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Semiconductor supply chain resilience and disruption: insights, mitigation, and future directions

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ABSTRACT

In recent years, the semiconductor supply chain has experienced dramatic changes, due to geopolitical tensions and public health events, which have provided insights into supply chain disruptions and the shortage economy. This review synthesises current research on semiconductor supply chain disruptions to offer a comprehensive analysis of the vulnerabilities of the semiconductor supply chain and resilience strategies. We begin with an overview of the key characteristics and complexities of the semiconductor supply chain. Focusing on geopolitical security issues and public health events, we provide a comprehensive overview of the challenges faced and mitigation strategies adopted. Moreover, we identify important gaps in the literature and propose future research directions, emphasising the need for innovative supply chain management practices and decentralised networks for necessary redundancy. Our analysis contributes to the ongoing discussion on how the robustness and adaptability of the semiconductor supply chain, to ensure its sustainability in the face of a rapidly changing global landscape.

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SUSTAINABLE DEVELOPMENT GOALS
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1. Introduction

1.1. Semiconductor supply chain disruptions

The Semiconductor Supply Chain (SSC) is a type of critical infrastructure that underpins the global technology industry (Callarman et al. 2004), enabling the production and distribution of semiconductors essential for a wide range of electronic devices, from smartphones to medical equipment to automobiles. This complex and highly integrated network (Figure 1) involves myriad stages, including design, development, fabrication, assembly, testing, packaging, and distribution, engaging a wide range of entities, from fabless companies to foundries and integrated device manufacturers (IDMs). The global scale of the supply chain, involving substantial investments in research and development (R&D) and high technological sophistication, has positioned semiconductors as foundational components of the modern digital economy, driving advancements in the fields of computing, communications, and consumer electronics.

However, the SSC faces numerous challenges and vulnerabilities, highlighted by recent disruptions such as the COVID-19 pandemic and geopolitical tensions like the Russia-Ukraine conflict and trade tensions between the US and China. These challenges underscore the critical need for enhanced resilience and strategic planning to avert future crises. For instance, the COVID-19 pandemic caused widespread factory shutdowns and shipping delays[1], while the Russia-Ukraine conflict has led to energy supply shortages and increased commodity prices[2]. These turbulent years have led to academic insights into the resilience and viability of the SSC (Fu et al. 2023). For example, unexpected fluctuations and shocks mean that supply cannot meet demand in a timely manner, and supply chains take time to recover (Simchi-Levi and Simchi-Levi 2020) and are subject to intense stress testings (Haren and Simchi-Levi 2020; Collier et al. 2023). Furthermore, Ivanov and Dolgui (2022a) note that resource shortages caused by extreme shocks and long-lasting disruptions may have global ripple effects on supply chains in the automotive and electronics industries. The complexity of the SSC, together with the critical nature of semiconductors across a wide range of technologies and critical factors (Figure 2), makes it a focal point of geopolitical and economic considerations (Matsuo 2015), and a balanced approach is required to manage risks and ensure continuity.

Strategies to strengthen the resilience of the SSC have become a priority interest for academia, industry

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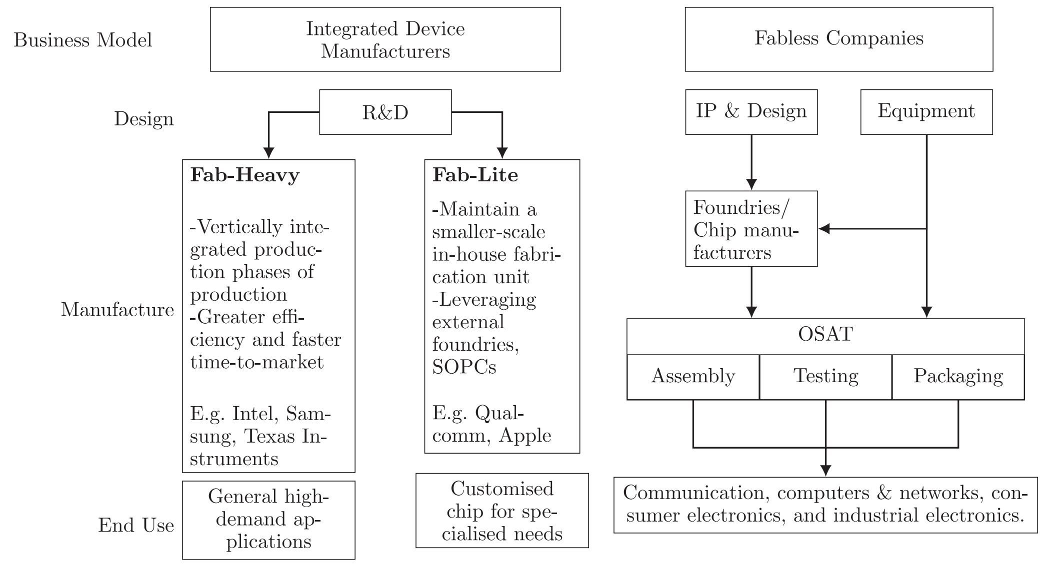

Figure 1. Structure of the semiconductor supply chain: business models.

stakeholders, and governments. Efforts include diversifying manufacturing bases (Lima et al. 2021; Shin et al. 2019), investing in domestic production capabilities, promoting international collaborations, and leveraging technological advancements such as artificial intelligence and big data analytics. Additionally, policy initiatives and government incentives aim to support the semiconductor industry, addressing challenges such as talent shortages and the need for innovation to keep pace with rapidly changing technological demands (Fu and Chien 2019). Ensuring the resilience and sustainability of the SSC (Okada and Shirahada 2022) is paramount to the continued growth and innovation of the global technology sector, making it a topic of great importance and interest.

This study comprehensively reviews the literature on SSC disruptions. We provide valuable insights into the development of resilient supply chain structures in the semiconductor industry and identify potential topics for future research. Historically, the prevailing assumptions in supply chain research have been challenged; these include the notions of uninterrupted supply despite occasional disruptions and the sufficiency of resources to meet demand, as discussed in seminal studies such as those by Ivanov and Dolgui (2022a) on supply shortages and the extensive reviews of the SSC literature by Mönch, Uzsoy, and Fowler (2018a, 2018b), and Uzsoy, Fowler, and Mönch (2018). From a value-creation perspective, as suggested by Ivanov (2023), contrary to the dominant cost efficiency-oriented thinking of previous years, the next generation of supply chain designs, as argued by Ivanov (2021a), should be dynamically adaptable and structurally changeable. This shift highlights the importance of innovative approaches to addressing current and future SSC challenges, underscoring the need for future research that not only addresses immediate disruptions but also ensures the long-term resilience and sustainability of the SSC.

1.2. Recent research on supply chain disruptions

First, we examine selected research reviews on supply chain disruptions to identify the key theories and frameworks (Table 1). The need for stress testing advocated by Simchi-Levi and Simchi-Levi (2020) and the strategic recovery frameworks presented by Simchi-Levi (2020) highlight the importance of preparedness and adaptability in supply chain management. The COVID-19 pandemic brought these issues to the forefront, with Haren and Simchi-Levi (2020) accurately predicting the timing of the pandemic and its impact on global supply chains.

Aldrighetti et al. (2021) emphasise the delicate balance between cost efficiency and resilience in the design of supply chain networks, suggesting that future research should explore dynamic adaptation models. This argument is consistent with that of Dolgui, Ivanov, and Sokolov (2018), who analyse the ripple effect of disruptions in one part of the supply chain cascadeing through the network, causing widespread impact. Dolgui, Ivanov, and Sokolov (2020) introduce the concept of the reconfigurable supply chain, also known as the X-network, highlighting the importance of flexibility and modularity in supply chain design to withstand and adapt to unexpected changes. Their work, along with that of Hosseini, Ivanov, and Dolgui (2019), who review quantitative methods (Akçalı and Çetinkaya 2011) for resilience

