Journal Pre-proof

Understanding Systemic Disruption from the Covid-19-induced Semiconductor Shortage for the Auto Industry

Vinay Ramani, Debabrata Ghosh, ManMohan S. Sodhi

PII: S0305-0483(22)00127-X
DOI: https://doi.org/10.1016/j.omega.2022.102720
Reference: OME 102720

To appear in: *Omega*

Received date: 31 October 2021
Accepted date: 25 June 2022

Please cite this article as: Vinay Ramani, Debabrata Ghosh, ManMohan S. Sodhi, Understanding Systemic Disruption from the Covid-19-induced Semiconductor Shortage for the Auto Industry, *Omega* (2022), doi: https://doi.org/10.1016/j.omega.2022.102720

Highlights

- Systemic disruptions cause shortages within a sector and across sectors
- We seek to understand the disruption of Covid on the auto industry hit by chips shortage
- A thematic analysis of 209 news articles brings out various causes and effects
- A stylized LP model with sequential scenarios illustrates impact within and across sectors

Understanding Systemic Disruption from the Covid-19-induced Semiconductor Shortage for the Auto Industry

June 28, 2022

Abstract

Covid-19 has allowed us to study systemic disruptions that impact entire industries. This paper explores how disruptions start, propagate, and continue over time by examining the semiconductor chip shortage faced by the auto industry during the years following Covid-19 in 2020. First, we carried out a thematic analysis of 209 pertinent newspaper articles. The analysis resulted in a thematic model of such disruptions with the interplay of various factors leading to the prolonged disruption to the auto sector. Second, we present the results from a stylized supply chain planning model run at different times to show how disruptions propagate to the auto and other sectors, causing systemic shortages. Overall, we contribute to the supply chain risk literature by focusing on system disruptions impacting entire industries versus normal disruptions affecting a particular company's supply chain.

Keywords: Systemic disruption, Covid-19, automotive, chips shortage, electronic industry

1 Introduction

While there is much literature on disruptions impacting downstream supply chain companies, there is relatively little on system-wide or systemic disruptions affecting not just one company but also an entire industry or industries.[1] Covid-19 and the pandemic-induced lockdown worldwide created demand surges alongside supply shocks, resulting in prolonged shortages for the auto industry and other industries. Indeed, the Organisation for Economic Co-operation and Development (OECD) has called for *system resilience* to tackle Covid-related disruptions (Ramos and Hynes, 2020).

[1]The Bank of International Settlements defines a *systemic disruption* as the "impact of one or a series of events that have the potential to threaten the stability of the financial system, with contagion effects among FMIs, financial institutions, financial markets and others" for the financial system. See www.bis.org.

Consider the chips shortage experienced by the auto industry following Covid-19 in late 2020, which at the time of writing was expected to continue through 2023 or even 2024. Semiconductor shortages have impacted nearly all global auto manufacturers, creating production halts and backlogs. The annual worldwide production losses were estimated as $110 billion by May 2021 (Wayland, 2021). As a result, the auto industry, chip manufacturers, and governments have turned their attention to mitigation strategies to secure sourcing and capacity expansion. For instance, the US government offered $50 billion incentives to Intel, Samsung, and the Taiwan Semiconductor Manufacturing Company (TSMC) to set up factories in the US. At the same time, BMW signed a semiconductor supply deal with Inova Semiconductors and Global Foundries in December 2021 to secure supplies in the future, as did Stellantis with Foxconn to design a new family of semiconductors for its electric vehicles. Other companies made cuts: Ford shut some of its factories throughout 2021 and prioritized some models over others, Tesla did not include a redundant backup unit in some parts of the world in its cars, and Volkswagen cut its night shifts in 2022.[2]

This paper seeks to understand systemic disruptions in supply chains by studying the chips shortage in the automotive sector in two ways. *First*, we carried out a thematic analysis of news articles on the Covid-19-led semiconductor shortage for the automotive industry to provide a thematic model of the causes and effects of the shortage. *Second*, we developed a stylized linear-programming-based supply chain planning model and ran it at different times to understand how shortages affect different industries and note the challenges of such modeling. Even with a stylized model and a central planner, we can see the continued impact of disruptions. Thus, we draw lessons and implications on how systemic disruptions start, propagate, and continue over time.

Our findings reflect that the interplay of external shocks and the reactions of the different supply chain players prolong the disruption to the supply chain, making the disruption "systemic." In the specific context of the chips shortage for the auto industry, Covid and the resulting lockdown in various countries were external shocks. The reaction of consumers, the chip manufacturers, and the auto manufacturers were internal shocks that led to further responses, transmitting and amplifying shortages through the global supply chain networks. As consumers demanded more electronic goods during work-from-home, the chip manufacturers reallocated capacity to the consumer electronics sector. The auto industry shut down and attempted to restart production. Further, the geographic concentration of chip manufacturing did not help due to long lead times, poor coordination between different tiers of the multi-tier auto industry, and the desire to over-order during periods of shortage.

[2] https://www.autocar.co.uk/car-news/business-tech%2C-development-and-manufacturing/latest-updates-semiconductor-chip-crisis

There are also findings regarding mitigation efforts. The auto industry players countered the disruption through short-term operational strategies such as product and assembly line prioritization. In the long-term, localization of sources, supplier consolidation, capacity planning through stockpiling, and capacity reservation emerged as mitigation strategies. The chip manufacturers and governments played a critical role in designing appropriate approaches to resolving the crisis. Governments assume an essential role through subsidies or direct investments for creating domestic manufacturing capacity. Increased capacity investments and hiring and training workers are among the critical approaches for chip manufacturers to expand capacity in response. Through our stylized model, we observed that the chip manufacturers' capacity increases, and the auto manufacturers' product mix changes cushion the impact of the semiconductor chip shortage.

In the rest of the paper, Section 2 reviews the related literature. Section 3 presents the results of a thematic analysis of the immediate causes and effects broadly regarding the disruption to the auto industry. Then, Section 4 presents an analytical model and the results we obtained from runs on five sequential scenarios that partition the timeline from January 2020 to December 2023. Finally, Section 5 discusses the implications of our study for researchers and managers.

2 Literature Review

Our study contributes to the supply chain risk literature in general by focusing on system disruptions affecting entire industries versus normal ones that impact a single company's supply chain. In particular, we extend the Covid-19-motivated supply chain literature by studying the case of the auto industry and the shortage of semiconductor chips. Our study seeks to contribute to the nascent Covid-19-motivated literature on long-term systemic disruptions in the risk-and-resilience literature that seeks to explain supply chain risk (Chopra and Sodhi, 2004; Tang, 2006; Sodhi et al., 2012; Chopra and Sodhi, 2014). Sodhi and Tang (2021c) have presented the notion of *extreme supply chain management* motivated by Covid-19. Scheibe and Blackhurst (2018) have brought up the idea of systemic risk in a supply chain, although their focus is primarily on the propagation within the supply chain. Additionally, Ivanov (2020a) and Ivanov and Dolgui (2020) consider the *ripple effect* for disruptions. However, the literature on understanding how systemic disruptions propagate and impact supply chains is still nascent. Our paper seeks to contribute to this stream with this study of the chips shortage in the auto industry, which shows how pandemic-led disruptions propagate through supply chains.

The OM literature looks at supply chain risks in two categories broadly – *operational risks* which relate to demand fluctuations, and *disruption risks*, which are low-likelihood events with significant impact (see for e.g. El Baz and Ruel, 2021; Choi, 2021; Ivanov, 2020a; Ivanov et al., 2018; Ivanov, 2020b). Within the the latter category, we may have *super disruptions* (Rozhkov et al., 2022), an example being Covid-19 pandemic. Ivanov (2020a) discusses the distinctive features of such disruption risks that are characterized by long-term existence, uncertainty, and propagation, emphasizing a systemic view of such (super)disruptions. Queiroz et al. (2020) review the literature tied to epidemics and propose a framework to study operational issues—adaptation, digitalization, preparedness, recovery, ripple effect, and sustainability—and suggest that the traditional supply chain models may not yield solutions to long-term global pandemic-led disruptions.

Chowdhury et al. (2021) identify key research themes: impact of Covid-19 pandemic; resilience strategies for managing impact and delivery; role of technology in implementing resilience strategies; and supply chain sustainability in the context of the pandemic. Among the issues studied, the key focus areas are – demand spikes for essential goods and services (Chowdhury et al., 2021; Ivanov and Dolgui, 2021; Gunessee and Subramanian, 2020; Queiroz et al., 2020); shortage of essential products (Hobbs, 2020; Sharma et al., 2020); on-time delivery failures (Ivanov and Das, 2020); supply disruptions and scarcity of parts (Baveja et al., 2020; Nikolopoulos et al., 2021; Singh et al., 2021); increased backlog due to production disruptions and labor shortages (Ivanov and Das, 2020; Mehrotra et al., 2020); and transportation delays and disruption in distribution channels (Choi, 2020; Ivanov and Dolgui, 2020).

Examining the ripple effect, Ivanov et al. (2014) describes it as "the impact of a disruption on supply chain performance and disruption-based scope of changes in the supply chain structures and parameters". Failure at one node in an intertwined network leads to a domino effect. Dolgui et al. (2020) states that ripple effect "refers to structural dynamics and describes a downstream propagation of the downscaling in demand fulfillment in the supply chain as a result of a severe disruption". Ivanov (2020a) and Ivanov and Dolgui (2020) study the ripple effect in the context of the pandemic-related disruptions. Furthermore, Haren and Simchi-Levi (2020) provide two examples of Covid-19-induced ripple effect in the supply chains of Fiat Chrysler Automobiles (now Stellantis) and Hyundai.

The pandemic-led disruption has also increased the emphasis on *supply chain resilience.* Supply chain resilience signifies the supply chain's ability to resist and recover to reach a (possibly new) steady-state, where consumer demand can be satisfied (e.g. Aldrighetti et al., 2021; Chopra et al., 2021; Shekarian and Mellat Parast, 2021; Rezapour et al., 2021; Hosseini et al., 2019; Ivanov et al., 2018). The idea is to develop capabilities for a fragile supply chain to mitigate the disruptions caused by the pandemic: inventory reservation; back-up and emergency inventory at the distribution center; reserve capacity (Sodhi and Tang, 2021a) and multi-level commons (Chopra et al., 2021) have been suggested as some supply chain resilience strategies in the recent Covid motivated supply chain literature. There is also empirical work in identifying the impact of supply chain resilience strategies (e.g Zakharov et al., 2020; Khalilpourazari and Hashemi Doulabi, 2021; Khalilpourazari et al., 2021; Jha et al., 2021). Ivanov and Dolgui (2021) also discuss the need to *adapt* supply chains to better prepare against future pandemics with a view to making supply chains more *viable* in the long-term (Ivanov and Dolgui, 2020).

