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Responding to the ripple effect from systemic disruptions: empirical evidence from the semiconductor shortage during COVID-19

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Abstract

Purpose – The ripple effect (i.e. disruption propagation in networks) belongs to one of the central pillars in supply chain resilience and viability research, constituting a type of systemic disruption. A considerable body of knowledge has been developed for the last two decades to examine the ripple effect triggered by instantaneous disruptions, e.g. earthquakes or factory fires. In contrast, far less research has been devoted to study the ripple effect under long-term disruptions, such as in the wake of the COVID-19 pandemic.

Design/methodology/approach – This study qualitatively analyses secondary data on the ripple effects incurred in automotive and electronics supply chains. Through the analysis of five distinct case studies illustrating operational practices used by companies to cope with the ripple effect, we uncover a disruption propagation mechanism through the supply chains during the semiconductor shortage in 2020–2022.

Findings – Applying a theory elaboration approach, we sequence the triggers for the ripple effects induced by the semiconductor shortage. Second, the measures to mitigate the ripple effect employed by automotive and electronics companies are delineated with a cost-effectiveness analysis. Finally, the results are summarised and generalised into a causal loop diagram providing a more complete conceptualisation of long-term disruption propagation.

Originality/value – The results add to the academic discourse on appropriate mitigation strategies. They can help build scenarios for simulation and analytical models to inform decision-making as well as incorporate systemic risks from ripple effects into a normal operations mode. In addition, the findings provide practical recommendations for implementing short- and long-term measures during long-term disruptions.

Keywords Supply chain resilience, Ripple effect, Systems thinking, Systemic risk, Semiconductor shortage, Case-study

Paper type Case study

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1. Introduction

The ripple effect (i.e. disruption propagation in networks) has been a visible topic in supply chain resilience and viability (Ivanov *et al.*, 2014; Chowdhury *et al.*, 2020; Li *et al.*, 2021; Sawik, 2022), constituting a critical systemic risk (Ghadge *et al.*, 2013; Garvey *et al.*, 2015; Llaguno *et al.*, 2022; Alikhani *et al.*, 2023). While a considerable body of knowledge has been developed for the ripple effect triggered by instantaneous disruptions, e.g. earthquakes or factory fires, little is known about the ripple effect under long-term disruptions (Dolgui and Ivanov, 2021; Ivanov and Dolgui, 2021; Sindhwani *et al.*, 2023). This novel context of long-term disruptions has appeared in the wake of the COVID19 pandemic and received increasing research attention (Ivanov, 2020; Singh *et al.*, 2021; Brusset- *et al.*, 2022; Delasay *et al.*, 2022).

Since 2020, companies worldwide have experienced significant shortages in the supply of semiconductors. Many countries worldwide imposed lockdowns of different extents to prevent the rapid spread of the coronavirus (Paul and Chowdhury, 2021; Queiroz *et al.*, 2022). Lockdowns and high levels of sickness led to employee shortages, leading to production disruptions (Rozhkov *et al.*, 2022; Li *et al.*, 2023). Further, bottlenecks at ports and shipping delays contributed to the shortage. Semiconductor producers had to carry additional shipping costs since the containers were stuck at ports for longer. Moreover, container shipping costs skyrocketed (Ramani *et al.*, 2022). Several other disruptions apart from the pandemic intensified the impacts of the following ripple effects. "A cold wave in Texas in early 2021 impacted production at the Samsung, Infineon Tech, and NXP semiconductor plants. In addition, a fire at the Renesas Electronics Corp facility in Japan added to the production disruptions related to the production of automotive chips" (Ramani *et al.*, 2022).

Besides, the legally protected know-how involved in semiconductor production contributed to the propagation of the shortage. Facilities mainly belong to US companies, while the US government prohibited the export of manufacturing equipment to several Chinese companies. "In addition, the US government imposed sanctions on Huawei Technologies and coordinated with TSMC [Taiwan Semiconductor Manufacturing Company] to prevent the sale of semiconductor chips to Huawei and ZTE. In anticipation of being put on a US trade blacklist, the firm began stockpiling chips in 2019, contributing to tight capacity at Huawei's leading foundry supplier TSMC" (Ramani *et al.*, 2022). As a result, some clients started buying more and hoarding the components to ensure their availability, leading to supply chain uncertainty (Bloomberg, 2022). The semiconductor shortage accordingly represented a unique challenge for companies dealing with long-term and overlapping ripple effects resulting from supply chain complexity, vulnerability, and volatility.

This study aims to complement and strengthen the existing research on the ripple effect in global supply chains, asking the following research question:

RQ1. How can companies mitigate the ripple effect in their supply chains resulting from a long-term, systemic disruption?

To answer the proposed research question, we qualitatively analysed secondary data on the ripple effects incurred by automotive and electronics supply chains. A multiple case study approach was used to study the complex structures of the ripple effect during COVID19, drawing on multiple sources of information (Eisenhardt and Graebner, 2007). The study focused on the empirical analysis of five published case studies and triangulated data from additional qualitative sources, analysing operational practices used by companies with a cost-effectiveness analysis (CEA) (Tuominen *et al.*, 2015). Applying theory elaboration as proposed by Fisher and Aguinis (2017) in the second step, we sequence the triggers of the ripple effect and uncover the disruption propagation mechanism during the semiconductor shortage in 2020–2022. In the last step, the measures to mitigate the ripple effect employed by the companies are delineated through a systems thinking approach, resulting in a causal loop diagram (CLD) (Sterman, 2001). In this context, the CLD helps to gain sense of the behaviour of a nonlinear system based on specific feedback structures (Sedlacko *et al.*, 2014).

Our results show that most of the triggers for the shortage were similar among the manufacturing industries. For instance, a decreased demand for vehicles at the beginning of the COVID-19 pandemic forced car manufacturers to limit chip procurement. In turn, increased demand for consumer electronics led to increased orders of chips from the industry. Semiconductor manufacturers hence devoted their production capacities to the electronics sector. The research demonstrates that both industries experienced common effects: production capacity reduction, factory shutdowns, longer lead times, reduced outputs, employee layoffs, product mix changes, increased costs, product unavailability, and delivery delays (MacCarthy and Ivanov, 2022). Among the identified measures, all case companies dealt with the ripple effects by including stockpiling, production capacity restriction, product mix adjustments, and production of their own chips. Specific mitigation strategies were applied only by the carmakers, which included partial production, sales strategy modernisation, and chip usage reduction.