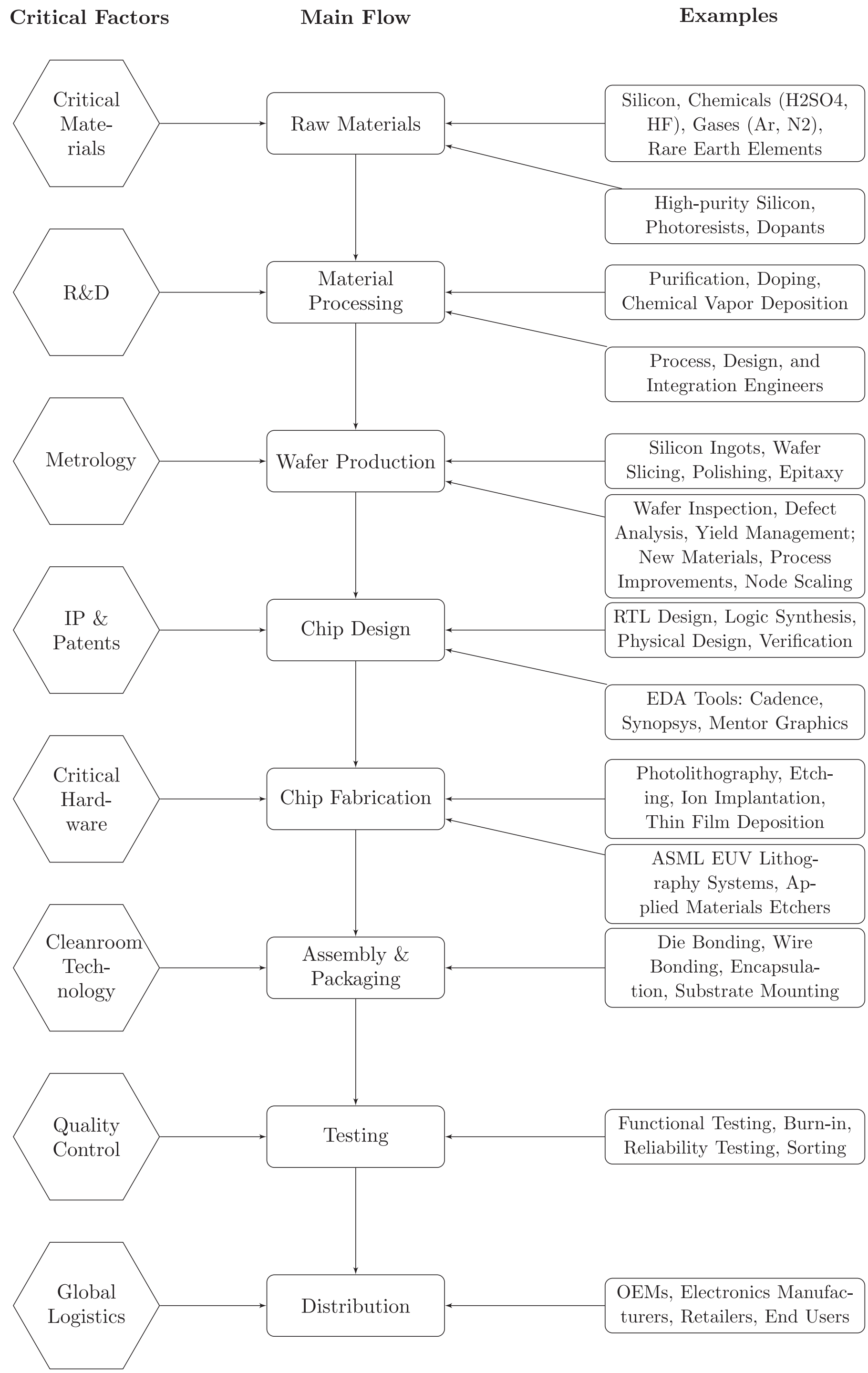

Figure 2. Semiconductor supply chain: integrated process flow and critical factors.

analysis, provides a foundation for understanding supply chain vulnerabilities and the capabilities needed to manage risks.

Ivanov's series of studies (i.e. Ivanov and Dolgui 2020, 2021, 2022b; Ivanov 2021b, 2022; Ivanov et al. 2022) contributes significantly to the field by describing a viable supply chain model that integrates the dimensions of agility, resilience, and sustainability. His research extends the concept of resilience to survivability, particularly in the context of intertwined supply networks (Feizabadi et al. 2023; Wang and Yao 2023) affected by the COVID-19 pandemic. Ivanov and Dolgui (2022a) further discuss the implications of the shortage economy for supply chain management, and Ivanov (2023) introduces the Industry 5.0 framework, advocating for a viability-based integration of resilience, sustainability,

Table 1. Critical comparison of previous literature reviews.

Selected Reviews	Method				Disruption				Industry		
Reference	Bibliometrics	Empirics	Simulation	Others	Natural disasters	Health crises	Geopolitics	Others	General	Semiconductor	Others
Saisridhar, Thürer, and Avittathur (2024)	✓		✓		✓			✓	✓		
Koh et al. (2023)		✓		✓				✓	✓		
Gandhi et al. (2023)				✓				✓		✓	
Ramani, Ghosh, and Sodhi (2022)	✓		✓			✓				✓	✓
Moosavi, Fathollahi-Fard, and Dulebenets (2022)	✓					✓				✓	✓
Dolgui and Ivanov (2021)		✓						✓	✓		
Xu et al. (2020)	✓							✓	✓		
Dolgui, Ivanov, and Sokolov (2020)	✓	✓		✓				✓	✓		
Mönch, Uzsoy, and Fowler (2018a)			✓	✓				✓		✓	
Ivanov et al. (2017)				✓				✓	✓		
Jiang, Quan, and Zhou (2010)				✓			✓	✓		✓	
Kleindorfer and Saad (2005)		✓		✓	✓			✓	✓		

Table 2. Descriptive summary of topics and keywords in recent studies on supply chain resilience.

Category	Keyword	Reference
Reconfigurability	Networking Effects, Flexibility, Modularity, Adaptability, Industry 5.0	Dolgui, Ivanov, and Sokolov (2020), Simchi-Levi and Simchi-Levi (2020), Simchi-Levi (2020), and Ivanov (2023)
Viability	Intertwined Supply Networks, Resilience, Agility, Sustainability, Recovery	Aldrighetti et al. (2021), Hosseini, Ivanov, and Dolgui (2019), Ivanov and Dolgui (2020, 2021, 2022b), Ivanov (2021b, 2022), Liu et al (2022) and Ruel et al. (2021)
Shortage Economy	Global Ripple Effect, Resource Scarcity, COVID-19, Local Shortages, Disruption Response	Dolgui, Ivanov, and Sokolov (2018), Haren and Simchi-Levi (2020), Ivanov and Dolgui (2022a), Ivanov (2021a), and Ivanov and Keskin (2023)

and human-centricity in the design of supply chains. The active usage of resilience assets framework proposed by Ivanov (2021a) for post-COVID-19 supply chain management focuses on lean resilience, balancing efficiency with the ability to respond to disruptions. This framework, along with the work of Ivanov and Keskin (2023), is particularly relevant to the SSC, which requires a delicate balance between lean operations and the ability to withstand and quickly recover from disruptions. (Table 2)

In summary, the literature presents a consensus on the need for supply chains to be stress-tested, reconfigurable, and adaptable to cope with disruptions. This review synthesises these perspectives, providing insights into the resilience and viability of SSC, and sets the stage for a detailed exploration of the methodologies, strategies, and technologies that can contribute to the development of robust SSC designs.

1.3. Importance of semiconductor supply chain disruptions

To understand the resilience and viability of SSCs (Simchi-Levi and Simchi-Levi 2020), it is important to first recognise the major disruptions that the semiconductor industry has recently faced. For instance, the chip shortage experienced by the automotive industry since late 2020 due to the impact of the COVID-19 pandemic has affected almost all global auto manufacturers (Münch and Hartmann 2023), creating production stoppages and backlogs (Ramani, Ghosh, and Sodhi 2022). The effects of this shortage are expected to last until 2023 or even 2024. The scarcity of semiconductors has far-reaching consequences. As Ivanov and Dolgui (2022a) point out, long-term resource shortages and hyper-inflation risks pose new and unexpected challenges that could have global ripple effects.

The magnitude of the issue is evidenced by the dramatics decline in automobile manufacturing (Hoppe and Podkowik 2022; Krolikowski and Naggert 2021). Volkswagen's headquarters factory in Wolfsburg, Germany produced approximately 300,000 vehicles in 2021 and 400,000 in 2022. Both figures are well below the pre-COVID-19 average of almost 780,000. One of the issues leading to the reduction in output was the chip shortages. Thomas Schaefer, CEO of Volkswagen, said that during the supply chain's most tumultuous time, suppliers abruptly cancelled deliveries with just one night's notice and chip prices rose by as much as 800%. Schaefer lamented, 'The costs are so ridiculously exorbitant; it's a nightmare for the firm'[3].

Over the past two years (2021–2022), chip supply constraints have cost US automaker Ford a production loss of 1.3 million cars. However, Ford's constrained chip supply is not related to cutting-edge silicon chips but rather to traditional-process chips using mature technology. Jim Farley, CEO of Ford, stated, 'One thing that keeps me up at night is traditional-process chips'[4]. These include the MOSFET chips that Ford is having difficult sourcing. The MOSFET chips used in Ford F-150 windshield wipers cost only US$0.4 per piece, but Ford suffered a production loss of 40,000 cars because of their shortage.