While studies on pandemic-led disruptions in supply chains are emerging, there remains significant scope to improve our understanding of systemic disruptions that affect entire industries. To address this gap, this paper undertakes a thematic analysis of news reports to draw out a cause-effect framework of the chip shortage disruption and its propagation through the automotive supply chain. We also develop a stylized analytical model to illustrate how disruptions propagate over time, leading to shortages to draw insights for mitigation.

3 A Thematic Analysis of the Auto Industry Chips Shortage

Semiconductor chips are essential to the production of a vehicle as many sensors and controllers require semiconductor chips. The applications of semiconductor chips include engine control, cruise control, power seats and windows, airbags, automatic braking systems, and entertainment systems (Boston et al., 2021). Moreover, vehicles are becoming more digital over time, requiring more chips. Semiconductors also have extensive applications in other sectors, including medical devices, computers, mobile phones, gaming systems, energy systems, and defense technologies (Ludwikowski and Sjoberg, 2021).

The industry is capital intensive, with long lead times associated with capital expansion. Wafer fabrication is a critical component of the semiconductor manufacturing process. The wafer fabrication process is technologically challenging, complex, and highly capital intensive (Swaminathan, 2000; Trivedi, 2021). For example, a fabrication facility may require \$4-20 billion investment, about two years to construct, and take two or three years on the learning curve to get the desired yield (Trivedi, 2021; Jie et al., 2021). Further, advanced tools, equipment procurement, research and development, and worker training may add several millions of dollars to costs (Swaminathan, 2000; Jie et al., 2021). In addition to the cost barriers, semiconductor manufacturing requires extensive human capital and learning-by-doing, making it difficult to replicate or copy (Appleyard, 1996). That is why, despite outspending TSMC on R&D over ten years, Intel lags behind TSMC in developing the most advanced semiconductor processes (Gallagher, 2021).

Consequently, the semiconductor industry has only a few dominating players, including Intel, NVIDIA, Qualcomm, Samsung Electronics, and TSMC (Bauer et al., 2020). Even within these, there is concentration, especially in the auto industry: TSMC produces around 92% of the world's most advanced chips and about 60% of the less advanced chips for the sector (Jie et al., 2021). There is also geographical concentration, with 80% of chip manufacturing taking place mainly in Japan, China, South Korea, and Taiwan (Gelsinger, 2021) with the US having 10-12% of the global chip manufacturing (Whalen, 2021).

This paper looks at the systemic disruption to the auto sector after Covid-19 first struck in 2020. In the last quarter of 2020, limited stocks and unavailability of semiconductors created a supply disruption for the auto industry, forcing production halts (Boston et al., 2021), reflecting the dependence of auto original equipment manufacturers (OEMs) on semiconductor chips (Fitch, 2021). We analyzed articles from popular press and media on semiconductor shortage in the automotive supply chains. Thematic analysis is a qualitative research method for *"identifying, analyzing, and reporting patterns (themes) within data"* (Braun and Clarke, 2006). Thematic analysis is not tied to any particular theory or methodology; for instance, grounded theory makes use of it (Sodhi and Tang, 2018). In particular, it is appropriate for exploratory studies such as ours.

We carried out the six steps of thematic analysis following Hastig and Sodhi (2020) and Sodhi and Tang (2018): (1) familiarization with the data, (2) generation of codes, (3) search for themes, (4) review of themes, (5) defining and naming themes, and (6) production of the report (Braun and Clarke, 2006). Step 1 needs further elaboration as the initial challenge was identifying the relevant literature sample. Steps 2–4 were iterative, involving data reduction, assignment of codes, and generation of sub-themes and themes. We followed a hierarchical approach in this regard where we named themes and sub-themes in Step 5, resulting in the thematic model in Section 3.1.

We developed our data corpus from the business press and other media articles from June 2019 to June 2021, using the Factiva database with the keywords 'chip shortage and automobile', 'chip shortage and supply chains,' and 'chip shortage and automotive.' We limited the search to the Financial Times; the Wall Street Journal; the New York Times; the Economic Times; the Economist; New Straits Times; Los Angeles Times; the Times; the Times of India; China Daily; South China Morning Post; Reuters; Washington Post; Forbes; Barron's; Business Insider; and Business Standard. After filtering out duplicates or articles that were not relevant, we were left with 209 articles for our corpus (Appendix, Table A1). Thematic analysis yielded the model we present in the subsection below.

3.1 A Thematic Model of Causes and Effects

Drawing out themes from the news articles helped us propose a cause-effect model (Figure 1). Overall, the pandemic led to lockdown, with varying severity across countries. The lockdown reduced the demand for automobiles which caused several plants to cut production or completely shut down. The automotive manufacturers subsequently canceled orders for various components, particularly semiconductor chips. In parallel, work-from-home led to increased demand for electronic products such as laptops, tablets, gaming consoles, headphones, and wireless routers; the semiconductor manufacturers reallocated their chip production capacities. In addition, the US imposed restrictions on trade with a few companies like Huawei and ZTE technologies based in China, which prevented semiconductor manufacturers like TSMC from trading with these firms. Uncertainties in business and the potential for future sanctions led several companies to hoard semiconductor chips, further aggravating the crisis.

With increased vaccination rates and phased re-opening of business activities towards the latter half of 2020, automobile demand increased as consumers returned to the market, requiring auto companies to increase production and place larger orders with the chip manufacturers. However, these manufacturers were already operating at near or full capacity, catering to other sectors. Other supply disruptions caused additional shipping and transportation delays. These disruptions included sporadic virus outbreaks at ports in China, a fire at the Renesas Electronics Corporation, a semiconductor manufacturer in Japan, and a cold winter storm in Texas, which has several semiconductor fabrication facilities.

Thematic analysis indicated that the stakeholders in the semiconductor chip shortage include auto manufacturers; suppliers; chip manufacturers; consumer electronic manufacturers; government, dealers, and end consumers. The auto manufacturers were severely impacted, leading to adverse effects such as production losses, lower sales, worker furloughs, and layoffs. The suppliers in the auto supply chains include the Tier-1 and 2 suppliers to the OEMs in a multi-tier network.

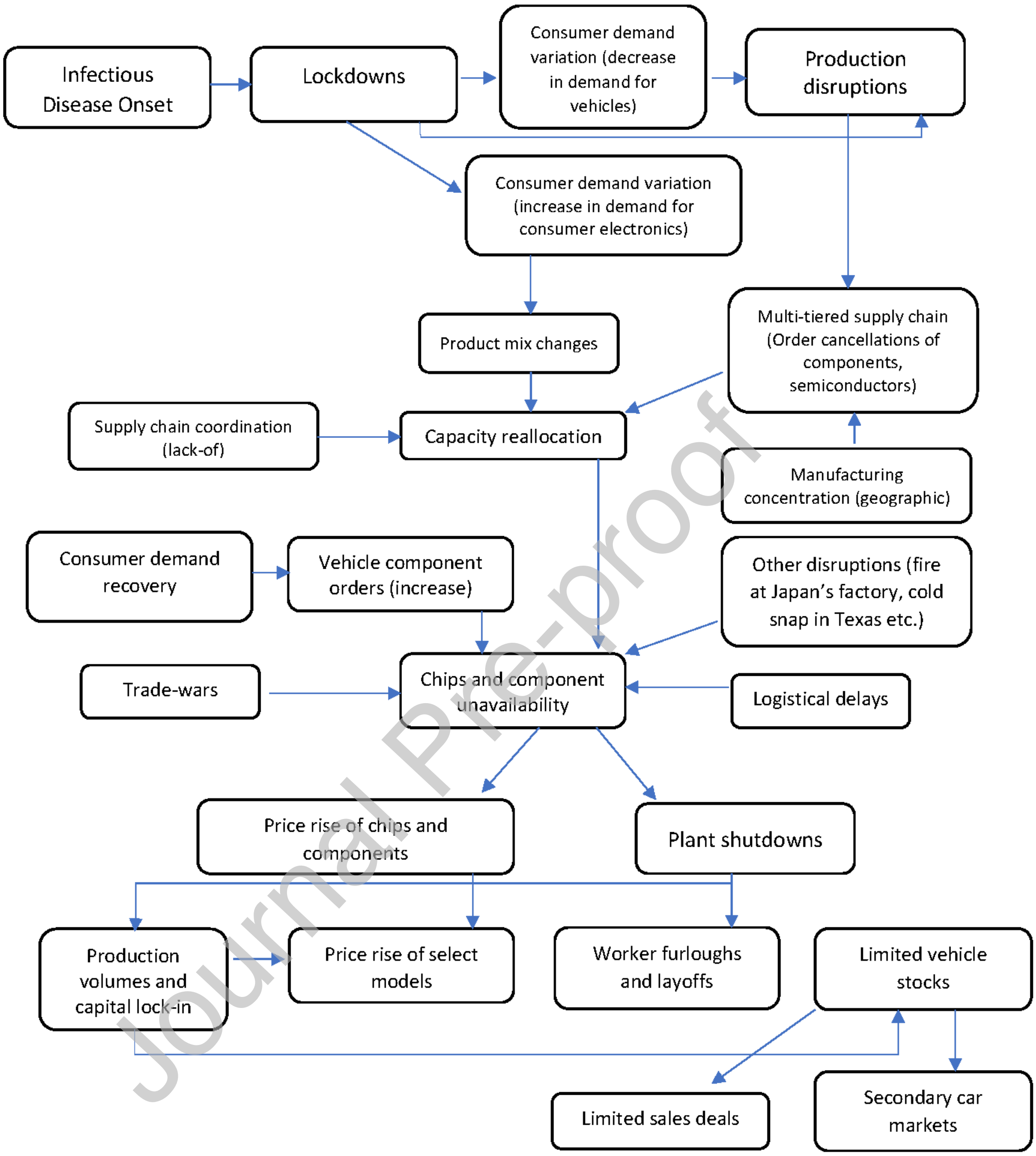

Figure 1: A thematic model of the systemic disruption to the auto industry, particularly in relation to shortage of semiconductor chips.

Other stakeholders include the chip manufacturers geographically concentrated in Asia, consumer electronic manufacturers, the various governments worldwide, and the car dealers and end consumers impacted by shortages.