Our study contributes to the domain of resilience and viability research (Ivanov, 2020; Singh *et al.*, 2021; Brusset *et al.*, 2022; Delasay *et al.*, 2022). We add to the academic discourse by explaining how specific strategies mitigate the ripple effect and synthesise the empirical findings into a CLD. The CLD particularly can be used in future research for building more nuanced scenarios in simulation and analytical models on the ripple effect and systemic risks under long-term disruptions. Our study provides managerial insights for implementing short- and long-term measures during long-term disruptions. The remainder of this paper is organised as follows: Section 2 analyses literature related to the ripple effect and the semiconductor shortage during COVID19. Section 3 presents the research methodology. Section 4 presents the case study results. Cross-case analysis, theory elaboration and building of the CLD follow in Section 5. We conclude in Section 6 by discussing the main findings of our research.

2. Research background

The ripple effect is one of the most prominent research avenues in supply chain resilience. Defined by Ivanov *et al.* (2014) as "*the impact of a disruption on supply chain performance and disruption-based scope of changes in the supply chain structures and parameters*" and later by Dolgui *et al.* (2020) as "*a downstream propagation of the downscaling in demand fulfilment in the supply chain as a result of a severe disruption,*" research on the ripple effect has been grown considerably as documented in literature reviews by Dolgui *et al.* (2020), Hosseini *et al.* (2019), Ivanov and Dolgui (2021), and Llaguno *et al.* (2022). Research published before the COVID19 pandemic has focused chiefly on the propagation of a single disruption through some downstream echelons (Li and Zobel, 2020; Li *et al.*, 2021; Hosseini and Ivanov, 2022). Valuable methods for mitigating the ripple effect through backup sourcing, capacity flexibility, and inventory optimisation have been developed (Ivanov, 2022a, b; Park *et al.*, 2022; Aldrighetti *et al.*, 2023).

While many component shortage mitigation strategies exist in the literature, most consider short-term solutions (Ivanov, 2017; Pavlov *et al.*, 2019; Lei *et al.*, 2021). It is implied that the shortage is temporary and can be recovered by some adjustments to the company's sourcing strategy, inventory, or ordering policy *after a disruption* (Ivanov *et al.*, 2019). Component shortages before the semiconductor crisis were mainly caused by distinct disruptions, such as an accident at a factory or a machine breakdown at one of the suppliers. Such single disruptions can indeed cause a ripple effect across the whole supply chain, but their impact can be mitigated in the short-term (Hosseini *et al.*, 2019; Dolgui *et al.*, 2020). However, the semiconductor shortage resulted from the long-term COVID19 pandemic. This worldwide pandemic is a unique and systemic disruption for the following reasons (Ivanov, 2020; Paul and Chowdhury, 2021; Ghadge *et al.*, 2022; Pavlov *et al.*, 2022; Hägele *et al.*, 2023):

(1) Long-lasting disruption with hardly predictable scaling and dynamics

(2) Simultaneous disruption in supply, demand, and logistics infrastructure

(3) Simultaneous disruption and epidemic spread

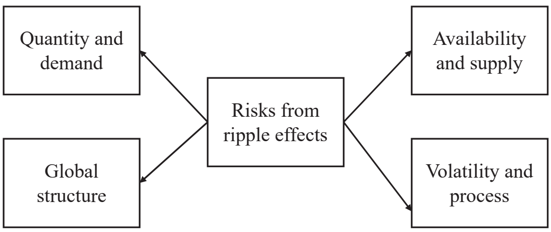
(4) Recovery *in the presence of a disruption*

The semiconductor shortage during the pandemic follows the above disruption specifics (Ramani *et al.*, 2022). As the COVID19 pandemic started and propagated worldwide, the automotive supply chain experienced many shocks. As a result of a decline in demand and limited production capacities, the automotive industry procured fewer semiconductors. At the same time, the demand for consumer electronics increased significantly. People started working remotely and spending more time at home in general. Therefore, gadgets like computer screens, laptops, headsets, and entertainment electronics like gaming consoles were highly desired. This forced semiconductor producers to allocate their already limited capacities to this sector. As the demand for vehicles started recovering towards the end of 2020, car manufacturers increased their production volumes. Thus, they ordered more semiconductor chips, leading to increased demand that propagated upstream. However, supplies could not meet the higher demand because of limited capacities. Semiconductors were unavailable in the amount required, which disrupted supply for the automotive industry.

During long-term crises, accordingly, disruptions are no longer only occasional incidents but transformed into long-term everyday challenges organizations face, which form a new business-as-usual-mode, blurring the lines between traditional operation's mode separation (Ivanov, 2024). Hence, more research must be devoted to revealing the traits of corporate decisions, which tackling multiple dimensions (see Figure 1). The semiconductor shortage represents unique challenges for manufacturing companies by causing a ripple effect and disruption cascading along the entire value chain when recovery measures should be taken *in the presence of a disruption*. Recent research poses that this novel context extends a traditional understanding of resilience toward supply chain viability as an ability to survive in the presence of long-term crises and disruptions compounding economic and societal aspects (Ivanov and Dolgui, 2020; Ivanov, 2022c, 2023; Ivanov and Keskin, 2023; Ivanov *et al.*, 2023). Related mitigations strategies emphasise taking adaptive measures to ensure the continuity and survivability of the supply chain to face the newly emerging continuous base of disruptions, which is becoming an essential part of the normal operations mode (Ivanov, 2024).

3. Research design

This research applies a multiple-case study approach suitable for (middle-range) theory development and refinement (Voss, 2010). Based on the empirical evidence, the study



Source(s): Ivanov *et al.* (2014)

Figure 1. Risks from ripple effects

elaborates on mitigation strategies to extend the understanding of how companies can cope with the ripple effect in their supply chains resulting from a long-term, systemic disruption. Figure 2 provides an overview of the research design. The unit of analysis is the mitigation practice already realised at the companies. The cases were selected based on the theoretical sampling method proposed by Eisenhardt (1989), involving 4 to 10 cases from multiple industries. Furthermore, quality procedures regarding external validity, construct validity, and reliability were in place to ensure methodological rigour (Yin, 2009) (Table 1).