The ripple effects of widespread disruptions across various industries using semiconductor technology extend beyond the automotive industry to consumer electronics (Kliesen and Werner 2022), telecommunications, and even critical medical equipments. As Dolgui, Ivanov, and Sokolov (2018) argue, ripple effects in supply chains can lead to cascading failures across interconnected networks, thereby exacerbating the initial impact of the disruption.

1.4. Objectives of the paper

The primary objective of this literature review is to provide a comprehensive and up-to-date analysis of research on SSC disruptions. Specifically, it explores two types of disruptions, namely security issues and public health events, and their implications for the semiconductor industry.

First, our review focuses on security issues caused by geopolitics, industrial shifts, and the US–China trade war. By examining the relevant literature, this section sheds light on the security challenges faced by the SSC and the impact of geopolitical factors on SSC disruptions. Second, our review considers disruptions arising from public health events of international concern. Drawing on studies related to the scale of supply chain viability and resilience, this section examines the effects of such events on the semiconductor industry. Finally, our review elucidates the challenges and opportunities associated with these disruptions. In summary, this paper seeks to understand SSC disruptions by answering the following questions:

(i) How do global public health crises and geopolitical dynamics affect SSC resilience, and what proactive strategies can be implemented to enhance this resilience effectively?
(ii) Based on the latest findings, what are the critical gaps in research on SSC disruptions, and what theoretical frameworks could guide the development of innovative solutions?
(iii) What specific policy measures and research initiatives should be prioritised to improve supply chain resilience, informed by current literature?

By addressing these research questions, our review provides a comprehensive understanding of SSC disruptions, identifies research gaps, and offers insights to researchers, practitioners, and policymakers.

1.5. Scope and organisation of the paper

Motivated by the recent disruptions and questions mentioned above, we conducted a comprehensive review of 203 articles. This review predominantly examined the academic literature on the supply chains, while incorporating important industry reports to better understand managerial discourse.

We adopted bibliometric techniques to identify research streams in the supply chain literature (Figure 3). The data collection process involved searching the Scopus database for articles and reviews written in English that contained specific terms related to supply chain resilience in their title or topic. For instance, the keywords consisted of the phrase 'semiconductor supply chain' combined with at least one of the following terms: 'resilience', 'resiliency', 'resilient', 'disrupt', and 'disruption'. In the Scopus database, we found that the earliest studies using the keywords 'semiconductor' AND 'supply' AND 'chains' AND 'resilience' was published in 2006.

As our research questions focussed on policies and geopolitical issues, some relevant studies or reports may not be included in the Scopus database. Therefore, Google Scholar was used as a supplementary source to ensure a comprehensive review and inclusion of relevant studies and reports that may not be indexed in the Scopus database. This approach allowed for a broader and more inclusive analysis of the subject, encompassing a wider range of academic and grey literature, including government reports, policy analyses, and other scholarly documents that not always captured by traditional academic databases.

The rest of this paper is organised as follows (Figure 4). In Section 2, we provide an overview of the main concepts in research on the semiconductor industry and the SSC to provide context for our review. Based on the most commonly discussed topics, such as inventory management, demand forecasting and manufacturing, we present a brief summary of recently published articles on semiconductors and electronics. In Sections 3 and 4, we discuss two types of SSC disruptions. Security and geopolitical issues are discussed in Section 3, and the impact of

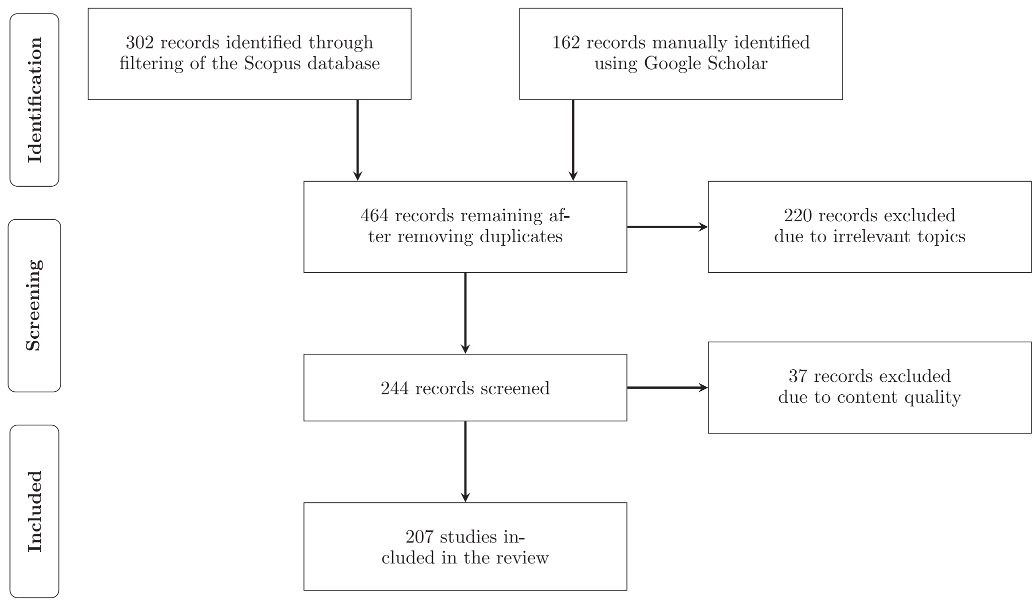

Figure 3. Review process for study selection.

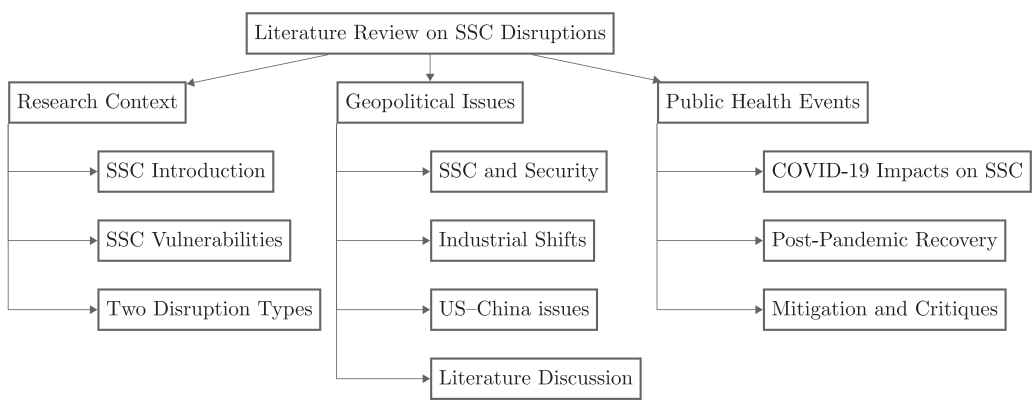

Figure 4. Structure of our literature review.

the COVID-19 pandemic is discussed in Section 4. In Section 5, we identify research gaps and suggest future research directions.

2. Overview of semiconductor supply chain disruptions

The SSC is a cornerstone of modern electronics, involving a complex network of entities that design, manufacture, test, package, and distribute semiconductors[5]. This supply chain is crucial for a wide range of products, such as smartphones, laptops, automobiles, and medical devices, all of which rely on microprocessors, memory modules, and integrated circuits powered by semiconductors. However, because of its complexity, the development of a semiconductor product can involve up to 1,200 process steps over a six-to-eight-week cycle and require travel over thousands of miles between different locations and companies involved in the production process. In this section, we briefly describe the SSC and identify two main types of disruptions to this supply chain.

2.1. *The semiconductor supply chain*

As semiconductors are used in a wide range of electronic devices, their supply chain plays a crucial role in business. In this section, we briefly present an SSC framework (Figure 2). The SSC has three main stages: (1) research and development (R&D), (2) production, and (3) end use. We adopt this three-stage structure for simplicity. Different classifications that further include production and production inputs can be found in studies such as Khan, Mann, and Peterson (2021).