Next, we provide the findings from the thematic analysis in two categories: (1) the causes and

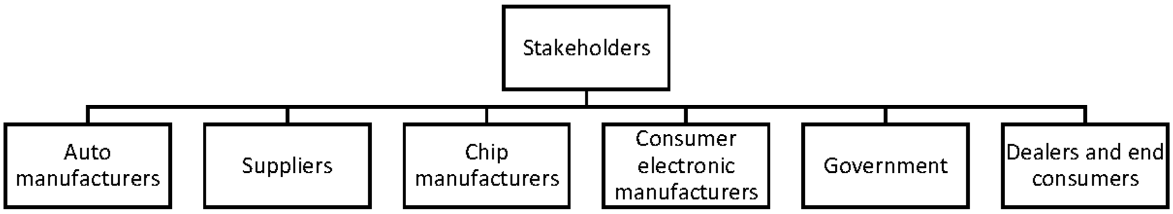

Figure 2: Stakeholders in the supply chain chip shortage, as identified through thematic analysis.

(2) the effects of the chip shortage on auto manufacturers.

3.2 The Causes

The main themes identified for the cause of semiconductor chip shortage include– (1) global pandemic, (2) supply disruptions, (3) auto supply chain complexity, (4) chip manufacturing re-alignment, (5) post-pandemic recovery, and (6) geopolitical risks (Figure 3). We discuss these below in detail.

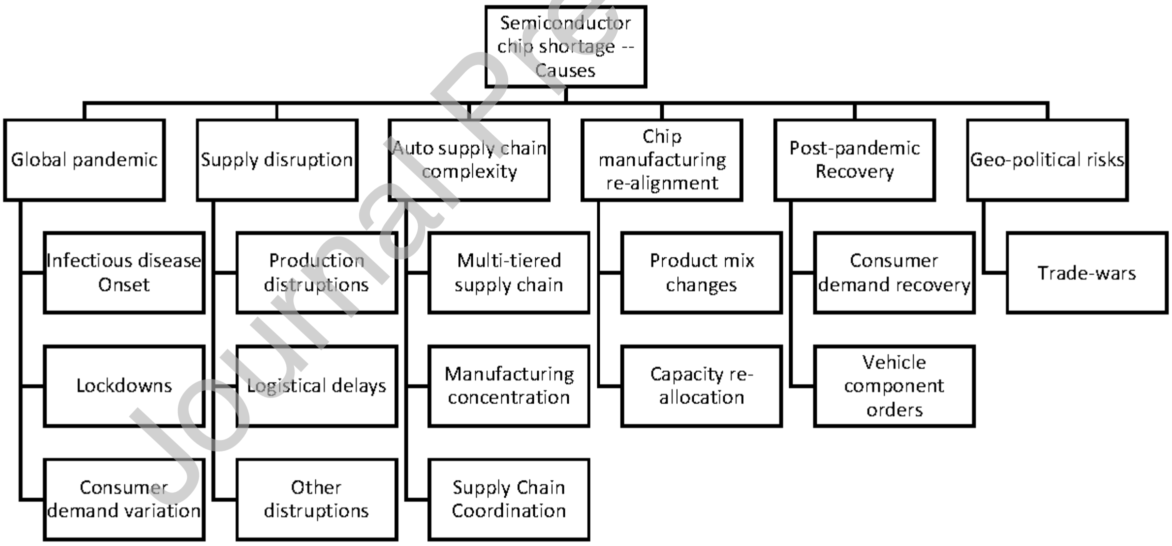

Figure 3: Causes of semiconductor chip shortage - themes and sub-themes

1. Global Pandemic: The sub-themes that emerge for the global pandemic are (a) infectious disease onset, (b) lockdowns, and (c) consumer demand variation (Table 1). A series of infections first reported in Wuhan, China, in December 2019 led to the identification of Covid-19. Subsequently, in March 2020, the World Health Organization (WHO) declared Covid-19 as a global pandemic (Oraby et al., 2021). The fear of the infectious disease with clinical manifestations ranging from mild fever to severe complications such as organ failure (Greyling et al., 2021) led many governments to impose lockdown of varying degrees to slow down the rapid spread of infection (Onyeaka et al., 2021). Governments also imposed restrictions on movement to reduce interaction between individuals, and non-emergency sectors were completely shut down. Internationally, many countries effectively suspended cross-border travel. The auto industry shuttered plants to prevent the spread of infection among workers on site. Further, consumer demand forecasts in the first half of 2020 were weak, so the auto companies operated many factories at reduced capacities or suspended production entirely. Varying degrees of lockdown in different countries implied similar degrees of shortages of workers.

No.	**Sub-theme**	**Underlying Codes**	**Reference**
1	Infectious disease onset	Covid-19, infection cluster, Hospitalization, Death, Virus Outbreak, Pandemic Restrictions	2, 5, 6, 9, 16, 18, 19, 21, 24, 26, 30, 31, 32, 33, 35, 37, 40, 43, 46, 48, 49, 54, 56, 60, 61, 63, 69, 70, 72, 74, 77, 78, 79, 80, 83, 87, 88, 91, 96, 99, 102, 105, 109, 111, 112, 114, 115, 116, 118, 123, 125, 129, 131, 134, 135, 136, 137, 139, 140, 141, 143, 148, 149, 156, 158, 162, 164, 169, 174, 176, 178, 182, 185, 186, 192, 194, 199, 203, 208
2	Lockdowns	Cars, Electronics, Home Appliances, Laptops, Wifi Routers, Tablets, Gaming Consoles	6, 8, 9, 14, 24, 27, 43, 53, 57, 58, 60, 61, 63, 66, 69, 73, 76, 77, 81, 85, 87, 93, 94, 95, 96, 99, 101, 102, 105, 110, 112, 114, 116, 118, 123, 124, 125, 127, 129, 130, 143, 152, 155, 158, 159, 161, 162, 166, 167, 169, 171, 178, 179, 181, 184, 187, 188, 189, 194, 195, 199, 201, 202, 205, 206
3	Consumer demand variation	Work from Home, Stay at Home, Digital Infrastructure, Online Meetings, Telecommunications, Broadband	2, 17, 24, 32, 35, 43, 44, 53, 54, 82, 86, 99, 106, 107, 113, 120, 135, 165, 183, 203, 206

Table 1: Semiconductor Chips Shortage – Global pandemic

2. Supply disruptions: These were (1) production or plant disruptions, (2) logistical delays, and (3) other disruptions (Table 2). Virus outbreaks in Taiwan and South Korea impacted plant production due to a shortage of workers (Hill et al., 2021). Several other disruptions, too, added to the shortages. A cold wave in Texas in early 2021 impacted production at the Samsung, Infineon Tech, and NXP semiconductor plants (Inagaki and Campbell, 2021). In addition, a fire at the Renesas Electronics Corp facility in Japan added to the production disruptions, as the fire damaged nearly two-thirds of the facility related to the production of automotive chips (Inagaki et al., 2021a). Logistical issues, primarily from shipping delays and congestion at the ports, compounded the problem. Infections at one of the busiest ports in Yantian in southern China led to delays in loading and unloading cargo. As containers got clogged at various ports, chip manufacturers faced increased shipping costs, with the cost of shipping using containers increasing nearly tenfold (Hill et al., 2021).

No.	Sub-theme	Underlying Codes	Reference
1	Production disruptions	Natural Disaster, Storm, Fire, Drought, Man-made Events, Power Outages, Power surge, Damaged equipment, Taiwan	21, 27, 31, 43, 67, 70, 73, 83, 99, 102, 105, 123, 124, 125, 126, 147, 183
2	Logistical delays	Ports Choking, Container Availability, Freight Transport, Motor Vehicle Parts, Railroad operator, shipping routes, logjams	41, 46, 60, 73, 87, 88, 99, 106, 109, 118, 127, 145, 149, 154, 175, 183, 206, 208
3	Other disruptions	Labor Shortage, labor Strike, Real-Estate	24, 31, 46, 67, 70, 95, 101, 162, 191, 203

Table 2: Semiconductor Chips Shortage – Supply disruption

3. Auto Supply Chain Complexity: The main sub-themes that emerge from the auto supply chain complexity are (a) multi-tiered supply chains, (b) manufacturing concentration, and (c) supply chain coordination (Table 3). The complex nature of automotive supply chains further aggravated the problem of shortages. For example, General Motors (GM) sources its auto parts from about 250 suppliers who procure their chips from 11 different semiconductor chip manufacturers (Whalen, 2021). An auto manufacturer places orders with Tier-1 suppliers like Continental AG and Bosch, who put their orders with Tier-2 suppliers such as NXP Semiconductors, Infineon Technologies AG, and STMicroelectronics (STM). Knowing that they may not be able to fulfill all orders using their existing capacity, these Tier-2 suppliers place orders with large semiconductor chip manufacturers like TSMC (Pan, 2021c). Order cancellations and shortages spread through the supply networks, with production concentrated in Asia and information delays in the multi-tiered global networks. The ability of suppliers, therefore, to procure additional chips was severely impacted by shortages.

No.	Sub-theme	Underlying Codes	Reference
1	Multi-tiered supply chain	Tiered supply, Tier 1,2,3, Bosch, Parts, Electronic control units, vertical procurement platform	24, 53, 60, 61, 70, 99, 105, 111, 135, 171, 190, 194, 195, 206, 208
2	Manufacturing concentration	80% factories Asia, TSMC foundries, over dependence	6, 25, 43, 44, 45, 46, 53, 55, 58, 60, 61, 63, 70, 82, 84, 86, 97, 99,102,107,110,111,112, 113, 114, 126, 129, 134, 136, 139, 140, 145, 146, 147, 148, 150, 159, 160, 161, 170, 178, 183, 198, 199, 202, 203
3	Supply chain coordination	Forecast update, information sharing, contract, JIT system, inventory, buffer, orders, Production technology complex, Information Flow	2, 4, 5, 24, 43, 45, 46, 47, 50, 51, 53, 58, 60, 61, 63, 64, 69, 73, 74, 77, 89, 107, 110, 111, 112, 117, 120, 130, 147, 151, 155, 159, 162, 171, 173, 175, 179, 181, 190, 191, 193

Table 3: Semiconductor Chips Shortage – Auto supply chain complexity

4. Chips manufacturing re-alignment: The main sub-themes that emerge are - (a) product mix changes, and (b) capacity re-allocation (Table 4). Chips manufacturers earn a higher margin on the high technology chips used by consumer electronics manufacturers instead of the low margins on the chips produced for auto manufacturers. As a result, the semiconductor manufacturers reallocated their production capacities toward producing high-end chips. Semiconductor manufacturers found it more profitable to meet the increased demand for 5G smartphones, tablets, video game consoles, and gaming platforms produced by Sony and Microsoft. In 2020, TSMC obtained only 4% of its revenues from the production and sale of automotive chips, but nearly 50% of its revenues from the chips produced for the smartphones (Hille and Inagaki, 2021). The higher margins for semiconductor manufacturers resulted in lesser incentives to alter their product mix, given that they already operated at total capacity.