3.1 Case selection and data collection

Following the scope of the study, cases were chosen from the population of existing companies affected by the ripple effects of COVID19. The cases were chosen from the automotive and consumer electronics industries, as the pandemic significantly affected those industries. Secondly, the selected companies had to represent different regions of the world to consider if the location impacted any noticeable decisions undertaken. Furthermore, the supply chains of the companies had to be global. Thirdly, the cases with different strategies applied were chosen to get a comprehensive overview of possible approaches. Finally, since the research is based on secondary data, choosing case companies with sufficient publicly available information was essential. The study's focus on the automotive and consumer electronics industries limits applicability of the findings, acknowledging that extant literature already tackled other industries such as the apparel and textile industry (Polyviou *et al.*, 2023). Table 2 gives an overview of the observed companies and initiatives and the analysed data sources.

This research applies secondary data collection, which serves as a reliable source for case study research and theory development (Eisenhardt and Graebner, 2007). Several operations and supply chain management studies have already conducted case study research on secondary data sources as they particularly provide up-to-date data (e.g. Meier *et al.*, 2023).

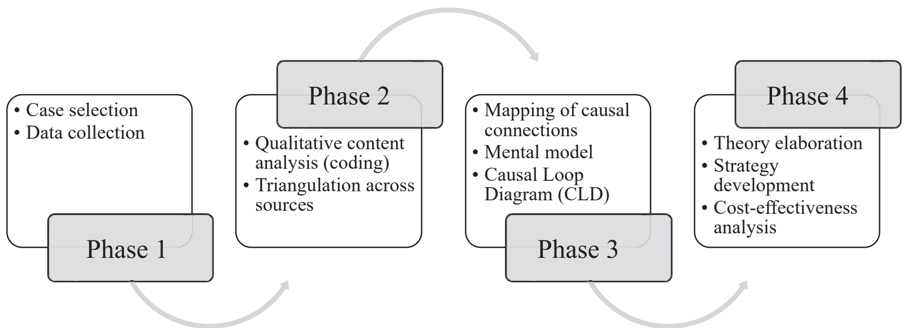


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Figure 2.
Research design

Table 1.
Quality procedures

Criteria	Realisation
Internal validity	Data analysis was performed by two researchers
External validity	Triangulation, comparisons across multiple sources
Construct validity	Collecting data from multiple sources
Inter-rater reliability	Exposing relevant parallels across multiple sources

Source(s): Yin (2009)

Cases	Scope	Sources
Tesla	Tesla, Inc., is an automotive company founded in 2003. It is focused on designing, developing, manufacturing, and selling electric vehicles with self-driving capability, stationary, as well as solar energy generation and storage systems	Media interviews/press releases, firm website pages, literature
Hyundai	Hyundai Motors is a multinational automotive manufacturer from South Korea founded in 1967. As an automotive manufacturer operating in all segments, Hyundai has mainly grown in the SUV, electric vehicle, and luxury segments in recent years	Media interviews/press releases, firm website pages, literature
Ford	Ford Motor Company is an American multinational automotive company founded in 1903 by Henry Ford. It owns the Ford and Lincoln car brands. Ford, as well, is operating in all car segments	Media interviews/press releases, firm website pages, literature
Sony	Sony Group Corporation is a Japanese multinational corporation founded in 1946. It is one of the world's largest consumer and professional electronics manufacturers. Its product portfolio includes various electronic products such as audio/video equipment, digital cameras, home appliances, video games, and gaming consoles	Media interviews/press releases, firm website pages, literature
Apple	Apple Inc. is an American multinational tech company founded in 1976. Apple's product portfolio includes smartphones, tablets, PCs, laptops, and smartwatches, as well as related software, accessories, services, and applications. Its supply chains are considered a benchmark among manufacturing companies	Media interviews/press releases, firm website pages, literature

Source(s): Table created by authors

Table 2. Case characteristics

To achieve a high reputation and trustworthiness of the data, we draw on multiple authoritative third-party sources, also to avoid researcher bias (Calantone and Vickery, 2010). The sources included public reports and websites, as well as professional newspapers and magazines such as Reuters, Forbes, and other journals. The triangulation of multiple data sources helped to achieve construct validity. For instance, information on the market share, production volumes, sales and revenue values were retrieved from Statista and compared with the main sources to conclude overall performance. The third-party data further reduced over-reliance on internal data, increasing reliability. The collected data of each case were saved in separate documents to prepare for the subsequent coding and analysis.

3.2 Data analysis and theory elaboration

To analyse the qualitative data, a qualitative content-analysis approach was conducted in a structured, abductive manner (Schreier, 2012). A deductive category system derived from the literature was used first to code the empirical data (see Figure 1). Final codes were built inductively when mentioned frequently in the documents based on the researcher's interpretation of the specific construct (see Figure 3). This allowed for flexible coding and clustering of the results. The codes on costs and revenues were particularly valuable to subsequently conduct the CEA (Bryan *et al.*, 2007). Following Fisher and Aguinis (2017), a theory-elaboration technique of structuring sequence relations was further used to refine the emerging constructs regarding industry contexts and their relationships with each other. In this approach, theory elaboration can be described as a process of conceptualising and executing empirical research using pre-existing conceptual models as a basis to

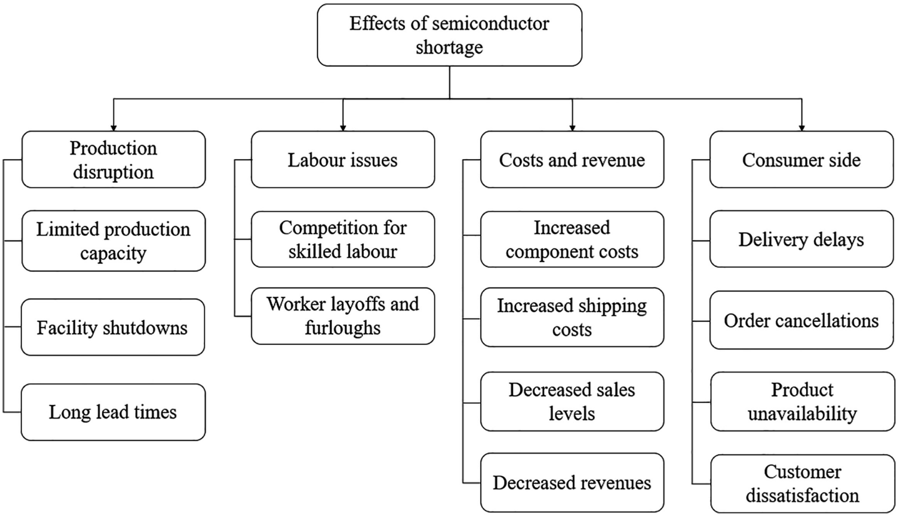

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Figure 3.
Coding scheme from the qualitative content analysis

develop new theoretical insights by structuring theoretical constructs and relations to explain empirical observations (cf. Fisher and Aguinis, 2017). Accordingly, the observed ripple effects were sequenced to establish cause-effect relationships. As a result, the propagation of the ripple effect through the supply chains could be demonstrated. Finally, ripple effect mitigation strategies could be deduced as practical guidelines for manufacturing companies.