R&D is the driving force behind the entire SSC. R&D includes both pre-competitive, exploratory studies and research on fundamental technologies and competitive research aimed at advancing a company's position in the semiconductor industry. R&D results have a significant impact on each segment of the SSC. Policymakers are particularly interested in R&D because it is a key driver of innovation and competitiveness in the semiconductor industry. For instance, Jennifer O'Bryan (2021), Government Affairs Director at SPIE, provides an in-depth review of public policy issues affecting semiconductor R&D, encompassing the supply chain challenges of funding and export controls. Rasiah and Wong (2021) assess the industrial upgrading of the semiconductor industry in East Asia, focussing on technological upgrading and the importance of R&D in attracting companies to frontier activities. The European Union (EU) also plays an important role in the value chain of R&D, and the European Commission plans to increase the EU's share of global semiconductor production by 2030 through investments in semiconductor R&D and manufacturing (De Boeck, Lèquepeys, and Kutter 2023).

Chip production is at the core of the SSC and can be divided into three segments: design, manufacturing (or fabrication), and assembly, testing, and packaging (ATP).

Design involves specification, logic design, physical design, and validation and verification (Mirhoseini et al. 2021). Specification determines the function of a chip and how it should work. Logic design and physical design transform a schematic diagram into a physical layout. The validation and verification stages ensure that the chips work as expected. In this process, electronic design automation (EDA) software is used to design complex chips containing billions of interconnected transistors and electrical components. Core intellectual property (IP) consists of reusable modular parts of designs, that can be licenced by design companies and incorporated into their designs (Khan, Mann, and Peterson 2021). Recent advances in product design analytics have enabled large companies such as Intel (Heiney et al. 2021) to achieve their sustainability and profitability goals.

For fabrication, a cylinder of semiconducting material is cut into disc-shaped wafers. It takes two steps to make chips from these wafers (Nakazawa and Kulkarni 2018; Hwang and Jang 2020; Yu and Lee 2020; Siess et al. 2020; Dong and Ye 2022; Lee et al. 2020; Misra et al. 2022; Wan and Shin 2022; Wang and Zhang 2016) creating transistors and electrical devices in layers of material inside the silicon and creating interconnects between electrical devices in insulating layers above the silicon. Circuits are formed by electrical devices and interconnects. Mönch, Uzsoy, and Fowler (2018a) provide a more detailed introduction to semiconductor productions, from wafer to final test. Neumaier, Pindl, and Lemme (2019) discuss the integration of graphene, an unconventional material with unique properties, into established semiconductor fabrication lines as a critical step towards commercialisation.

Table 3. Impact of vulnerabilities at different stages of the SCC.

SSC Stage	Limited Suppliers	Complexity, Globalisation	Long Lead Time	Specialty Shortage
R&D	High	High	Medium	Critical
Design	Medium	High	Medium	Critical
Fab	Critical	High	Critical	High
ATP	Medium	High	High	Medium
End-Use	Low	Medium	Medium	Low

In the ATP process, a finished wafer containing dozens of chips arranged in a grid pattern is cut into separate chips, mounted on a frame with wires that connect the chips to external devices, and then enclosed in a protective casing. The ATP stage of the SSC is currently experiencing significant advancements and challenges due to the offshore nature of most outsourced semiconductor assembly (Jo et al. 2019) and test facilities. Research on the ATP stage of the SSC emphasises security (Chang, Chang, and Wang 2022), quality (Quinn and Loferer 2013; Cheon et al. 2019; Chen et al. 2021; Li et al. 2022), information transparency (Lu et al. 2013), and strategic geographic positioning. Noor et al. (2023) discuss the major shifts underway in the semiconductor industry, advanced packaging techniques, and the importance of packaging R&D to address design and security challenges.

Semiconductors have a wide range of end uses across various industries. Integrated device manufacturers such as Samsung and Intel make huge profits on the demand side by providing high-quality memory and CPUs. In consumer electronics products such as smartphones, laptops, tablets, and televisions, semiconductors are used for functions such as processing, memory, and display. As technology continues to advance, the demand for semiconductors and their end uses will continue to grow.

2.2. *Vulnerabilities in the event of disruptions*

The SSC, like any complex global supply chain (Mohammad, Elomri, and Kerbache 2022), is susceptible to various vulnerabilities in the event of disruptions. Technology giants such as Apple (SinghKang, SinghBhatti, and Patil 2023) also face vulnerabilities in the SSC network. These vulnerabilities arise from the interdependencies, geographic dispersion, and complex coordination required within the semiconductor industry. Understanding and addressing these vulnerabilities is crucial to mitigating the impact of disruptions and ensuring the resilience of the SSC (Table 3).

One key vulnerability is the dependece on a limited number of suppliers for critical components and materials (Sharma et al. 2023; Yu et al. 2024). The semiconductor industry often operates under a just-in-time manufacturing model (Firth et al. 2006) in which production schedules (Chung et al. 2019; Liu et al. 2019) are closely synchronised with the availability of inputs. However, disruptions caused by geopolitical tensions or public health events can affect the flow of materials, leading to shortages and production delays. When few alternative suppliers exist or in-house production capacity is limited, supply chain vulnerability increases (Leu and Liu 2022).

Another vulnerability arises from the complex and global nature of the SSC (Mohammed and Khan 2022). The SSC involves the coordination and synchronisation of activities across multiple tiers of suppliers, manufacturers, and distributors, often spanning different countries and regions. Disruptions affecting one part of the supply chain can quickly propagate upstream or downstream, amplifying the overall impact through a ripple effect. Studies demonstrate how these ripple effects impact on the flow of goods and materials (Brusset et al. 2023), circular flows (Park et al. 2022), and recovery (KEk et al. 2022). This vulnerability is particularly pronounced when disruptions occur simultaneously in multiple regions or when key production hubs are affected.

Furthermore, the long lead times inherent in semiconductor manufacturing contribute to vulnerability in the event of disruptions occur (Sharma et al. 2023; Welling, Noel, and Ismail 2021). The semiconductor industry operates on extended product development cycles, with substantial investments in R&D, production tools, and fabrication facilities. Taking non-volatile memory as an example, Chen and Chien (2018) develop a decision-making framework for demand forecasting in semiconductor manufacturing (Chien et al. 2024), which is crucial given the long lead times and the need for smart production to mitigate disruptions. Disruptions can affect the delicate balance between supply and demand, leading to imbalances that will take time to correct. This vulnerability can exacerbate the impact of disruptions, resulting in prolonged shortages or overcapacity. The increasing complexity of semiconductor products and the need for specialised knowledge and expertise also create vulnerability. In light of the digital transformation of the supply chain (Mitra, Kapoor, and Gupta 2022), the SSC relies on skilled labour, IT expertise, and specialised equipment. Industry 4.0 also highlights the need to develop human capital in the logistics and supply chain sector (Rahman et al. 2022). Disruptions can affect the availability of skilled personnel, limit access to critical knowledge, or impair the functioning of specialised equipment, thereby affecting overall production capacity and product quality.

Table 3 descriptively illustrates the vulnerabilities at different stages of the SSC. The impact levels are indicative and may vary depending on specific contexts and business models.

2.3. Classification of disruptions

In the realm of supply chain management and the semiconductor industry, recent years have seen the emergence of two distinct types of disruptions, which have generated considerable research interest (Table 4).

The first type of disruption revolves around security issues stemming from geopolitics, industrial shifts, and the US–China trade war. These factors have significantly affected the SCC, prompting a re-evaluation of current research and requiring further research into new avenues to address these security challenges.

The second type of disruption centres on public health events of international concern. These events, which can have far–reaching consequences, pose significant challenges to supply chain resilience, particularly in the semiconductor industry. The viability of supply chains is also being tested. It is therefore imperative to examine the implications of these events and identify strategies to enhance supply chain resilience in the face of such disruptions (Ivanov and Dolgui 2020, 2021).

3. Security issues and geopolitical disruptions

3.1. Overview of security issues in the semiconductor supply chain

Security issues in the SSC have become increasingly important in recent years, as the semiconductor industry has become more globalised and interdependent (Lincicome 2021). These issues include concerns about technology transfer, IP theft, and the potential for foreign governments to exploit supply chain vulnerabilities. To address these concerns, a trend towards deglobalisation and localisation of the semiconductor industry has emerged as countries and companies seek to reduce their dependence on foreign suppliers and protect their IP (Nagata et al. 2023; Sami et al. 2024).

Since 2019, the US has implemented a series of increasingly extensive export controls on the SSC. The initial policy was based on national security concerns about critical infrastructure. The export controls targeted Huawei, a Chinese national champion whose global revenue in 2019 was close to that of Microsoft (Bown 2020a, 2020b). In September 2020, media reported that Chinese semiconductor foundry company SMIC could be blocked from purchasing US–made equipment, semiconductor designs, and software by being added to the Entity List[6]. In July 2019, the Japanese government announced potential new export controls on key inputs for semiconductor manufacturers in South Korea, such as hydrogen fluoride, fluorinated polyimides, and photoresist.