5. Post-pandemic recovery: The sub-themes related to post-pandemic recovery include – (a) consumer demand recovery, and (b) vehicle component orders (Table 5). Towards the latter

No.	Sub-theme	Underlying Codes	Reference
1	Product mix changes	5G chips, mobile phones, smartphones, webcams, 8mm old chips, 12 mm chips, sophisticated chips, cutting-edge technology, component mix, critical components	1, 2, 4, 10, 24, 38, 41, 43, 45, 54, 56, 58, 60, 61, 70, 87, 112, 115, 120, 121, 122, 128, 129, 135, 139, 140, 150, 159, 183, 199, 202, 206
2	Capacity re-allocation	capacity shifting, High Margins, Low Margins, Profitable, Cutting Edge Technology, digital technology, high speed cellular technology	4, 15, 18, 19, 21, 22, 23, 35, 40, 43, 45, 46, 49, 60, 66, 67, 70, 73, 75, 79, 86, 87, 99, 102, 111, 112, 123, 129, 134, 135, 139, 144, 146, 151, 155, 157, 171, 174, 175, 177, 179, 188, 189, 197, 198, 200

Table 4: Semiconductor Chips Shortage – Chip manufacturing re-alignment

half of 2020, as countries began the gradual phasing away from lockdown, demand for automobiles increased as consumers preferred to use their transportation (Narasimhan, 2021). As auto manufacturers increased their production of cars, they also placed a greater demand for semiconductor chips that propagated upstream. However, due to limited chip manufacturing capacities, their suppliers informed auto manufacturers that they could not meet the increased demand (Root, 2021). The prolonged unavailability of chips led to the shortage, and the automotive industry halted or postponed the production decisions due to the shortage.

No.	Sub-theme	Underlying Codes	Reference
1	Consumer demand recovery	Strong demand, Boom, Strong Bookings, Spike, Surge, Economic Recovery, Back to life, Momentum, Global Growth	11, 15, 16, 22, 24, 27, 28, 31, 50, 51, 54, 55, 56, 58, 60, 61, 66, 67, 71, 76, 79, 80, 82, 88, 94, 98, 106, 109, 111, 112, 132, 138, 141, 142, 143, 144, 149, 152, 157, 158, 167, 183, 186, 194, 200, 203, 204, 208
2	Vehicle component orders	EV Plugs, ABS, Power Windows, Catalytic Converters, Dashboard Display, Electronic Control Units, Batteries, Stabilizers, Sensors	2, 15, 24, 35, 39, 40, 43, 46, 52, 54, 55, 58, 60, 61, 67, 68, 69, 70, 77, 80, 86, 87, 99, 105, 109, 112, 114, 116, 119, 127, 130, 135, 137, 139, 140, 142, 144, 145, 157, 162, 167, 169, 171, 175, 176, 184, 185, 188, 191, 192, 196, 197, 198, 201, 206, 208, 209

Table 5: Semiconductor Chips Shortage – Post-pandemic recovery

6. Geopolitical risk: The sub-theme related to geopolitical risk includes trade wars (Table 6). The US government imposed a ban on exporting semiconductor chip manufacturing equipment to a few companies in China (Yamamitsu and Kelly, 2021). This impacted Semiconductor Manufacturing International (SMIC), China's largest chip manufacturer. Chip manufacturing involves advanced and complex technology, and the intellectual property for the design of chips is mainly concentrated in the companies in the US. The trade ban resulted in some of SMIC's clients hoarding chips (Whalen et al., 2021). In addition, the US government imposed sanctions on Huawei Technologies and coordinated with TSMC 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 Huaweis leading foundry supplier TSMC. SCMP reported that the *"shortage was exacerbated by double booking from chip buyers anxious to secure inventory, which itself was a consequence of supply chain uncertainty created by the US-China tech war"* (SCMP, 2021)

No.	Sub-theme	Underlying Codes	Reference
1	Trade-wars	Trade war, Tariffs, Ban, US-China Trade war, US-China tensions, geopolitical environment, US sanctions, technological supremacy, SMIC, Huawei, national security, stockpiling, hoarding, defence	1, 4, 24, 35, 38, 43, 46, 55, 57, 60, 61, 62, 69, 70, 74, 75, 87, 89, 92, 96, 99, 111, 112, 114, 121, 129, 130, 139, 162, 204

Table 6: Semiconductor Chips Shortage – Geo-political risks

Next, we identify themes that detail the effects of the semiconductor shortage.

3.3 The Effects

We identify the main themes for the effects of semiconductor chip shortage - (a) Production Disruption, (b) Inflationary Pressures, (c) labor Issues, and (d) End consumer and dealer issues (Figure 4).

1. Production disruptions: The sub-themes that we identify are – (a) chips and component unavailability, (b) plant shutdowns, and (c) production volumes and capital lock-in (Table 7). As the post-pandemic increase in demand propagated upstream in the auto supply chain, the chip manufacturers already operating at full capacities could not meet the additional demand placed by the suppliers of the auto manufacturers. The impact of the semiconductor chip shortages led auto

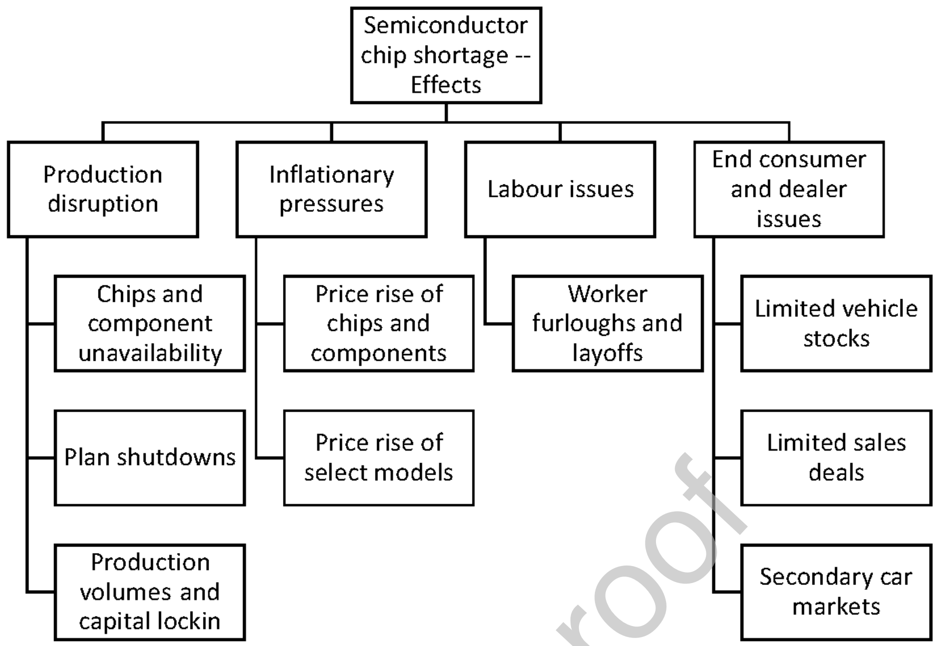

Figure 4: Effects of semiconductor chip shortage - themes and sub-themes

manufacturers to shut down plants globally. GM suspended production in three of its US, Canada, and Mexico plants. Due to the non-availability of components, GM suggested to *"build vehicles without certain components, and then add them in at a later date"* (Levin, 2021). Ford canceled its production schedules at its Kansas City plant (Whalen, 2021). Volkswagen and several Japanese manufacturers like Honda and Nissan had to adjust production at their factories in Japan and North America (Kay, 2021a). Auto manufacturer Tesla too suspended production of its Model 3 sedan for a few weeks (Daniel, 2021). Further, electric car start-ups NIO and Xpeng faced production disruptions in China due to the non-availability of semiconductor chips (Ren, 2021). In response, several auto manufacturers, such as Tesla, announced making complete payments in advance to secure supply, thereby leading to the lock-in of capital (Denton, 2021).

2. Inflationary pressure: The main sub-themes that emerge are – (a) price rise of semiconductor chips and components and (b) price rise of select models (Table 8). The shortage, coupled with higher shipping costs, led to an increase in the price of chips. For example, STMicroelectronics (STM), Europe's largest chip manufacturer, increased the price of chips in June 2020 (Pan, 2021b). The impact of the price increase of chips caused the auto manufacturers to increase the price of their vehicles. Consumers in the US faced a rise in price on some select models to the order of $5000 (Ajmera, 2021). Dealers reduced offers and discounts to consumers due to the non-availability of

No.	Sub-theme	Underlying Codes	Reference
1	Chips and component unavailability	Chip Shortage, Suppliers, Spare parts, Full capacity, Orders, Module, Constituent, Doors, Windscreen Wipers, Integrated Circuits, Remote Control Units, Infotainment, Power Steering, Anti-Lock Brakes, Power Management, Systems Monitoring, Just-in-Time, Parts Makers	2, 8, 9, 12, 13, 15, 18, 24, 25, 26, 28, 29, 31, 33, 34, 37, 40, 43, 44, 46, 47, 48, 49, 50, 54, 55, 56, 58, 59, 60, 61, 64, 68, 69, 75, 77, 83, 84, 88, 93, 94, 99, 100, 102, 111, 112, 114, 115, 116, 118, 123, 125, 126, 133, 142, 145, 148, 159, 160, 162, 168, 170, 171, 174, 176, 182, 191, 194, 198, 205, 206, 207
2	Plant shutdowns	Production halts, factory shutdowns, idle plants, production cuts, factory output cuts, manufacturing index, slow manufacturing activity, idle line, idle auto factories, domestic car manufacturing, production shutdowns, shutdown extension, extended cuts, vehicle production losses	18, 25, 26, 33, 35, 36, 42, 45, 63, 68, 69, 74, 83, 96, 102, 103, 104, 108, 111, 114, 117, 127, 131, 133, 142, 148, 149, 163, 172, 179, 180, 184, 195, 197, 200, 206
3	Production volumes and capital lockin	Carmakers' production, production capacity, production volume, domestic production, production plans, vehicle output, production constraints, vehicle lines, lost production, advanced payment, secure supply	2, 3, 7, 15, 19, 20, 24, 25, 26, 42, 43, 45, 47, 58, 64, 65, 70, 75, 84, 87, 93, 97, 102, 107, 111, 112, 132, 133, 155, 161, 162, 171, 175, 178, 179, 181, 185, 199, 203

Table 7: Production disruption

models (Kay, 2021a). Tesla announced that the shortage of semiconductor chips was the primary reason for increasing the price of its Model 3 vehicle by about $500 (Denton, 2021). Not just new vehicles, the price of used cars too increased by about 10% as the absence of newer models shifted consumer demand to secondary car markets (Smith and Stubbington, 2021). Lastly, the global chip shortage also led to the increased price of consumer electronics (including washing machines and refrigerators) to grow, indicating the cross-sectoral inflationary pressures caused by the lack of chips (Kay, 2021b).