3.3 Systems thinking and causal loop diagram

Systems thinking and system dynamics (SD) modelling deals with the nonlinear behaviour of complex systems over time (Morecroft, 1992), aiming to understand how feedback structures determine a system's behaviour (Coyle, 1996). Following Davis *et al.* (2007), SD is also increasingly used as a methodology for theory development. Particularly for longitudinal and nonlinear processes, they can help to build a more comprehensive and precise theory from so-called simple theory (Davis *et al.*, 2007). CLDs are the most important qualitative modelling method in systems thinking (Coyle, 1996; Sterman, 2001). They comprise a set of nodes and edges, connected by arrows denoting the causal influences among them. To better understand the propagation of the ripple effect, a systems thinking approach was applied to determine causal connections and establish cause-effect relationships between the variables, followed by an attempt to lead back these effects directly to the causes. In our analysis, we sequenced the impacts of the ripple effect (i.e. demand variations, labour shortages, lockdowns, facility shutdowns, and operating with limited capacities), to construct the cause-effect relationships. The feedback structure was incorporated by closing cycles between the single actor's actions (i.e. automakers could increase their production levels and ordered more semiconductors, at the same time suppliers could not satisfy the increased demand since orders from other industries overtook their capacities). Such structured mapping incrementally added and connected the observed variables to the CLD.

4. Within-case analysis

4.1 Tesla

When the COVID-19 pandemic started, the semiconductor shortage caused rollout delays of Tesla's long-awaited electric pickup and semi-trailer trucks (Ashcroft, 2022). The start of production of both models was planned for 2021 but was postponed to 2022 and 2023, respectively. Tesla had to temporarily close one of its plants in California at the beginning of 2021 because of component shortages. However, in the second half of 2020, Tesla's orders reached the highest level in the company's history, increasing by 45%. This number was under the 500.000-unit sales goal for the year, even though the COVID-19 pandemic was at its peak (Cohen, 2021). As of 2021, Tesla reported that deliveries in 2021 increased by 87% compared to 2020 (Ashcroft, 2022). When looking at the rest of the car manufacturers, such results were surprising, considering that Tesla cars usually require more chips than others.

Several factors enabled Tesla's resilience during the disruption. Besides traditional strategies, such as building safety stock, Tesla found creative ways to approach the problem. Firstly, they usually "produce iterations of vehicle models that often stretch back over generations" (Ashcroft, 2022). Tesla is a more flexible company that designs and builds vehicles from scratch. The expertise of internal software engineers helped to maintain operations and production plans. According to the company's CFO Zachary Kirkhorn: "our expertise in the chip industry and consistent messaging to suppliers has helped us manage supply chain challenges" (Ashcroft, 2022). He also claimed that Tesla did not reduce its production forecasts with suppliers. Instead, they were adding capacity in the fastest way possible. CEO Elon Musk admitted that Tesla managed to alter the software rapidly to use different types of chips for the vehicles. "We were able to substitute alternative chips and then write the firmware in a matter of weeks. It is not just a matter of swapping out a chip; you also have to rewrite the software" (Hawkins, 2021). In some cases, after rewriting the software, one chip could perform dual functions.

As a result, the number of semiconductors needed for vehicles was decreased due to the company's strategic use, leading to production maximisation (Zimmerman, 2022). According to Elon Musk, the shortage "has served as a forcing function for us to reduce the number of chips in the car" (Zimmerman, 2022). Tesla's semiconductor supplier base comprises 43 vendors, which provide around 1,600 unique silicon chips. Discovering alternative ways of applying them enabled cost reductions, production maximisation, and decreased failure points. Secondly, the company's management realised a need to decrease dependence on Asian semiconductor vendors even before the pandemic. Therefore, it was decided to put effort into producing its chips in-house. Additionally, Tesla decided to use a new material technology–silicon carbide (SiC) instead of commonly used pure silicon. "The unique properties of silicon-carbide make it much more energy efficient and durable relative to traditional silicon wafers. Due to their improved thermal conductivity, SiCs reduce energy loss by as much as 50%" (Cohen, 2021). By producing its own semiconductor materials during the pandemic, Tesla has made its supply chain more resilient and avoided "a short-term crisis" (Cohen, 2021).

4.2 Hyundai

Despite the semiconductor shortage impacting automotive supply chains worldwide, Hyundai maintained constant production levels. For instance, Hyundai Motor India was ahead of its primary competitors in the country, Maruti Suzuki and Mahindra & Mahindra. They both were forced to cut down production because of chip shortages. On the contrary, Hyundai handled the crisis by altering the product mix and allocating available components to produce high-demand models. "The semiconductor supply issue is common for all OEMs, and everyone is under the same challenging conditions. But the results are totally different depending on their operational efficiency, flexibility, and manpower dedication. My message to our factory is to be more flexible, creative, and agile," says Hyundai Motor India's CEO SS Kim. As a result, while Maruti Suzuki reported a decline in production of 60%, Hyundai has been operating at the same levels as before (Cenizo, 2022).

However, such a strategy proved successful in developing countries like India, as demanded car models offer fewer features and, therefore, involve fewer chips. European and US customers prefer models like Tucson, Santa Fe, and Santa Cruz. Therefore, the company is looking into other strategies to secure chip availability. According to Hyundai's Global COO Jose Munoz: "Having our industrial power, I think, is a key strategy to try to localise the production of chips. Not this year because, as you know, this is a big picture that takes quite a lot of time and big investment to increase the production of chips" (Horn, 2022). In October 2021, Munoz announced that the company was planning to produce its own automotive chips to limit its reliance on suppliers, which still needed to improve with many challenges (Jin, 2021). A partner company, Hyundai Mobis, would be a significant participant in the plan development process. Successful implementation would ensure local supply and lower reliance on foreign vendors (Jin, 2021).