Table 4. Summary of SCC disruptions.

Type	Description	Example	Possible Effects on SSC
Geopolitical and Security Issues	Disruptions arising from geopolitical tensions, industrial shifts, and trade conflicts	US–China trade war impacting global semiconductor distribution and production	**Positive Effect:** Prompts innovation in remote operations and automation, reduces dependence on single sources, and emphasises the need for flexible, resilient supply chain strategies to mitigate future disruptions **Negative Effect:** Leads to supply chain fragmentation, increased lead times, regulatory hurdles, and uncertainty in trade policies, affecting production and procurement (Chen et al. 2023)
Public Health Events	Challenges to supply chain resilience due to global health crises	COVID-19 pandemic testing the viability of SSCs and prompting the need for resilient strategies	**Positive Effect:** Highlighting the importance of supply chain flexibility and redundancy (Chang and Kuo 2018) to respond effectively to sudden shifts in demand, production, and distribution **Negative Effect:** Disruptions due to factory closures, labour shortages, and disruptions in logistics and transportation

In light of the recent digitalisation push in the semiconductor industry, driven by advancements in Industry 4.0, another key security concern among semiconductor manufacturers is cyber attacks against their information systems. Researchers at Texas Instruments Inc. has conducted several studies on cyber-physical IT assessment tools, such as Cayetano et al. (2018) and Laghari et al. (2023, 2021). These tools are used to identify security vulnerabilities among current semiconductor companies, and such studies reveal a lack of focus on cybersecurity programmes (Budak et al. 2022). Despite the importance of information systems in SSC management, studies have so far largely overlook this aspect. However, software such as MES and ERP systems forms the backbone of SSC operations, leaving room for future research on this topics. A recent literature review conducted by Cheung, Bell, and Bhattacharjya (2021) on cybersecurity in supply chain management offers valuable insights that can inform further exploration of this critical area.

Opportunities and risks coexist in the context of uncertainty. As Chorzempa (2023) points out, companies and governments face much greater uncertainty and must evaluate the risk of dependence on both the US and China. In this section, we review the development of the SSC and discuss the major changes over time. We then present the results of a detailed literature review carried out to identify and analyse the security challenges faced by the SSC.

3.2. Geopolitical factors affecting the semiconductor industry

3.2.1. Impact of industrial shifts on the semiconductor supply chain

The semiconductor industry has seen major changes in terms of global distribution in recent decades (Figure 5). In the 1970s and 1980s, the US was the dominant player in the industry. However, Japan began to compete with the US as the leading producer of semiconductors (Irwin 1996). The 1980s marked the beginning of a period in which semiconductors were central to major trade conflicts. As part of the 1986 US–Japan

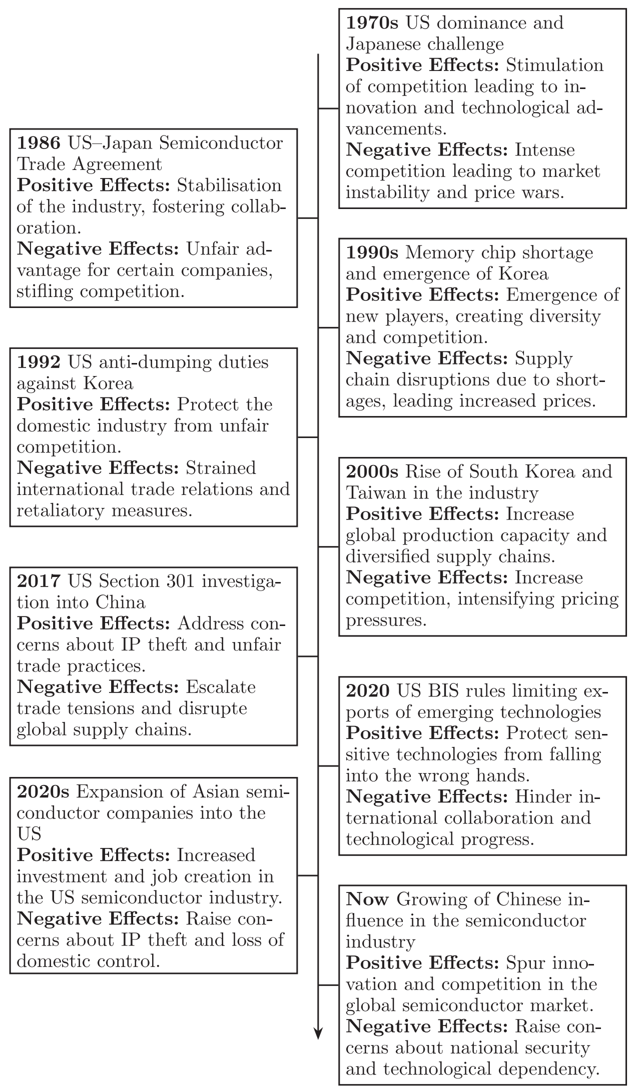

Figure 5. Key Events in the Development of the Semiconductor Industry.

Semiconductor Trade Agreement, the Japanese government agreed to end the 'dumping' of semiconductors on global markets and to guarantee 20% of its domestic semiconductor market to foreign producers within five years.

With Japanese supply limited and the US industry having exited the dynamic random-access memory (DRAM) market, there was a shortage of memory chips. This opportunity accelerated the development and entry of other semiconductor companies. In the 2000s, South Korean companies Samsung and SK Hynix became major players in the global semiconductor industry, with a focus on memory chips, which are essential components of many electronic devices. They quickly became major players in the memory chip market, and the US government imposed anti-dumping duties on Korean DRAM chips in 1992. The differences between these two disputes have been widely discussed. Notably, unlike Japan, with its passive government support, South Korea settled the dispute in court (Young 2004).

Taiwan also emerged as a major player in the semiconductor industry, becoming the 'Silicon Valley of the East' (Mathews 1997), with companies such as TSMC and UMC becoming major producers of semiconductors. Taiwan's semiconductor industry benefited from a strong government focus on industry development, as well as a large pool of experienced engineers and technicians. South Korea and Taiwan (Danilin and Yaroslav 2023) have become world leaders in the production of the smallest and most technologically advanced chips (10 nm and below). However, this could change within three to five years, as leading Taiwanese and South Korean companies plan to build cutting-edge manufacturing plants in the US.

European countries have a strong R&D presence in the semiconductor industry (Schneider-Petsinger 2021; Ejdys and Szpilko 2023), with research centres and universities contributing to the development of new technologies. It is widely recognised that competitiveness is linked to innovation capacity, in particular the ability to engage in open innovation processes (Huggins et al. 2023). The EU is working to increase its competitive advantage over other regions in the industry. Under the European Chips Act of 18 April 2023, the EU will continue to invest in strengthening the semiconductor ecosystem[7]. Ciani and Nardo (2022) report that the EU is a net importer of transistors, diodes, and similar semiconductor devices (mainly from China), as well as electronic integrated circuits (mainly from Taiwan). In particular, Taiwan is the leading source of EU imports of processors, other electronic circuits, DRAM, and multi-combinational memories.

In recent years, China has also become a major player in the global semiconductor industry, with the Chinese government heavily investing in the semiconductor industry. Chinese companies such as Huawei, HiSilicon, and SMIC, have become major players in the global market. However, the industry still faces challenges in terms of IP and technology transfer.

3.2.2. The US–China trade war and its implications

In 2017, the US government Launched an investigation into China's unfair trade practices under Section 301, the same law that ultimately led to the 1986 US–Japan Semiconductor Trade Agreement (Bown 2020a).

The trade war between the US and China has led to the imposition of tariffs, export controls, and other trade restrictions on various goods, including semiconductors. These measures have disrupted the flow of semiconductor components, materials, and equipment between the two countries. As a result, semiconductor manufacturers have faced challenges in sourcing critical inputs, leading to supply chain disruptions and potential shortages.

One of the consequences of US–China trade war is the reconfiguration of global supply chains. As reported by Varas et al. (2020), the key driving force behind location competitiveness is government incentives. US incentives are at the lower end of the range, well below those of Asian countries with a large semiconductor manufacturing footprint. The cost advantage of other countries over the US has led to shifts in production facilities, new manufacturing partnerships, and a search for alternative suppliers in regions outside the direct scope of the trade war. To mitigate the risks associated with the trade war, semiconductor companies have been forced to reassess their supply chain strategies and diversify their sourcing locations. Such efforts aim to reduce dependency on a single country or region and strengthen supply chain resilience.