3. Labor issues: The main sub-theme related to labor issues are – worker layoffs and furloughs (Table 9). There were labor shortages both at the chip manufacturer and auto manufacturer echelons. Chip manufacturers use advanced technology, and hence there is a need for highly skilled workers. The pandemic disrupted the availability of workers at the plants, impacting chip pro-

No.	Sub-theme	Underlying Codes	Reference
1	Price rise of chips and components	Rising prices, inflation outlook, commodity costs, shortages of inputs, freight costs, container shipping costs, factory gate prices	7, 16, 30, 35, 46, 73, 79, 88, 92, 93, 96, 105, 109, 111, 112, 143, 169, 178, 183, 195, 203
2	Price rise of select models	Inflation, consumer prices, consumer price index, dealer margins, demand surge, freight costs	7, 16, 35, 46, 71, 72, 88, 93, 96, 98, 101, 111, 143, 166, 169, 183, 195, 203

Table 8: Inflationary pressures

duction. At the end of the auto manufacturers, temporary production halts implied that auto manufacturers had to cut down the shift hours and, in some cases, furlough or layoff workers. For example, Daimler cut the working hours of about 18,500 workers in its factories. Also, Ford announced that its production cuts would impact nearly 2000 workers (Lea, 2021). Furthermore, Jaguar Land Rover suspended production at two of its plants (Keown, 2021), causing downtime for thousands of its workers. Volkswagen too furloughed several workers (Miller, 2021).

No.	Sub-theme	Underlying Codes	Reference
1	Worker furloughs and layoffs	Temporary layoffs, factory workers, plant workers, idle factory, furloughed workers, worker hours	18, 40, 45, 60, 71, 149, 170, 174, 189, 199, 204, 205

Table 9: Labor issues

4. End-consumer and dealer issues: The main sub-themes that emerge are - (a) limited vehicle stocks, (b) limited sales deals, and (c) secondary car market (Table 10). Due to the scarcity of semiconductor chips, auto manufacturers could produce only specific vehicle models, severely impacting the choice available to the consumers. As a result, car dealers could carry only limited stock of vehicles and deals they could offer to consumers (Kay, 2021a). The limited stock impacted the secondary market consisting of used and rental cars. Limited choices and lower production of new vehicles fueled the demand for used cars. Furthermore, during the pandemic, restrictions on travel implied that the demand for rental cars decreased. As a result, rental car agencies sold their fleet of cars to generate cash (Rampell, 2021).

No.	Sub-theme	Underlying Codes	Reference
1	Limited vehicle stocks	Car dealers, model non-availability, monthly sales loss, automobile dealers association, limited supplies, reduced inventory, waiting period, auto sales, retail sales, empty dealerships	18, 27, 43, 45 50, 51, 69, 78, 90, 105, 126, 177, 182
2	Limited sales deals	Less deals, less choices, shrivelling discounts, new-vehicle incentives	18, 27, 45, 50, 51, 69, 78, 90, 126, 153, 177, 195
3	Secondary car markets	Car rentals, used cars and trucks, customer sentiment, used vehicle prices, used models, used car market	18, 51, 56, 96, 158, 195, 199

Table 10: End consumer and dealer issues

4 Modeling the Chips Shortage for Auto Industry

We next sought to understand how the factors associated with the different themes in Section 3 act together to create and propagate the effects of disruption. The simplest – and therefore the most transparent – stylized model we could adopt is one for a central supply chain planner to shed light on the systemic disruption for the auto industry. Such a model could then be run at different times as the situation changed to see the overall impact on backlog and production. Below, we describe such a model and then present the combined results of runs for different "scenarios" over time.

4.1 A Stylized Planning Model

Consider a central planner who seeks to maximize supply chain profit with a (stylized) planning model with three 'industries' with one commodity representing each industry: automotive, other, and consumer electronics (Figure 5). All three sectors compete for chip allocation, produce finished goods, and distribute them to downstream consumers.

Each sector represented by a corresponding plant i receives $X_{i,t}$ chips from the semiconductor manufacturer, and produces a quantity $Y_{i,t}$. The plant can also carry inventory $I_{i,t}$. The plant sells quantity $Z_{i,t}$ to meet demand $D_{i,t}$ or have backlog $B_{i,t}$. The production decision can either meet sales demand or result in inventories, while the sales decision can either meet consumer demand or result in the backlog. We assume that backlog at each plant i decays with the factor $\lambda \leq 1$ per period, i.e., only $\lambda B_{i,t-1}$ from the previous period are carried over. Producing a unit product in any sector requires one chip. Each plant manufacturing product i has capacity $C_{i,t}$ at time t, and the capacity at the semiconductor manufacturer is C', which is constant over time. R_i is the

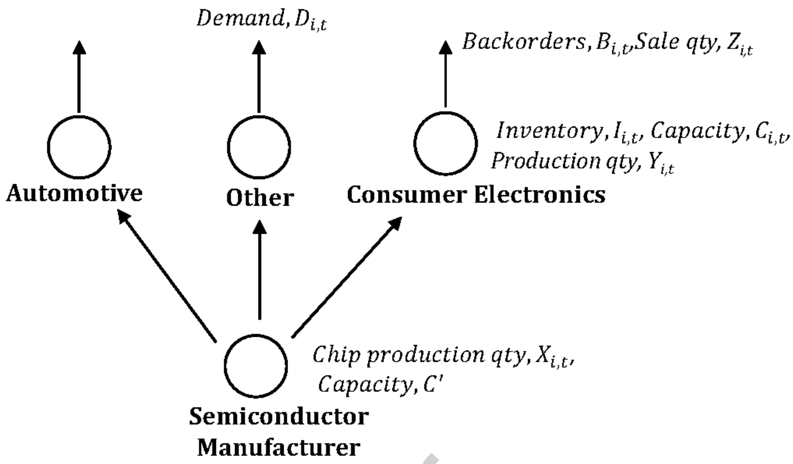

Figure 5: Supply Chain Schematic

marginal revenue of product i, P_i is the penalty per period for the backlog, and H_i is the holding cost per period for each unit of the i^{th} product. The unit cost of production of the i^{th} product is c_i'. Table 11 provides the notation for easy reference.

Notation	Description
R_i	Marginal revenue of product i
P_i	Penalty per period for backlog of product i
H_i	Unit holding cost per period for each unit of product i
c_i'	Unit cost of product i
$D_{i,t}$	Demand of product i at time t
$X_{i,t}$	Chips production quantity for product i at time t
$Y_{i,t}$	Finished good production quantity of product i at time t
$Z_{i,t}$	Sale quantity of product i at time t
$I_{i,t}$	Inventory of product i at time t
$B_{i,t}$	Backorder of product i at time t
λ	Decay factor for backlog
$C_{i,t}$	Capacity of plant i at time t
C'	Capacity of semiconductor manufacturer

Table 11: Model notations

In this model, the objective of the centralized planner is to maximize profits for the entire supply chain, i.e., revenue generated from sales of finished products less the inventory holding and backorder costs of the finished products, and the unit cost of production:

$$\text{Maximize } \Sigma_t \Sigma_i \Big[\{ R_i Z_{i,t} - P_i B_{i,t} - H_i I_{i,t} - c_i' X_{i,t} \} \Big] \quad (1)$$

The constraints are listed below. The chip manufacturer has capacity constraints (inequality 2). We have flow and resource constraints at the i^{th} sector manufacturer, with the production quantity constrained by the chips availability or capacity at each plant in each period (inequality 3). Moreover, we need to ensure the flow constraint at each plant where sales in the current period can be satisfied by the production quantity in the current period and inventory from the previous period that can result in additional inventory $I_{i,t}$ (equation 4). Consumer demand in the current period and the backlog from the previous period must also balance out with sales or result in a backlog in the current period (equation 5). All variables also need to be non-negative (equation 6).

$$\Sigma_i X_{i,t} \leq C' \text{ for all } i,\ t \tag{2}$$

$$Y_{i,t} \leq \min(C_{i,t}, X_{i,t}) \text{ for all } i,\ t \tag{3}$$

$$Z_{i,t} + I_{i,t} = Y_{i,t} + I_{i,t-1} \tag{4}$$

$$D_{i,t} + \lambda B_{i,t-1} = Z_{i,t} + B_{i,t} \tag{5}$$

$$X_{i,t}, Y_{i,t}, Z_{i,t}, B_{i,t}, I_{i,t} \geq 0, \text{ for all products } i \text{ and times } t \tag{6}$$

4.2 Model Run Setup

Our purpose in running this model was to plan centrally up to the decision horizon, assuming the plan is implemented for a certain period until the supply or demand situation changes, and then plan again from that time on. Thus, we ran this model for five different "scenarios" that partition the four years from October 2019 to October 2023 with monthly time buckets.

The **base scenario** is the pre-Covid-19 phase with flat demand in all sectors and sufficient capacity at the chip manufacturer; there is no backlog of demand in any industry. In **scenario 1**, the production is shut down in the auto sector, while demand for consumer electronics is increasing because of lockdown and work-from-home arrangements resulting in increased demand for chips. Recall that two of the sub-themes for production disruption are *plant shutdowns* and *chips and component unavailability* (Figure 3). Furthermore, the sub-themes – *lockdown* and *consumer demand variation* represent the conditions depicted in Scenario 1, where the demand for electronic items increased (Figure 2). **Scenario 2** has production restored in the automotive plant, and demand for cars remains flat. However, electronics sector demand continues to trend up. The scenario is consistent with the theme *post-pandemic recovery* and the sub-theme *consumer demand recovery.*

In **scenario 3**, the auto sector prioritizes producing higher-margin car models (as Ford and Tesla did, among other manufacturers) as a mitigation strategy and can buy more chips at a higher price. Finally, **scenario 4** incorporates the mitigation strategy of additional capacity. We observe that with additional capacity (considered to be 70000 chips), backlogs of the other sector reduce, and chips allocation and production of finished goods for all the three sectors are restored (Table 12).

Item	**Base scen.**	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**
Time	Oct'19-Feb'20	Mar'20-Sep'20	Oct'20-Dec'21	Jan'22-Dec'22	Jan'23-Oct'23
Context	Pre-pandemic	Auto shut-down	Electronics demand	Auto demand decreases	Increased chip capacity
Demand	Flat for all sectors	Rising for electronics	Rising for electronics	Lower demand level for auto	Flat for all sectors
Mitigation	-	-	-	Auto product mix altered	Added chip capacity
Disruption	-	Auto plant shutdown & electronics demand uptrend	Continued electronics demand uptrend	-	-

Table 12: Details of the five sequential scenarios used for model runs

Table 13 shows the parameter values.