4.3 Ford

Ford was struck by the COVID19 pandemic in 2020 and the following semiconductor scarcity mainly in 2021. That year, Ford expected a loss of up to 2,5 billion US dollars of its earnings due to the shortage (Wayland, 2021). "The company's revenue came to over 136 billion US dollars in 2021. This was up from 127 billion US dollars in 2020 but still 12% under pre-pandemic financial recordings" (Carlier, 2022). According to Leonard (2021), Ford expected a 1.1 million units decline in production in 2021 due to the semiconductor shortages. That year, Ford was forced to suspend production at several plants in the United States for 2–4 weeks because of components unavailability (Leonard, 2021). The company's management admitted they needed to rethink their approach. One of the strategies Ford used was partial production. This means that as many vehicles as possible were pre-assembled without missing components and stored, waiting until they were available. The objective was to deliver orders to customers faster instead of starting the manufacturing only when all components were in stock. Nonetheless, the management realised that a long-term solution to ensure supply was necessary since the semiconductor shortage would only finish after a while.

According to Ford's CFO, John Lawler, Ford started "working on a 'modernisation of sales processes' that relies on leaner inventory and higher turn rates. The goal is to have car buyers use an ordering process for purchasing, which would allow dealerships to hold less inventory" (Leonard, 2021). This means that the company moved its focus to a built-to-order strategy. Even though fewer cars will be at dealerships, the demand visibility can be increased (Garland, 2021). "Now, where we see the order bank helping us is we actually see it simplifying the industrial system because we'll know exactly what we're going to build," Lawler said (Garland, 2021). Additionally, Ford's CEO claimed that the automaker is increasing safety stocks of vital components, allocating them to the most profitable models, using a dual-sourcing strategy when possible, and examining chances for design interchangeability for parts where only single-sourcing is available.

4.4 Sony

Sony experienced severe supply chain disruptions caused by the semiconductor shortage. "Historically, Sony, being a Japanese company, has followed a just-in-time production strategy to avoid stockpiling components before the need for them. Whilst this strategy has allowed Sony to operate a more cost-efficient production process, they have been left vulnerable to supply chain disruptions" (Mangold, 2021). Considering the shortage, a just-in-time strategy was challenging to follow. Sony was forced to reduce production capacity for some of its products as a short-term measure. One of them is digital cameras. The company had to suspend orders on several models. Before the COVID-19 outbreak, Sony used to produce and hold old models of cameras and lenses, even though there were more modern ones. However, due to a lack of components, the company gave up on the original Alpha 9 and Alpha 7R II (Schneider, 2021). Sony had to repeatedly lower its sales forecast for the new PlayStation 5 from 16 to 14,8 million to 11,5 million units in 2021 (Ashcraft, 2022).

In order to secure the availability of vital components long-term, Sony decided to cooperate with one of the top semiconductor manufacturers, TSMC. Fingas (2021) states that both companies "are teaming up to build a semiconductor factory in Kumamoto, Japan that would tackle 'strong global market demand' for specialised chips". In particular, Japan Advanced Semiconductor Manufacturing will be constructed as a TSMC subsidiary in the area. Sony will invest around 500 million US dollars, having a minority stake. The construction was planned to begin in 2022, and production is expected to start towards the end of 2024. The facility is supposed to supply both Sony and the automotive industry. Therefore, car manufacturer Denso Corp. and the Japanese government will also invest in the project (Ergöçün, 2021).

4.5 Apple

Apple has survived the challenges imposed by the COVID19 pandemic without severe consequences. However, with its sophisticated supply chain, even Apple was not immune to the lack of components. One of the keys to Apple's supply chain success is close collaboration with key suppliers. Additionally, the company tries to ensure its tier 1 suppliers get enough components from tier 2 suppliers. Therefore, Apple negotiated with TSMC to prioritise Apple's orders to secure chip availability. "TSMC is Apple's exclusive manufacturer of the A-series chips that go into iPhone and iPad devices, as well as the M-series chips used in Apple Silicon Macs. For the iPhone 13, TSMC is manufacturing the new Apple-designed A15-chip on a 5-nm fabrication process" (Mayo, 2021). However, these negotiations did not help the company avoid the chip shortages entirely. According to Bloomberg (2022), "Apple Inc. Is likely to slash its projected iPhone 13 production targets for 2021 by as many as 10 million units as prolonged chip shortages hit its flagship product, according to people with knowledge of the matter."

Initially, the company planned to assemble 90 million units of the iPhone 13 series that year but was forced to decrease the outcome because their suppliers could not provide enough parts. Despite this, Apple's CEO Tim Cook claimed: "Our supply chain actually does very well consider the shortages because it is a fast-moving one and the cycle times are very short. There is very little distance between a chip being fabricated and packaged and a product going out of the factory" (Das, 2022). Nonetheless, Apple is planning to take steps in efforts to improve its sourcing strategy and reduce its dependence on Asian suppliers. According to Cook, 60% of the chip supply originated from Taiwan, which he considers not a strategic position (Gurman, 2022). In November 2022, he revealed that Apple has decided to implement local sourcing and procure a share of semiconductors from a facility in Arizona. He will most likely talk about a plant expected to open in 2024 and will be managed by TSMC. He also mentioned that the company might look for European suppliers without specifying a country (Gurman, 2022).

5. Cross-case analysis

To compare the five cases, key constructs were identified and compared across the single cases to gain insights regarding the ripple effects induced by the semiconductor shortage.

Table 3 summarises the cross-case analysis for each case. Building on this summary of the roots of the ripple effects in supply chains due to semiconductor shortage, a mental model is built with the theory elaboration approach (Figure 4), while subsequently, the CLD is

Ripple effects	Tesla	Hyundai	Ford	Sony	Apple
Decreased demand at the beginning of the pandemic		X	X		
Increased demand after the peak of the pandemic	X	X	X		
Demand stagnation after the peak of the pandemic				X	X
Demand exceeds supply	X	X	X	X	X
Internal competition for scarce components	X	X	X	X	X
Poor conditions between different tiers		X	X		
High dependence on semiconductors	X	X	X	X	X
Geographical concentration of suppliers	X	X	X	X	X
Increased demand in consumer electronics				X	X
Capacity reallocation to other industries		X	X		
Low bargaining power against other industries	X	X	X		

Note(s): "X" means that the specific ripple effect was observed in the case
Source(s): Table created by authors