Furthermore, the US–China trade war has raised concerns over IP protection and cybersecurity. The semiconductor industry is characterised by extensive IP rights (Chen, Khan, and Iftikhar 2021), and the trade war has increased concerns about the theft or violation of these valuable assets. Both countries have implemented measures to protect IP, including export controls and restrictions on technology transfer, affecting collaboration and knowledge sharing within the industry. For instance, on 3 January 2020, the Bureau of Industry and Security (BIS) of the US Department of Commerce unveiled the first in a series of proposed rules to limit the export of emerging technologies[8].

Addressing the implications of the US–China trade war for the SSC requires a comprehensive understanding of evolving trade policies, the regulatory landscape, and geopolitical dynamics. It also requires proactive supply chain risk management strategies, such as diversifying supply chain sourcing, developing contingency plans, and fostering partnerships with trusted suppliers and manufacturing facilities located in regions less affected by the trade war. However, some scholars (Luo and Van Assche 2023) argue that the US Act does not mark the end of

Table 5. Summary of SSC literature on geopolitical and security concerns.

Categories	Keywords	References
Security Issues	IP control, Reverse engineering, Logic obfuscation, Cybersecurity, National security	Gandhi et al. (2023), Liao and Hu (2007), Laghari et al. (2023), Lambert et al. (2013) and Shamsi et al. (2019)
Outsourcing	Dynamic capability, Global Value Chain, China's integration, Foreign dependence, Integration	Grimes and Du (2020), Khan, Mann, and Peterson (2021), Lee, Gao, and Li (2017), and Malkin and He (2024)
Localisation	Supply chain independence, China's reliance, Localised innovation, Workforce development	Chang et al. (2021), Dally and Su (2022), Frieske and Stieler (2022), Mousavi et al. (2022), Peters (2022), and To (2021)
Industrial Policies	China's semiconductor strategy, US support policies, CHIPS Act, EU-Taiwan cooperation	Goodman, VerWey, and Kim (2019), Jeong (2022), Khan (2020), Nordin and Stünkel (2022), and VerWey (2019)
Other		Gong et al. (2022) and Nicholas et al. (2023)

the liberal international order and that there is room for negotiation between the two geopolitical rivals.

3.3. Analysis of the literature on geopolitical disruptions

The main categories of geopolitical disruptions identified in our literature review include security issues, outsourcing, cross-regional collaboration, localisation, global value chain, and industrial policies (Table 5). We discuss these categories in detail below.

In terms of security issues, IP controls have generated much discussion because chip manufacturing involves multiple IPs that are mainly concentrated in companies in the US. Although IP and related technology transfer could help semiconductor companies to develop core competence and allow them to gain competitive advantages (Liao and Hu 2007), IP theft is achievable through reverse engineering. Integrated circuit camouflaging and logic locking (Subiah and Chinnathevar 2024) are two techniques that can thwart reverse engineering by end users or foundries. Shamsi et al. (2019) conduct a comprehensive review of hardware IP protection through logic obfuscation.

The critical importance of localised SSC innovation, education, and R&D is widely recognised in the literature. For example, Chang et al. (2021) state that the success of Taiwan's semiconductor industry can be attributed to R&D investments at the industry level and the government's unwavering commitment to cultivating engineering skills and talent. In a report to the US government, Dally and Su (2022) recommend that a portion of funds be dedicated to creating a national microelectronics training network for the future semiconductor workforce. However, with few local graduates and unattractive salaries, specialised semiconductor workers are in short supply. Over the next 10 years, South Korea's semiconductor industry is expected to face a shortage of at least 30,000 workers, according to the Korea Semiconductor Industry Association[9]. Dynamic outsourcing could be an alternative to localisation. Applying concepts from transaction cost economics, the resource-based view, and dynamic capabilities view, Khan, Mann, and Peterson (2021) analyse the most important factors in the development of outsourcing, using the Delphi and analytic hierarchy process method. Their research identifies the most influential sub-factors in the development of outsourcing for back-end semiconductor equipment companies.

Cross-regional collaborations are now treated with great care. The White House acknowledges that the Creating Helpful Incentives to Produce Semiconductors (CHIPS) Act of 2022 'will reduce our dependence on critical technologies from China and other vulnerable or overly concentrated foreign supply chains'[10]. Nordin and Stünkel (2022) report that following the announcement of the European Chips Act in February 2022, the EU seeks to cooperate more closely with Taiwan on chip production. However, the Taiwanese government seems to prefer a steady stream of smaller but successful cooperation projects to ensure long-term engagement. The recent trade tensions between Japan and Korea also pose unique challenges, as they threaten the availability of specialised and necessary chemicals that are not easily substitutable without imports. Goodman, VerWey, and Kim (2019) argue that such risks are likely to force companies in the industry to make seemingly counter-intuitive investment and sourcing decisions related to specialised chemicals. This insight into the chemical supply chain provides a valuable new perspective for future research on the US–China trade war. The localisation of SSCs has been proposed as a way out of the global supply chain uncertainty. For example, To (2021) suggests that localising supply chains may reduce China's reliance on foreign technology, but it will be costly and commercially unviable. Peters (2022) further argues that significant changes in strategic economic and national security linked to the rise of China in an increasingly multipolar world mean that the US no longer occupies its post-war position as the sole superpower.

The global semiconductor value chain is a related research topic. Lee, Gao, and Li (2017) argue that a latecomer country like China may find it difficult to develop a competitive semiconductor industry. Low-end semiconductor markets cannot be easily distinguished from high-end markets, which means that they cannot be leveraged by indigenous companies. These authors conclude that successful catching-up requires the growth of indigenous firms rather than dependence on foreign direct investment. Grimes and Du (2020) examine the implications of China's current integration into the global semiconductor value chain and find that, even with some movement up the value chain, such as the emergence of HiSilicon and general growth in the design sector, much of the higher value added activity in China continues to be dominated by major global companies. They also argue that the current tensions between the US and China have highlighted China's exposure to critical dependencies on foreign technology in semiconductor development. The decoupling of international supply chains could negatively affect the future of China's semiconductor industry.

VerWey (2019) discusses China's current semiconductor industrial policies. According to a recent report from the Office of the United States Trade Representative (USTR), China's strategy is to create a closed-loop semiconductor manufacturing ecosystem with self-sufficiency at every stage of the manufacturing process, from integrated circuit design and manufacturing to packaging and testing, and the production of related materials and equipment[11]. To achieve this goal, certain Chinese policies have the potential to (1) force the creation of market demand for indigenous semiconductor products, (2) gradually restrict or block market access to foreign semiconductor products as competing domestic products emerge, (3) force technology transder, and (4) grow non-market based domestic capacity, thereby disrupting the fabric of the global semiconductor value chain[12].

The US government support's policies for the semiconductor industry have also undergone tremendous changes (Jeong 2022). Since 2020, legislation to provide comprehensive support with a substantial budget has been introduced, promoting cooperation with Congress. In June 2020, the bill for the CHIPS for America Act was drafted, with the aim of funding R&D and secure technology supply chains to revive the domestic semiconductor manufacturing industry. This was followed by the American Foundations Act of 2020, aimed at providing subsidies to promote the expansion of semiconductor manufacturing facilities. The two bills were included in the United States Innovation and Competition Act of 2021 in June 2021 and passed by the Senate. Khan (2020) concludes that the US's export controls on semiconductor technology were relaxed in 2018, leading to an expansion of exports to China, particularly exports of SMEs and chips. However, the US has recently tightened its export licencing policies and applied stricter controls on military end-uses and end-users, as well as on other major Chinese entities.

4. Disruption of public health events

4.1. Public health events as a disruptive force

Public health events, such as infectious disease outbreaks, have the potential to disrupt global supply chains on a scale that challenges SSC viability. For example, the COVID-19 pandemic had significant impacts on the SSC, causing disruptions in production and logistics and leading to shortages in the industry. It also led to an increased demand for electronic devices, causing strain in the supply chain and leading to increased pricese (Albrecht and Steinrücke 2020) and reduced availability of certain products. In this section, we first summarise how the pandemic influenced the SCC and then classify the literature according to related topics (Table 6).

4.2. Impact of public health event on the semiconductor supply chain

The SSC was profoundly affected by the COVID-19 pandemic, with several challenges straining that strained industry operations. We summarise the key research questions and possible mitigation strategies in the selected literature and then identify some possible research gaps (Figure 6).

One of the major hurdles during the COVID-19 pandemic was the occurrence of production disruptions caused by various factors. Because of supply shortages and restrictions, many semiconductor manufacturing facilities were forced to close or operate at reduced capacity. This led to a decrease in production and a slowdown in meeting demand. With a multi-tier supply chain, the semiconductor industry relies on a complex network of suppliers, and disruptions in any part of the supply chain can lead to shortages of crucial components needed for chip manufacturing, causing ripple effects throughout the supply chain (Ivanov and Dolgui 2022a). For instance, restrictions at one of the busiest ports in Yantian, southern China, led to delays in loading and unloading cargo (Ramani, Ghosh, and Sodhi 2022).