Plants/sector data			
-	Automotive	Other	Consumer Electronics
Marginal Revenue	30	40	100
Inventory holding cost/unit/month	3	4	20
Backlog cost/unit/month	6	8	40
λ	0.9	0.9	0.9
Capacity	15000	10000	60000
Semiconductor data			
Marginal Revenue	9	12	30
Inventory holding cost/unit/month	1	1	3
Backlog cost/unit/month	2	2	6
Cost per unit	5	6	15
Capacity	50000		

Table 13: Input data for the model

Over these four years and the five scenarios, demand for the automotive sector was flat at 15,000 units except in Scenario 3 (Jan-Dec'22), when it fell to 10,000 units. The demand for the 'other' sector is flat at 10,000 units throughout the horizon. In comparison, the electronics sector has an S-shaped demand with 16,000 units in the base scenario, linearly increasing to 37,000 units over scenarios 1 and 2, and then muted demand after that (Figure 6).

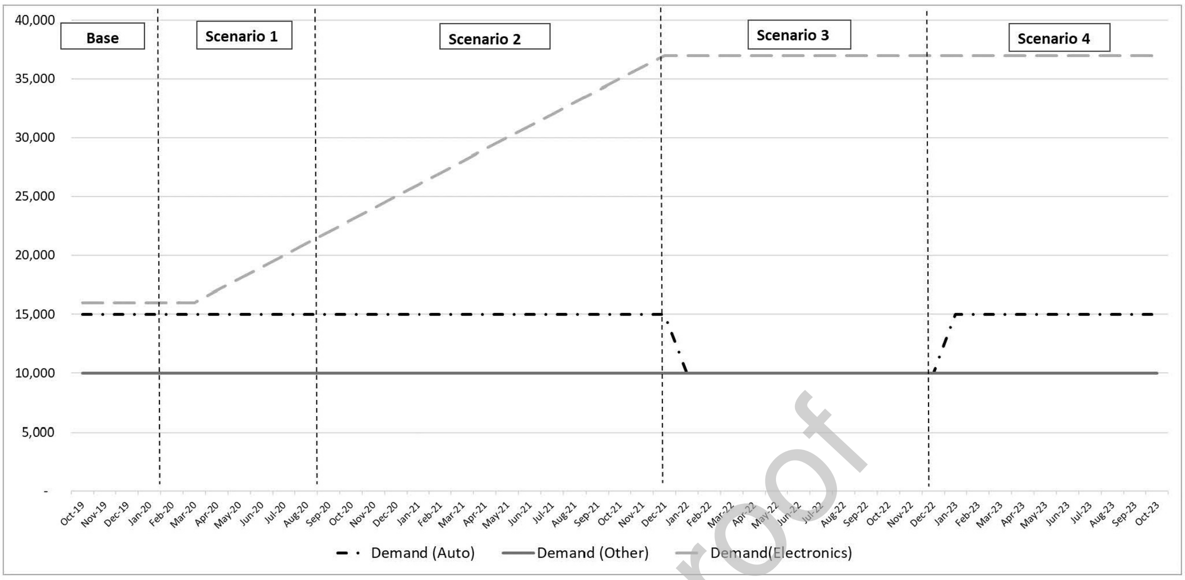

Figure 6: Demand Data

4.3 Results

The results from the five runs for the scenarios across four years show that starting from a situation of no backlog in the **base scenario**, systemic disruptions can lead to continued and significant shortages, potentially impacting other sectors as well, even with the demand that is known by the central planner to be flat or trending up. In **scenario 1**, plant shutdowns result in a rapid backlog increase for the automotive plant. The increased demand for chips by the consumer electronics sector has resulted in more allocation of chips and rising production to meet demand. In **scenario 2**, the backlog reduces as automotive production is restored. However, the growing demand for electronics chips and allocation of chips capacity for the electronics sector creates a capacity crunch at the chip manufacturer, resulting in the lower allocation of chips to the automotive industry. Therefore, backlog builds again in the auto sector due to the scarcity of chips. **Scenario 3** considers changing product mix as a mitigation strategy that automotive manufacturers adopted by changing their product mix towards high-end models with higher margins. There is a lower backlog for the automotive sector as demand is softer and more chips are allocated for producing premium models. However, backlog increases for the 'other' sector. Finally, in **scenario 4**, the backlog of the 'other' sector is reduced, and chips allocation and production of finished goods for all the three sectors are restored with a hefty infusion of additional chips capacity in place. Figure 7 shows each scenario's backlog and production quantities stitched together across the timeline.

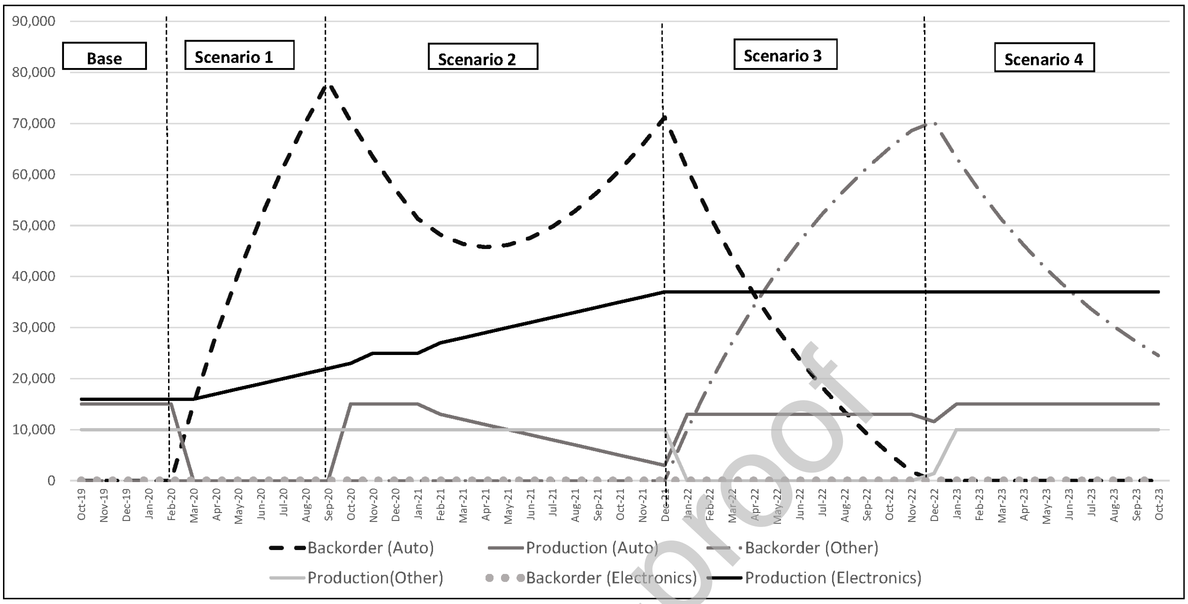

Figure 7: Backlog and production quantities for all scenarios

5 Discussion

We sought to understand systemic disruption in supply chains by studying the auto industry's experience of 2020-22. First, we analyzed news reports to draw out the causes and effects of disruptions in the auto sector following the advent of Covid-19 in 2020. Then, we created a stylized mathematical programming model with one chip supplier and three manufacturers representing the three sectors to see the impact of some of the identified factors. Despite the narrow set of assumptions, known flat or up-trending demand, and a central planner seeking to maximize supply chain profits, we see the shortages spreading within and across sectors. Thus, we get some insight into the system behavior, which can only get more complicated if more realistic modeling assumptions are used. Below, we discuss the implications for practice and research.

5.1 Implications for practice

At the time of writing, the systemic disruption by Covid-19 has led to additional supply chain issues such as worker shortage in the transportation, shipping, and retail sectors (Loeb, 2021; BBC, 2021), further contributing to within-sector and cross-sector impact. Managers have to consider a systemic view of supply chains that goes beyond immediate upstream or downstream entities to consider mitigation strategies such as:

1. *Product prioritization*: Some auto manufacturers *prioritized* vehicle models by allocating the scarce chips to those vehicles where the margins are relatively higher to reduce the impact on profits. They achieved such a product mix by moving from producing vehicles that use low-end chips to those that use high-end chips. For example, smart EV producers like Xpeng uses high-end artificial intelligence (AI) chipsets (Ren and Pan, 2021). In scenario 3, we saw that product mix changes help although the demand is also lower. At the same time, other sectors may experience a backlog.

2. *Stockpiling, capacity expansion, and flexibility*: Capacity expansion is crucial in mitigating the adverse impact of systemic disruptions, as we saw in scenario 4. However, the experience of the auto sector across all the previous scenarios also suggests that we need *flexible* plant and labor capacity for manufacturing. Capacity investments, backup capacity, shared capacity, and stockpiling are more comprehensive approaches to consider (Sodhi and Tang, 2021b). Reserve or shared capacities can also be used to counter shortages from disruptions.

3. *Partial assembly*: Several auto manufacturers planned to build the vehicles without the components (involving the semiconductor chips) and then complete the assembly when the parts become available from the suppliers (Swanson, 2021); however, we did not consider this scenario where the assumption is that some of the components that are only sporadically available can be installed at the end.

4. *Sourcing*: Auto manufacturers have followed alternative strategies for sourcing. One is *near-shoring* as in the case of the US government giving chip manufacturers incentives to set up US plants. Also, Hyundai Motor Co and Kia Corp. want to shift specific chips to South Korean designers and localize auto chip production (Yang, 2021). Another strategy is *direct sourcing* from chip suppliers to secure supplies as Volkswagen, and some other auto companies have done (Schwartz and Steitz, 2021; Inagaki et al., 2021b). An extreme example is Tesla considering purchasing a semiconductor plant to ensure supplies (Denton, 2021).

5. *Supply chain coordination and consolidation of supplier base* - Our thematic analysis indicated that lack of coordination between the auto manufacturers and their suppliers could also be

a cause of supply disruptions. Therefore, *better information coordination* between the auto manufacturers and the upstream supply chain entities, and more *reliable forecasting* of orders for chips can be useful. Indeed, Wolfgang Schafer, CFO of the German components group, Continental, noted that the supply crisis *"was partly caused by unreliable estimates from carmakers themselves"* (Campbell et al., 2021). Furthermore, the Chinese state-owned car manufacturer Changan Automobile mitigated the shortage problem by *bringing* Tier-1 and Tier-2 suppliers into a single platform (Pan, 2021a). OM and SCM literature has extensively analyzed the improvements realized from better coordination and information flows (Lee and Whang, 1999; Fiala, 2005; Croson and Donohue, 2006). Managers, therefore, would benefit from sharing short-term and long-term operational plans with their suppliers and vice-versa to better respond to crises and mutually benefit. Companies can extend the capabilities of their current systems to reduce information delays and enhance visibility (Hastig and Sodhi, 2020).