Table 3.
Cross-case analysis

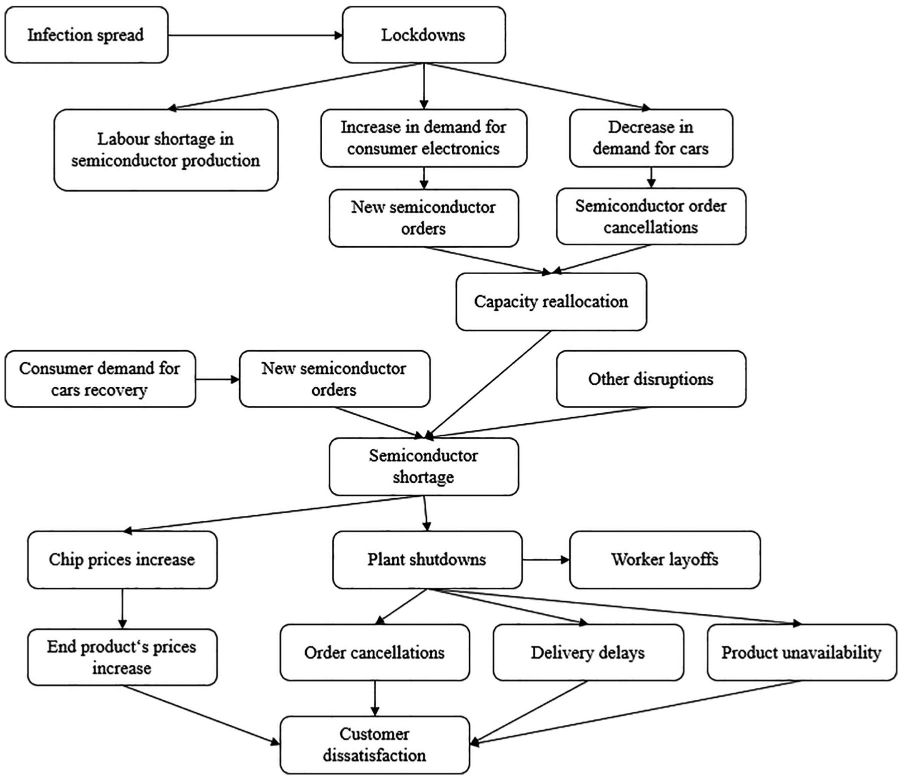

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Figure 4.
Mental model

constructed with the systems thinking approach (Figure 5). Thus, the mapping of the mental model shows causal connections which describe the behaviour of the emergent system within the CLD.

5.1 Mapping of the causal connections into a CLD

The spread of coronavirus infection led to lockdowns. Lockdowns, in turn, have multiple consequences. Consumer demand shifts were observed in both industries. Demand for cars decreased and increased for consumer electronics. Additionally, labour shortages due to the lockdown forced semiconductor manufacturers to reduce production capacity. As demand for cars declined, automakers cancelled orders for semiconductors. On the contrary, electronics companies placed new chip orders to satisfy increased product demand. As a result, semiconductor manufacturers reallocated their capacities to the electronics sector. After the pandemic's peak, vehicle demand started recovering, leading to new orders from car manufacturers. Suppliers, in turn, were unable to fulfil them. This led to a semiconductor shortage. Other disruptions, like cold waves in Texas and a fire at a plant in Japan, worsened the crisis. As a result of the shortage, on the one hand, prices for ships and, ultimately, end products increased. On the other hand, production in both industries was disrupted, which led to factory shutdowns, long lead times, worker layoffs, product unavailability, customer dissatisfaction, and lower sales levels. Figure 4 presents the CLD and the logical feedback mechanisms. There are three feedback mechanisms which influence the dynamics of the system, indicated with R (reinforcing) and B (balancing):

(1) Production disruption cycle (reinforcing). As many manufacturing companies had to cut down production volumes by closing facilities or cutting shifts and working hours, many workers had to be laid off. Due to the resulting component scarcity, car and electronics manufacturers had to reduce production capacity. As a result, production

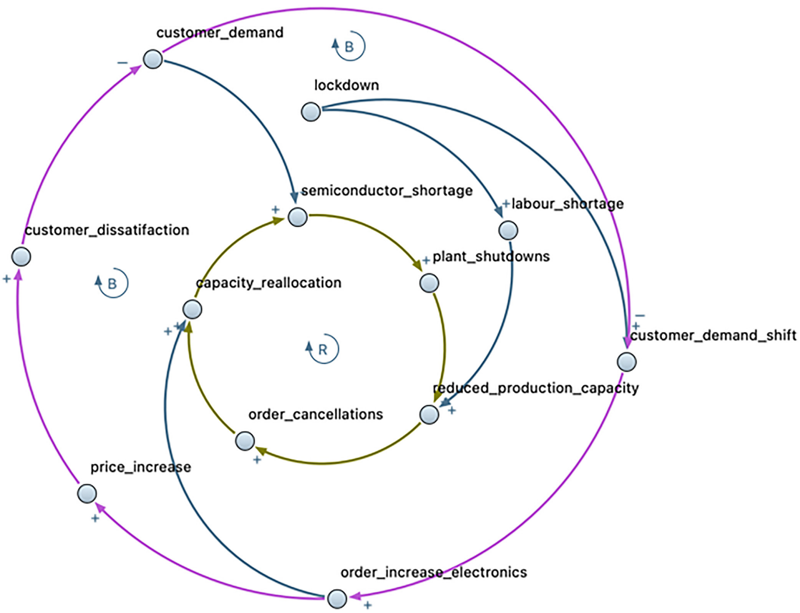

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Figure 5.
Causal loop diagram

operations at some factories were restricted, while other plants were shut down at least temporarily.

(2) Increased costs and prices cycle (balancing). As a consequence of the disruption, shipping costs worldwide increased. The semiconductor shortage and higher shipping costs resulted in increased chip prices. Such development forced manufacturers to raise prices for their products as well. As fewer new models were available at dealerships, used car prices also increased by around 10%. Consumer electronics, including oversized home appliances like washing machines, dryers, and fridges, became pricier, and delivery times increased.

(3) Consumer dissatisfaction cycle (balancing). Due to the lack of semiconductors, many companies could manufacture not all products from their portfolio. Several car, camera, and smartphone models were unavailable for a specific time. This significantly impacted choice diversity for consumers. Long lead times caused delivery delays and order cancellations, leading to customer dissatisfaction.

