGISTIQUA IEEE), pp. 1–6.

The Wall Street Journal, July 5. 2021. Container Shipping Prices Skyrocket as Rush to Move Goods Picks Up.

Wellian, E., and C. Cordon 2022. Henkel: Digital as Enabler to Drive Sustainability, IMD-7-2420 Case Collection.

———. 2020. PMI: Disrupting the Tobacco Industry. IMD Case Collection, IMD-7-2180.