With systemic disruptions, it is unlikely that a company's mitigation efforts would be enough. It would have to work with the ecosystem of suppliers, competitors, and governments.

Suppliers: Suppliers can use long-term and short-term approaches to increase capacity. In our model, the increased capacity of the chip manufacturers is represented by Scenario 4, allowing the auto production to get back to pre-Covid level with zero backlogs. In the context of the auto industry and chip makers, several chip manufacturers announced a capacity expansion in 2021, not just for existing chips but with new technologies.

Suppliers can speed up their production processes in the short term, including by delaying scheduled maintenance. In the context of this paper, chip makers tried to eke out more supply through changes to manufacturing processes by opening up spare capacity to rivals, auditing customer orders to prevent hoarding, and swapping over production lines (Jeong and Strumpf, 2021).

Government: Covid-19 has helped shed light on how governments could address systemic disruptions in the future. The severe impact of the semiconductor chip shortage has led several governments to undertake mitigation strategies to moderate the severity of the crisis. The US government initiated a 100-day *review of critical supply chains* that include semiconductor chips, medical equipment, batteries, and rare earth minerals - to reduce the dependence on foreign suppliers (Gallagher, 2021; Jones and Charter, 2021; Oreskovic, 2021). In addition, the US Congress passed an emergency funding bill to the tune of $52 billion *"to boost domestic supply chain production and lure the best of the foreign semiconductor chip manufacturers to open new advanced* *manufacturing facilities in the United States"* (Sanger, 2021). The US government has also coordinated with the Taiwanese government and TSMC, in particular, to ensure that the US auto manufacturers are not disrupted (Klein, 2021; Swanson, 2021).

Similarly, the EU plans to invest approximately $125 billion into reviving domestic chip production (Blanchard, 2021). In Asia, South Korea plans to provide *subsidies* to chip manufacturers to increase domestic production. China also promoted domestic production and assistance in supply chain coordination between the semiconductor manufacturers and the auto companies by preparing a handbook that lists chips suppliers and demand from auto manufacturers (Qu, 2021).

5.2 Implications for Research

Although the supply chain risk literature has developed over time, that on systemic disruptions is relatively nascent. As such, there are many research areas by way of analytical, empirical, mathematical programming, simulation, and other research.

For empirical research, other sector-specific studies tied to Covid-19 would help generalize our work on the auto sector. Additionally, the themes and sub-themes identified in our study can be used in empirical research on systemic disruption to develop instruments with the proposed sub-themes as constructs for research involving surveys.

Analytical or simulation models could expand the literature on the lack of coordination and information delays (developed as a sub-theme in our paper) for systemic disruption. Analytical models can compare stockpiling, reserve capacity, and shared capacity to identify the best setting for each strategy.

The mathematical programming model we presented is stylized and can be easily expanded. Decentralized decision-making, information delays, and lack of coordination between different supply chain entities can further aggravate chip shortages in our model. The model can also be extended to consider labor shortages and distribution costs of chips and finished goods[3] to show even more instability and the propagation of the disruption. Recall that the disruption is propagating despite flat or up-trending demand known to the central planner. Introducing demand variability would exacerbate the shortages in the supply chain.

Overall, systemic disruption in supply networks is ripe for further research that would also have important implications for practice.

[3] We thank the anonymous reviewer for this suggestion.

References

Ajmera, A. (2021). Some U.S. car shoppers are paying $5,000 over a vehicle's retail price - Cox Automotive . Reuters. https://tinyurl.com/yze8oj4j.

Aldrighetti, R., Battini, D., Ivanov, D., and Zennaro, I. (2021). Costs of resilience and disruptions in supply chain network design models: a review and future research directions. *International Journal of Production Economics*, 235:108103.

Appleyard, M. M. (1996). How does knowledge flow? Interfirm patterns in the semiconductor industry. *Strategic management journal*, 17(S2):137–154.

Bauer, H., Burkacky, O., Kenevan, P., Lingemann, S., Pototzky, K., and Wiseman, B. (2020). Semiconductor design and manufacturing: Achieving leading-edge capabilities. McKinsey & Co. https://tinyurl.com/yf8pxxus.

Baveja, A., Kapoor, A., and Melamed, B. (2020). Stopping covid-19: A pandemic-management service value chain approach. *Annals of Operations Research*, 289(2):173–184.

BBC (2021). How serious is the shortage of lorry drivers? BBC News. https://www.bbc.com/news/57810729.

Blanchard, B. (2021). EU seeks greater Taiwanese investment as chip shortage bites . Reuters. https://tinyurl.com/yz5qzzsp.

Boston, W., Fitch, A., Colias, M., and Foldy, B. (2021). How Car Makers Collided With a Global Chip Shortage. The Wall Street Journal. https://tinyurl.com/yjfra5jb.

Braun, V. and Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology*, 3(2):77–101.

Campbell, P., Inagaki, K., and Bushey, C. (2021). Continental says poor forecasting partly to blame for carmaker chip shortage. The Financial Times. https://tinyurl.com/yfz2zclu.

Choi, T.-M. (2020). Innovative bring-service-near-your-home operations under corona-virus (covid-19/sars-cov-2) outbreak: Can logistics become the Messiah? *Transportation Research Part E: Logistics and Transportation Review*, 140:101961.

Choi, T.-M. (2021). Risk analysis in logistics systems: A research agenda during and after the covid-19 pandemic. *Transportation Research Part E: Logistics and Transportation Review*, 145:102190.

Chopra, S. and Sodhi, M. (2004). Supply-chain breakdown. *MIT Sloan Management Review*, 46(1):53–61.

Chopra, S. and Sodhi, M. (2014). Reducing the risk of supply chain disruptions. *MIT Sloan Management Review*, 55(3):72–80.

Chopra, S., Sodhi, M., and Lücker, F. (2021). Achieving supply chain efficiency and resilience by using multi-level commons. *Decision Sciences*, 52(4):817–832.

Chowdhury, P., Paul, S. K., Kaisar, S., and Moktadir, M. A. (2021). Covid-19 pandemic related supply chain studies: A systematic review. *Transportation Research Part E: Logistics and Transportation Review*, 148:102271.

Croson, R. and Donohue, K. (2006). Behavioral causes of the bullwhip effect and the observed value of inventory information. *Management Science*, 52(3):323–336.

Daniel, W. (2021). Tesla slips as report says the EV maker will idle Model 3 line at its Fremont factory for two weeks . Business Insider. https://tinyurl.com/yefal3oj.

Denton, J. (2021). Elon Musk Blames Tesla Price Hikes on a Critical Parts Shortage. Will His Fix Work? . Barron's. https://tinyurl.com/yhqoccxf.

Dolgui, A., Ivanov, D., and Rozhkov, M. (2020). Does the ripple effect influence the bullwhip effect? an integrated analysis of structural and operational dynamics in the supply chain. *International Journal of Production Research*, 58(5):1285–1301.

El Baz, J. and Ruel, S. (2021). Can supply chain risk management practices mitigate the disruption impacts on supply chains resilience and robustness? Evidence from an empirical survey in a COVID-19 outbreak era. *International Journal of Production Economics*, 233:107972.

Fiala, P. (2005). Information sharing in supply chains. *Omega*, 33(5):419–423.

Fitch, A. (2021). Chip Shortage Drives Tech Companies and Car Makers Closer. The Wall Street Journal. https://tinyurl.com/yfw2tueg.

Gallagher, D. (2021). Chips Political Moment Will Need to Last. The Wall Street Journal. https://tinyurl.com/y8mc87sv.

Gelsinger, P. (2021). The EU must play a long game for semiconductor success. Financial Times. https://tinyurl.com/ye4bkfmk.

Greyling, T., Rossouw, S., and Adhikari, T. (2021). The good, the bad and the ugly of lockdowns during covid-19. *PloS one*, 16(1):e0245546.

Gunessee, S. and Subramanian, N. (2020). Ambiguity and its coping mechanisms in supply chains lessons from the covid-19 pandemic and natural disasters. *International Journal of Operations & Production Management*.

Haren, P. and Simchi-Levi, D. (2020). How coronavirus could impact the global supply chain by mid-march. Harward Business Review, February 28, 2020.

Hastig, G. M. and Sodhi, M. S. (2020). Blockchain for supply chain traceability: Business requirements and critical success factors. *Production and Operations Management*, 29(4):935–954.

Hill, S. Y., Paris, C., and Yang, S. (2021). Virus in Asia Creates Trade Bottlenecks . The Wall Street Journal. https://tinyurl.com/yzdtgl9x.

Hille, K. and Inagaki, K. (2021). TSMC predicts gross profit margins of 50% after global chip shortage . Financial Times. https://tinyurl.com/yhkpduzf.

Hobbs, J. E. (2020). Food supply chains during the covid-19 pandemic. *Canadian Journal of Agricultural Economics/Revue canadienne d'agroeconomie*, 68(2):171–176.

Hosseini, S., Ivanov, D., and Dolgui, A. (2019). Review of quantitative methods for supply chain resilience analysis. *Transportation Research Part E: Logistics and Transportation Review*, 125:285–307.

Inagaki, K. and Campbell, P. (2021). US cold snap pushes Toyota to brink of factory shutdowns . Financial Times. https://tinyurl.com/yhsabrz5.

Inagaki, K., Dempsey, H., and Campbell, P. (2021a). Nissan warns of third year of losses as chip shortage hits turnround . Financial Times. https://tinyurl.com/yet969ng.

Inagaki, K., Keohane, D., Yang, Y., and Miller, J. (2021b). Global chip shortage puts car supply chain under the microscope . Financial Times. https://tinyurl.com/yyycwuxo.

Ivanov, D. (2020a). Predicting the impacts of epidemic outbreaks on global supply chains: A simulation-based analysis on the coronavirus outbreak (covid-19/sars-cov-2) case. *Transportation Research Part E: Logistics and Transportation Review*, 136:101922.

Ivanov, D. (2020b). A blessing in disguise or as if it wasnt hard enough already: reciprocal and aggravate vulnerabilities in the supply chain. *International Journal of Production Research*, 58(11):3252–3262.

Ivanov, D. and Das, A. (2020). Coronavirus (covid-19/sars-cov-2) and supply chain resilience: A research note. *International Journal of Integrated Supply Management*, 13(1):90–102.