5.2 Cost-effectiveness analysis on mitigation strategies

The case companies employed different measures to cope with the ripple effect induced by the semiconductor shortage. Tesla, for instance, was forced to postpone the launch of its electric pickup and semi-trailer trucks and temporarily close one of its plants in California to safe costs. Tesla applied traditional strategies, such as piling up its inventory, but also came up with creative solutions. In-house engineers quickly rewrote specific chips' software to use them for other functions. "We were able to substitute alternative chips and then write the firmware in a matter of weeks," Elon Musk said. "It is not just a matter of swapping out a chip; you also have to rewrite the software" (Hawkins, 2021). As a result, some chips could perform more than one usual function, which helped reduce the number of chips required for one vehicle. Discovering alternative ways of applying them enabled cost reductions, production maximisation, and decreased failure points. Moreover, the company managed to produce semiconductors in-house, which helped to avoid "a short-term crisis, where potential supply chain bottlenecks of six months or more could have derailed production" (Cohen, 2021).

Hyundai altered its product mix to deal with the semiconductor crisis and allocated its available components to the most demanded car models. This way, the company could successfully manage the shortage in the Indian market. Popular car models in developing countries are cheaper and less feature-heavy, which enabled the company to operate at the usual levels. However, this strategy was not applicable in developed countries, where favoured models possess more features and, therefore, require more chips. Hyundai, therefore, was not able to concentrate on the production of premium models with higher much like European OEMs did. Aiming to reduce its reliance on foreign semiconductor suppliers, the company eventually decided to produce its own chips. "This takes a lot of investment and time, but this is something we are working on," Hyundai's Global COO, Jose Munoz, said (Jin, 2021). The company is developing a plan for a project with its partner Hyundai Mobis.

Ford had to suspend production at several plants in the United States for 2–4 weeks because of components unavailability. As a result, the company experienced a significant sales volume reduction, expected at 1.1 million units, in 2021. One of the countermeasures implemented was partial production. To deliver customer orders as fast as possible, thousands of vehicles were partially assembled without missing components, which were added after they were in stock. Further, the company decided to modernise its sales processes. The company applied a make-to-order production strategy to increase demand visibility, meaning production started only after placing the order. Additionally, Ford worked on increasing safety stocks of vital components, allocates them to the most profitable models, uses a dual-sourcing strategy when possible, and examines chances for design interchangeability for parts where only single-sourcing is available.

As a short-time measure, Sony had to halt the production of several camera models and lower its production plants for the new PlayStation 5. Moreover, Sony decided to cooperate with its vital supplier TSMC to benefit from prioritised supply. According to Fingas (2021), both companies “are teaming up to build a semiconductor factory in Kumamoto, Japan that would tackle strong global market demand for specialised chips”. In particular, Japan Advanced Semiconductor Manufacturing will be constructed as a TSMC subsidiary in the area. Sony will invest around 500 million US dollars, having a minority stake. The facility will, however, begin to operate only in 2024.

Apple could successfully survive the challenges imposed by the COVID19 pandemic due to close communication with its suppliers. In 2021, the company managed to negotiate with its semiconductor supplier TSMC that Apple’s orders would be fulfilled with priority. Unfortunately, it was still insufficient to avoid the shortage impact, and the production forecasts for iPhone 13 had to be decreased by 10 million units. Nonetheless, CEO Tim Cook mentioned a need to decrease dependence on Asian suppliers through additional investments. Apple has already decided to procure chips from a new facility in Arizona, which is expected to operate in 2024. Additionally, the company might look for new suppliers in Europe. An overview of the cost-effectiveness analysis is depicted in Figure 6 and Table 4.

6. Discussion and conclusion

The COVID19 pandemic disrupted manufacturing supply chains worldwide. The semiconductor shortage has disrupted consumer electronics and automotive production processes, causing a ripple effect along the entire value chain. Many companies and their supply chains needed more time to prepare for the crisis. Usual component shortage mitigation strategies imply short-term scarcity of certain parts and suggest mostly short-term measures (see Table 4). To go beyond short-term measures, we conducted a case study approach. The goal of the case studies was to gain a deeper understanding of ripple effects

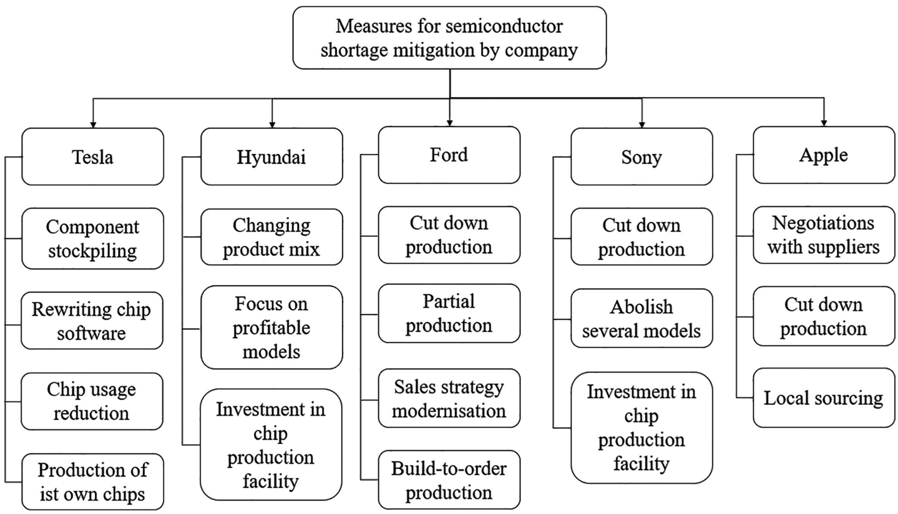

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Figure 6. Measures for semiconductor shortage mitigation

Table 4.
Cost-effectiveness analysis

Measures	Cost implications	Effectiveness	Cases
Production cut downs	Cutting variable costs, but decreased sales	Short-term	Tesla, Ford, Sony, Apple
Prioritising production with higher margins	Increased revenues	Short-term	Hyundai
Partial production	Cutting variable costs, but decreased sales	Short-term	Ford
Engineering changes	Investment in re-engineering activities	Mid- to long-term	Tesla
Supplier negotiations	Increased component costs	Short-term	Sony, Apple
Stock pilling	Increased stocking- and shipping costs	Short-term	Tesla, Ford, Sony
Sales modernisation	Increased revenues	Mid-term	Ford
Investment in addition component supply	Remarkable investments into new production facilities	Long-term	Tesla, Hyundai, Sony, Apple

Source(s): Table created by authors

during long-term disruptions and identify which measures were implemented by each company to mitigate the ripple effect. Data from multiple sources, such as company websites, websites of supply chain consulting agencies, and articles from business magazines, were merged to get a complete overview of each company's actions in 2020–2022. The findings particularly contribute to the growing academic discourse on appropriate mitigation strategies. While Polyviou *et al.* (2023) found supplier concentration and carrier diversification as potential measures to mitigate the ripple impact of supply disruptions during COVID19 in the apparel and textile industry, the present results particularly vote for investment in engineering change activities, sales modernisation, as well as investments into the flexibilization of production facilities.