Public health events can also affect consumer demand and behaviour. In times of uncertainty and crisis, consumer spending patterns may change, leading to changes in demand for semiconductor products. For example, during the COVID-19 pandemic, demand for electronic devices and communication technologies increased due to the rise of remote work and online activities. Meanwhile, demand for certain applications, such as automotive or consumer electronics, may have decreased because

Table 6. Impact of the COVID-19 pandemic on the SSC.

Pandemic impact	Keyword	References
Production Disruptions	Production slowdown, Facility closures, Labour issues, Disruption propagation	Frieske and Stieler (2022), Hasan, Bellenstedt, and Islam (2023), Ishak et al. (2022), Suh and Choi 2022, Tonke and Grunow 2018, Ziarnetzky et al. 2018, Ziarnetzky et al. (2019), and Ivanov and Dolgui (2021)
Consumer Demand	Surge in remote work and online activities	Lamsal, Devkota, and Bhusal (2023), Zhong et al. 2022, and Marinova and Bitri (2021)
Logistical Delays	Port congestion, Shipping disruptions, Lockdown interventions	Oraby et al. (2021) and Ramani, Ghosh, and Sodhi (2022)
Talent Shortages	Workforce development, University outreach	Thorbecke (2021)
Post-Pandemic Recovery	Keyword	References
Government Policies	Reshoring, Compensation, Bankruptcy risks	Cai and Luo (2020), Patil and Prabhu (2021) and Elia et al. (2021)
Economic Recovery	Unbalanced demand-supply and Chip shortages, Production adjustments	Ahmad (2020), Ramani, Ghosh, and Sodhi (2022), Rozhkov et al. 2022, Sodhi et al. 2023 and Panwar, Pinkse and Marchi (2022)
Demand Fluctuations	Demand forecasts, Panic buying	Wang and Chen 2019, Barnes, Diaz, and Arnaboldi (2021), Chien, Lin, and Lin (2020), and Hasan, Bellenstedt, and Islam (2023)

Questions

(1) How did the COVID-19 pandemic affect the global SCC in its initial stages?
(2) What is the strategic importance of the semiconductor industry in navigating global challenges, and how has the pandemic affected it?
(3) How have COVID-19-related disruptions highlighted vulnerabilities in SSCs, and what measures can mitigate these risks?
(4) What are the specific disruptions caused by the pandemic in supply chains and how can businesses respond effectively?
(5) How does the lag in industrial production relative to services growth affect post-pandemic economic recovery, particularly in relation to supply chains?

Literature Contributions

- Identify the immediate impacts of COVID-19 on semiconductor production, such as facility closures and logistic challenges.
- Emphasise the critical role of the semiconductor industry in modern economies and the compounded effect of pandemic-induced disruptions.
- Provide insights into supply chain resilience and propose strategies to strengthen supply chains in the face of such global shocks.
- Analyse various dimensions of supply chain disruptions and suggest comprehensive approaches for recovery and strengthening against future crises.
- Offer a perspective on the uneven recovery between industrial production and services, underscoring the long-term implications for supply chains.

Critiques

- The pandemic has exacerbated existing socio-economic inequalities, yet there reveals a gap in addressing how these inequalities affect and are affected by supply chain disruptions and industry responses. Research should explore the social dimensions of the pandemic's economic impact.
- There's a lack of clarity on the long-term effects of semiconductor industry localisation on innovation and competition caused by the pandemic as well as interconnection with geopolitical issues.
- There is a scarcity of theory based frameworks that guide how industries and economies can prepare for, respond to, and recover from such global health event disruptions.
- The role of digital transformation in enhancing supply chain resilience needs more in-depth investigation.

Figure 6. Selected Questions, Findings, and Critiques from the SSC Literature.

of the economic slowdown or changes in consumer priorities. Marinova and Bitri (2021) study the solutions offered by the semiconductor industry and the initiatives implemented by Europe, the US, and especially China to help their countries and companies adapt to the chip shortage in the post pandemic years.

Logistical delays were also a major concern during this period. Ports were congested because of a massive influx of goods, leading to container availability issues. Moreover, shipping routes experienced disruptions and traffic jams, creating further delays in the transportation of semiconductor products. Ishak et al. (2022) argue that supply chain adaptive strategies combining robustness, agility, and resilience had a significant impact on the performance of semiconductor companies during the COVID-19 pandemic. From a broader perspective, Ivanov and Dolgui (2021) review recent operations research studies dealing with disruption propagation and structural dynamics in supply chains, with a focus on mathematical modelling methods. Oraby et al. (2021) discuss lockdown scenarios in representative countries and note that increasing rates of social contact can all benefit from well-timed lockdown interventions.

The pandemic also triggered other disruptions in the SCC, particularly concerning labour-related issues. Infectious diseases outbreaks can lead to employee absences, labour shortages, and restrictions on the personnel movement. Labour shortages and strikes affected the workforce during the pandemic, resulting in reduced production capacity and difficulty meeting demand. Pandemic outbreaks in Taiwan and South Korea affected plant production by causing labour shortages. In short, the pandemic exacerbated an existing talent shortage problem. The Taiwan office of photolithography systems supplier ASML Holding NV's said that it was forced to contact second-tier universities and colleges in Taiwan and abroad to address talent shortages, as job poaching is not a long-term solution[13].

Overall, the pandemic had far-reaching effects on the SSC, causing major disruptions in production, demand, logistics, and labour. These disruptions led to shortages, longer lead times, and increased costs for many industries reliant on semiconductors.

4.3. Recovery of the semiconductor industry from disruptions caused by public health events

In general, government policies following public health events help to boost the recovery process. Elia et al. (2021) suggest that reshoring policies must be supported by and combined with industrial policies to strengthen the competitiveness and sustainability of production systems. Although production has gradually resumed since the COVID-19 pandemic, Cai and Luo (2020) report that business has been difficult for many SMEs because of the slowdown of the global economy. Since the COVID-19 outbreak, these companies have faced increased risks of bankruptcy, and if these risks worsen, a systemic financial crisis could occur. This suggests that governments should take steps to control the bankruptcy risks of SMEs, as they provide for most jobs.

Demand fluctuations are challenging problems in the post-pandemic semiconductor industry. Although Bauer et al. (2020) expected overall demand to be 5%–15% lower in 2020 than in 2019, Gartner Inc.[14] later verified that global semiconductor revenue in 2020 was US$466.2 billion, an increase of 10.4% compared to 2019. Chien, Lin, and Lin (2020) propose a novel UNISON reinforcement learning framework, focussing on the realistic needs of a leading distributor of semiconductor components and modules, to dynamically select the optimal demand forecasting model for specific products with corresponding demand patterns.

Consumer tastes and behaviours can also differ considerably during and after a public health event. For instance, Barnes, Diaz, and Arnaboldi (2021) report that consumer behaviour during the pandemic was characterised by 'panic buying'. Using big data from social media, these authors apply text mining and compensatory control theory to demonstrate early warnings of potential demand issues. Similar research topics and methodologies can shed light on semiconductor end-use consumption. An unexpectedly rapid economic recovery (Panwar, Pinkse, and Marchi 2022) has worsened an already unbalanced situation in terms of demand and supply of semiconductors.

Auto chips are considered an important asset of the post-pandemic semiconductor industry. Indeed, auto manufacturers rely haevily on semiconductor chips for various functions in vehicles, such as advanced driver assistance systems, infotainment systems, and engine control units. Assuming that governments would offer incentives to car buyers in 2020, Bauer et al. (2020) estimate that the automotive industry would experience year-over-year growth of 28%–36% in 2021, which was an optimistic recovery scenario. According to a report published by Global Market Insight[15], the automotive electronics market was worth more than US$270 billion in 2017 and is expected to exceed US$390 billion in 2024, with a compound annual growth rate (CAGR) of more than 6.5% (Ahmad 2020). Towards the second half of 2020, as the automotive industry ramped up production, it ran into a significant obstacle: a shortage of semiconductor chips. Increased demand for automobiles led to the demand for these chips, creating a ripple effect upstream in the SSC. However, chip manufacturers faced limited manufacturing capacities and were unable to meet the sudden surge in demand from the automotive industry. This prolonged unavailability of chips caused a shortage, disrupting the automotive industry's production plans.

Auto manufacturers were forced to halt or postpone their production decisions because of the shortage of critical components[16]. The impact of the chip shortage reverberated across the entire automotive industry, leading to production halts, backlogs, and potential loss of revenue. Several auto manufacturers had to reduce or adjust their production schedules, which affected their ability to meet consumer demand and fulfil orders. The shortage also highlighted the vulnerability of the automotive supply chain and the need for more robust strategies to manage disruptions and ensure a stable supply of semiconductor chips. Ramani, Ghosh, and Sodhi (2022) summarise systemic disruptions in supply chains by studying the chip shortage in the automotive industry. They also test a stylised mathematical programming model with one chip supplier and three manufacturers to determine the impact of some of the identified factors and they find that shortages propagate within and across sectors.

5. Discussion

5.1. Future research areas

The SSC, essential to the global economy, faces both challenges and opportunities for innovation and enhanced resilience. As we move forward, several emerging trends and strategic directions are shaping the future of this critical industry. Our review of SCC vulnerabilities and disruptions identified several research gaps.

(1) *Geopolitical considerations and resilient design of supply chain networks*. According to Aldrighetti et al. (2021) and Shih (2020), there is a need to re-evaluate the extent and nature of globalisation of supply chains. Geopolitical dynamics, particularly with regard to China, play a major role in shaping the future of the SSC. As China seeks to reduce its dependence on Western technology, the global semiconductor industry must navigate the challenges of technology transfer and national security risks[17]. Strategies for managing these risks (Kuo et al. 2023) include diversifying supply chains and using additional restrictions and subsidies to incentivise companies to reduce their exposure to geopolitical uncertainties. Future studies could investigate the trade-offs between global diversification and localised supply chains, considering factors such as geopolitical risks, trade barriers, and local economic incentives.

(2) *Decentralised supply chain models for enhanced resilience*. Koh, Dolgui, and Sarkis (2020) show that the decentralised framework of blockchain technology (DiMase et al. 2016; Xu et al. 2019; Rekha et al. 2021; Calzada et al. 2023; Tan et al. 2023) mitigates risks and disruptions in transport and logistics. Future research should focus on the design of decentralised supply chain networks, leveraging insights from the burgeoning field of blockchain studies, as suggested by Pournader et al. (2020) and Yang et al. (2023). This is particularly important for the semiconductor industry, which is characterised by long lead times and complex global networks. The potential of blockchain to address these unique challenges offers a promising method for enhancing SSC resilience.

(3) *Strategic responses to supply chain disruptions*. In light of the recent disruptions discussed above, the semiconductor industry is focussing on strategic responses (Ishak et al. 2023) to enhance its resilience and agility. Simulating (Chen et al. 2017) and planning for extreme supply and demand disruptions has become a priority, as has re-evaluating just-in-time inventory strategies[18]. Creating digital twins for critical parts of the supply chain (Seok, Cai, and Park 2021; Nguyen et al. 2023) allows for better simulation and testing of scenarios, enabling faster and more informed responses to unforeseen events. Other approaches such as the fast chain models and flexible models, are aimed at industries that need to respond quickly respond to market trends or seasonal fluctuations in demand[19]. Future research on these strategic responses, such as agility and increased data sharing with suppliers[20], could provide insights to enhance the ability to respond quickly to disruptions.

(4) *Digitalization and Industry 4.0 for supply chain resilience*. The adoption of Industry 4.0 technologies (Ivanov, Dolgui, and Sokolov 2019; MacCarthy and Ivanov 2022) plays a crucial role in mitigating SSC disruptions by equipping supply chain planners with advanced capabilities for enhanced decision-making. Digitalization tools such as IoT (Ben-Daya, Hassini, and Bahroun 2019; Oi et al. 2022); AI (Baryannis et al. 2019; Gopal et al. 2022); and big data analytics (Rai et al. 2021; Alizadeh et al. 2020; Chang et al. 2022; Jahani et al. 2023) enable real-time monitoring and predictive analytics, leading to proactive management of potential disruptions. For instance, simulation optimisation techniques (Hartwick et al. 2023; Zhang et al. 2020) applied to production scheduling can significantly improve operational efficiencies and adaptability (Ghasemi et al. 2024). These technologies facilitate a more agile response to unforeseen changes in semiconductor supply and demand, improving overall supply chain resilience. This review underscores the necessity of exploring the impact of digital technologies in creating robust SSC systems, especially under the pressures of geopolitical issues, disrupted globalisation and market volatility. Researchers are encouraged to delve into recent reviews and studies, such as Ghasemi et al. (2024) and Mönch et al. (2020), which provide comprehensive insights into the application and benefits of these advanced technologies in modern SSC.

5.2. Academic implications

Building on previous research, this study contributes to the analysis of supply chain resilience and disruptions in the semiconductor industry. First, we provide a comprehensive and timely review of the literature and summarise the proposed mitigation strategies. We also identify several key research gaps. For instance, it is surprising that the topics of IP, hardware, software, and raw materials (Chakrabarti et al. 2022), which are essential to the processing of semiconductor products, are not addressed in the literature. Furthermore, little is known about the effect of the lack of R&D and design professionals on the SSC. Addressing the lack of such key elements is even more important in the face of disruptions such as geopolitical issues.

Second, for more general interest and multidisciplinary insights, our review identifies and collects additional sources of literature from closely related domains such as international trade, industrial organisation, political science, human resource management, and global strategies (Frost and Hua 2019). These valuable complementary publications enrich the current stream of research on supply chain disruption. Given the complex and global nature of the SSC, future research should investigate how mitigation strategies in the face of disruptions can be adapted to and scaled across different environments, cultures, and economies to ensure broad applicability and effectiveness.

The trend towards the localisation of the semiconductor industry and other critical industries, driven by the COVID-19 pandemic, raises questions about its long-term impact on global innovation ecosystems, supply chain resilience, and geopolitical dynamics. The evolving geopolitical landscape also presents a complex web of risks for global industries. Thus, research is needed to develop more sophisticated models for assessing and managing geopolitical risks, particularly in sectors critical to national security and economic stability. This includes understanding the interplay between national policies, international relations, and industry strategies.

5.3. Practical implications

To combat SSC vulnerabilities, governments, industries, and organisations could deploy various strategies aimed at enhancing SSC resilience. These efforts can mitigate risks of disruption, whether from geopolitical conflicts, technological shifts, or public health events.

Governments around the world have recognised the strategic importance of semiconductors and have implemented several measures to secure and strengthen their supply chains. One notable approach is the implementation of market-driven incentive programmes designed to geographically diversify the semiconductor manufacturing base. For instance, the US has proposed a US$50 billion incentive programme that is expected to double the country's advanced semiconductor manufacturing capabilities over the next decade[21]. Such initiatives aim not only to bolster domestic localised manufacturing but also to mitigate risks related to geopolitical tensions and trade barriers (Ochonogor et al. 2023). Moreover, governments are urged to promote global trade and international collaboration in R&D and technology standards, as well as to encourage public investment in science and engineering education and to reform immigration policies to attract global talent[22].

Policymakers also play a critical role in shaping the environment in which the semiconductor industry operates to combat disruptions. It is recommended that policies aim not for complete self-sufficiency but rather for nuanced and targeted approaches that strengthen supply chain resilience. This includes ensuring a global level playing field, protecting IP rights, and avoiding broad unilateral restrictions on technology and suppliers. In addition, our review calls for policies that address the talent shortage and stimulate upstream innovation.

On the industry front, companies are actively looking for ways to make their supply chains more resilient, adopting various frameworks and mitigation strategies. For instance, this includes the development and alignment of technology blocks among major players in the semiconductor industry to ensure compatibility throughout the value chain[23]. Additionally, out literature review reveals that a shift towards an agile supply chain network model is a critical strategy. Such a model facilitates multiple pathways for supply chain operations, effectively reducing the risk of single points of failure and enabling a balance between cost efficiency and resilience[24].

5.4. Limitations

This study has certain limitations. First, it only covers the literature from the past 17 years, drawn from a key electronic academic database (i.e. Scopus) and manual searches from Google Scholar. Second, the articles selected for review and analysis are mainly limited to peer-reviewed academic journals, which generally provide high quality content. Other types of texts, such as conference papers and reports, are difficult to evaluate and thus conference papers are less included. However, collecting data from more sources could lead to a better understanding of this topic.

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Data availability statement

The data that support the findings of this study is available from the corresponding author upon reasonable request.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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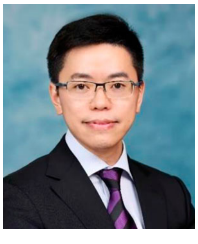

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