6.1 Theoretical implications

Literature on the ripple effect mitigation is relatively nascent, having its roots in the seminal work by Ivanov *et al.* (2014). While there are already studies providing specific insights into the ripple effect of COVID19 in single industries, i.e. in the medical industry in Turkey (Yilmaz *et al.*, 2023), the present study complements existing research by studying the semiconductor shortage in the automotive and electronics industry. In this vein, it can be indeed concluded that the semiconductor shortage is not a regular disruption but a systematic one. For the specific context of the automotive industry, the study draws parallels to other specific types of short-term ripple effects, such as the horizontal bullwhip effect (cf. Gruchmann and Neukirchen, 2019), showing that demand variations are not just present between first-tier suppliers within one industry but also between two or more industries. Thus, the research adds to the academic discourse by describing the mechanism of systemic disruptions through a CLD and explaining how certain strategies mitigate the related ripple effects for intertwined supply networks (Ivanov, 2024).

Future research may particularly use the proposed CLD and observed mitigation strategies for building more nuanced scenarios in simulations and analytical models on the ripple effect studying systemic risks under long-term disruptions. While we observed differences between the automotive and customer electronics case companies (e.g. a prioritised access to component suppliers for the electronics cases), the simulations may provide further insights into proactively managing ripple effects. While the observed mitigation practices incorporate the (traditional) resilience practices, such as supply chain flexibility that arises from product substitution, flexible contracting, supplier switching, portfolio diversification, and dynamic pricing practices (Balakrishnan and Ramanathan, 2021), some particularly go beyond reactive resilience towards supply chain viability. First, long-term disruptions lead to the long-term adaptation of supply chain structures (supply chain strategy level, i.e. closing factories) that may last after the end of the disruption. Second, the required adaptions affected not just operations but also marketing (i.e. product mix, sales strategy) or sustainability strategies (He and Harris, 2020). Third, engineering change management practices are coming to the fore in the context of long-term disruptions (Gollmann *et al.*, 2023).

6.2 Managerial implications

Implications for the semiconductor industry: Our analysis showed that companies in both industries applied stockpiling, which implies accumulating more extensive semiconductor stocks to ensure the future availability of components. Some companies tried to place orders well in advance (e.g. Sony), while others established closer communication with critical suppliers and negotiated prioritisation for their orders (e.g. Apple). For instance, Apple decided to procure a share of semiconductors from a future plant in Arizona. However, poor supply chain visibility was mentioned as one of the contributors to the adverse effects companies experience due to semiconductor shortage. Accordingly, one of the objectives is to increase supply chain visibility and improve forecasting and procurement decisions (Ivanov *et al.*, 2021). In this vein, companies may make use of digital technologies. Adopting digital twin technologies (DTT), for instance, enhances resilience by providing real-time visibility, facilitating quick decision-making, and enabling immediate actions or responses to disruptions in the supply chain. Moreover, visibility can be achieved from enhanced monitoring using DTT (Burgos and Ivanov, 2021).

Implications for the semiconductor industry: Specifically in the automotive industry, partial assembly is a widely implemented strategy during COVID19. Semiconductor scarcity has made building parks of unfinished vehicles wait for the availability of components (e.g. FORD). Such an approach is likely not applicable to consumer electronics since electronic devices are highly integrated with chips. Their installation is embedded into the production process, which does not allow adding them later for most products. Some companies, such as Ford, decided to modernise sales strategy by sacrificing the number of cars available at dealerships and using a build-to-order production approach. This gives a better overview of orders and facilitates inventory management. Such a strategy can be applied in the automotive industry. To reduce the number of chips required for a vehicle, Tesla developed a unique solution to rewrite the software of several semiconductor types (Ashcroft, 2022). Such an approach, however, requires high technological engineer expertise, which is only available for some companies. Notably, automotive firms allocated available components to the most demanded and profitable models. The same trend could be observed in consumer electronics, where firms halted production of specific models temporarily or even permanently.

Implications for digital transformation: One major element decreasing ripple effect during long-term disruptions is the application of digital technologies (Balakrishnan and Ramanathan, 2021; Ivanov and Dolgui, 2021). Digital technologies in supply chain management can be considered disruptive technologies that influence modern SC management (Ivanov *et al.*, 2019). They significantly support viability as increasing complexity and structural variety in supply networks require data availability and capable data processing technology (Balakrishnan and Ramanathan, 2021). To mitigate long-term ripple effects, blockchain technology is promising (Gruchmann *et al.*, 2023), acknowledging that blockchain initiatives are often on a pilot stage (Gong *et al.*, 2022). In this vein, blockchain technology particularly enhances collaboration practices by supporting the sharing of information between two or more parties in a transparent way and recording the data among the single supply chain members (Balakrishnan and Ramanathan, 2021; Gong *et al.*, 2022; Gruchmann *et al.*, 2023).

6.3 Limitations

The usage of only secondary sources is a limitation of the study. Only publicly available information could be used to identify measures that companies took to deal with the semiconductor shortage. Companies may not communicate sensitive information about their operations. Accordingly, future research may collect primary data through interviews and surveys to blend with the present findings. Additionally, the study is focused to the automotive and consumer electronics industries representing a boundary condition for transferability of the results. Experience in other manufacturing industries, such as the LED lightning or power turbines/solar industries, might lead to developing additional ripple effect mitigation strategies applicable more generally. Finally, only the practices of manufacturing companies were considered in the study. The semiconductor shortage is critical, and other stakeholders may contribute to its solution. For instance, governments of different countries realise the importance of chip availability and invest in new production facilities. Their actions must also be considered in the decision-making process by the supply chain managers. Future research may tackle these limitations, for instance, by investigating the use of supply chain digitalisation for advanced mitigation strategies. Future research can focus on determining how digital transformation can support companies and their supply chains in case of systemic disruption.

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