Ivanov, D. and Dolgui, A. (2020). Viability of intertwined supply networks: extending the supply chain resilience angles towards survivability. a position paper motivated by covid-19 outbreak. *International Journal of Production Research*, 58(10):2904–2915.

Ivanov, D. and Dolgui, A. (2021). Or-methods for coping with the ripple effect in supply chains during covid-19 pandemic: Managerial insights and research implications. *International Journal of Production Economics*, 232:107921.

Ivanov, D. et al. (2018). *Structural dynamics and resilience in supply chain risk management*, volume 265. Springer.

Ivanov, D., Sokolov, B., and Dolgui, A. (2014). The ripple effect in supply chains: trade-off efficiency-flexibility-resiliencein disruption management. *International Journal of Production Research*, 52(7):2154–2172.

Jeong, E.-Y. and Strumpf, D. (2021). Why the Chip Shortage Is So Hard to Overcome . The Wall Street Journal. https://tinyurl.com/yhltqcu5.

Jha, P. K., Ghorai, S., Jha, R., Datt, R., Sulapu, G., and Singh, S. P. (2021). Forecasting the impact of epidemic outbreaks on the supply chain: modelling asymptomatic cases of the covid-19 pandemic. *International Journal of Production Research*, pages 1–26.

Jie, Y., Yang, S., and Asa, F. (2021). The World Relies on One Chip Maker in Taiwan, Leaving Everyone Vulnerable . The Wall Street Journal. https://tinyurl.com/yj7o2xau.

Jones, C. and Charter, D. (2021). Joe Biden vows to fix semiconductor supply shortage. The Times. https://tinyurl.com/yj55peu8.

Kay, G. (2021a). Here are some of the car models most likely to be in shorter supply due to the global chip shortage . Business Insider. https://tinyurl.com/yfdkqqmg.

Kay, G. (2021b). Your home improvement project just got a lot more expensive. From dishwashers to paint and fertilizer, here are the goods in short supply. . Business Insider. https://tinyurl.com/yj6okxod.

Keown, C. (2021). Volvo Crushed Earnings. The Truck Maker Can Shrug Off the Chip Shortage. Barron's. https://tinyurl.com/yfz3z9sf.

Khalilpourazari, S., Doulabi, H. H., Çiftçioğlu, A. Ö., and Weber, G.-W. (2021). Gradient-based grey wolf optimizer with gaussian walk: Application in modelling and prediction of the covid-19 pandemic. *Expert Systems with Applications*, 177:114920.

Khalilpourazari, S. and Hashemi Doulabi, H. (2021). Robust modelling and prediction of the covid-19 pandemic in canada. *International Journal of Production Research*, pages 1–17.

Klein, J. X. (2021). 'No immediate magic bullet': White House to discuss supply chain review results next week . South China Morning Post. https://tinyurl.com/yffd4llh.

Lea, R. (2021). Ford and Mercedes join traffic jam caused by microchip shortages. The Times. https://tinyurl.com/yk533fws.

Lee, H. and Whang, S. (1999). Decentralized multi-echelon supply chains: Incentives and information. *Management Science*, 45(5):633–640.

Levin, T. (2021). GM and Ford are warning investors of billions in lost earnings this year due to the global chip shortage. Business Insider. https://tinyurl.com/yel2ykks.

Loeb, W. (2021). Another Crisis In Retail: Labor Shortage Will Get Worse. Forbes. https://tinyurl.com/yzhmlrlc.

Ludwikowski, M. and Sjoberg, W. (2021). Semiconductor shortage and the U.S. auto industry. Reuters. https://tinyurl.com/yhhsgqlv.

Mehrotra, S., Rahimian, H., Barah, M., Luo, F., and Schantz, K. (2020). A model of supply-chain decisions for resource sharing with an application to ventilator allocation to combat covid-19. *Naval Research Logistics*, 67(5):303–320.

Miller, J. (2021). German carmakers enlist Merkel as they battle chip shortage. Financial Times. https://tinyurl.com/y5bantvn.

Narasimhan, T. E. (2021). Shortage of semiconductors, price hikes pull January auto sales into red. Business Standard. https://tinyurl.com/yg4aobav.

Nikolopoulos, K., Punia, S., Schäfers, A., Tsinopoulos, C., and Vasilakis, C. (2021). Forecasting and planning during a pandemic: Covid-19 growth rates, supply chain disruptions, and governmental decisions. *European Journal of Operational Research*, 290(1):99–115.

Onyeaka, H., Anumudu, C. K., Al-Sharify, Z. T., Egele-Godswill, E., and Mbaegbu, P. (2021). Covid-19 pandemic: A review of the global lockdown and its far-reaching effects. *Science Progress*, 104(2):00368504211019854.

Oraby, T., Tyshenko, M. G., Maldonado, J. C., Vatcheva, K., Elsaadany, S., Alali, W. Q., Longenecker, J. C., and Al-Zoughool, M. (2021). Modeling the effect of lockdown timing as a covid-19 control measure in countries with differing social contacts. *Scientific Reports*, 11(1):1–13.

Oreskovic, A. (2021). Chips, vaccines, and 'techno autocracies' - Why Big Tech and Biden are going to be friends. Business Insider. https://tinyurl.com/yjmxybc9.

Pan, C. (2021a). Semiconductor shortage sees Chinas carmakers, chip suppliers join forces to tackle the problem . South China Morning Post. https://tinyurl.com/yfq22hvf.

Pan, C. (2021b). Europes No 2 chip maker STMicroelectronics reportedly to raise prices from June 1, citing materials shortages . South China Morning Post. https://tinyurl.com/yztoz784.

Pan, C. (2021c). Global chip shortage likely to last through 2021 and even into 2022 as industry grapples with increasingly complex market forces . South China Morning Post. https://tinyurl.com/yhfwmzgk.

Qu, T. (2021). Beijing intervenes to ease chip shortage, prevent disruptions in domestic car production . South China Morning Post. https://tinyurl.com/y9rlgjh7.

Queiroz, M. M., Ivanov, D., Dolgui, A., and Wamba, S. F. (2020). Impacts of epidemic outbreaks on supply chains: mapping a research agenda amid the covid-19 pandemic through a structured literature review. *Annals of Operations Research*, pages 1–38.

Ramos, G. and Hynes, W. (2020). A systemic resilience approach to dealing with Covid-19 and future shocks. OECD. https://tinyurl.com/yelrrbjj.

Rampell, C. (2021). Dont freak out about inflation yet. The Washington Post. https://tinyurl.com/yf23bwjo.

Ren, D. (2021). Teslas Chinese rivals NIO, Xpeng report mixed sales fortunes in May amid global chip shortage . South China Morning Post. https://tinyurl.com/ydmw6zhu.

Ren, D. and Pan, C. (2021). Electric cars may get the chance of a lifetime to replace petrol guzzlers faster as they emerge unscathed in chips shortage. South China Morning Post. https://tinyurl.com/ybee4s94.

Rezapour, S., Farahani, R. Z., and Morshedlou, N. (2021). Impact of timing in post-warning prepositioning decisions on performance measures of disaster management: A real-life application. *European Journal of Operational Research*, 293(1):312–335.

Root, A. (2021). The Chip Shortage Is Getting Worse at the Worst Possible Time. Barron's. https://tinyurl.com/yzy2rzmz.

Rozhkov, M., Ivanov, D., Blackhurst, J., and Nair, A. (2022). Adapting supply chain operations in anticipation of and during the covid-19 pandemic. *Omega*, page 102635.

Sanger, D. E. (2021). Senate Poised to Pass Huge Industrial Policy Bill to Counter China . The New York Times. https://tinyurl.com/yxqezsas.

Scheibe, K. P. and Blackhurst, J. (2018). Supply chain disruption propagation: a systemic risk and normal accident theory perspective. *International Journal of Production Research*, 56(1-2):43–59.

Schwartz, J. and Steitz, C. (2021). Volkswagen points finger at suppliers over car chip shortage. Reuters. https://tinyurl.com/yfqbw2ty.

SCMP (2021). Why there is a global semiconductor shortage, how it started, who it is hurting, and how long it could last. South China Morning Post. https://tinyurl.com/yfyngzkf.

Sharma, A., Adhikary, A., and Borah, S. B. (2020). Covid-19s impact on supply chain decisions: Strategic insights from nasdaq 100 firms using twitter data. *Journal of Business Research*, 117:443–449.

Shekarian, M. and Mellat Parast, M. (2021). An integrative approach to supply chain disruption risk and resilience management: a literature review. *International Journal of Logistics Research and Applications*, 24(5):427–455.

Singh, S., Kumar, R., Panchal, R., and Tiwari, M. K. (2021). Impact of covid-19 on logistics systems and disruptions in food supply chain. *International Journal of Production Research*, 59(7):1993–2008.

Smith, C. and Stubbington, T. (2021). The summer of inflation: will central banks and investors hold their nerve? . Financial Times. https://tinyurl.com/yjko77vw.

Sodhi, M. and Tang, C. (2021a). Rethinking industrys role in a national emergency. *MIT Sloan Management Review: MIT's Journal of Management Research and Ideas.*

Sodhi, M. S., Son, B.-G., and Tang, C. S. (2012). Researchers' perspectives on supply chain risk management. *Production and Operations Management*, 21(1):1–13.

Sodhi, M. S. and Tang, C. S. (2018). Corporate social sustainability in supply chains: a thematic analysis of the literature. *International Journal of Production Research*, 56(1-2):882–901.

Sodhi, M. S. and Tang, C. S. (2021b). How to Prepare Supply Chains for the Next Global Shock . Barron's. https://tinyurl.com/yh38uf2y.

Sodhi, M. S. and Tang, C. S. (2021c). Supply chain management for extreme conditions: Research opportunities. *Journal of Supply Chain Management*, 57(1):7–16.

Swaminathan, J. M. (2000). Tool capacity planning for semiconductor fabrication facilities under demand uncertainty. *European Journal of Operational Research*, 120(3):545–558.

Swanson, A. (2021). Global Chip Shortage Challenges Bidens Hope for Manufacturing Revival. The New York Times. https://tinyurl.com/ydaxpla5.

Tang, C. S. (2006). Perspectives in supply chain risk management. *International Journal of Production Economics*, 103(2):451–488.

Trivedi, A. (2021). Want a New Factory to Make Car Chips? Thatll Be $4 Billion, Please. Bloomberg. https://tinyurl.com/y78gjqrd.

Wayland, M. (2021). Chip shortage expected to cost auto industry $110 billion in revenue in 2021. CNBC. https://tinyurl.com/yj8zzp9b.

Whalen, J. (2021). White House to hold another semiconductor summit with industry leaders as chip shortage worsens. The Washington Post. https://tinyurl.com/yf86hae6.

Whalen, J., Albergotti, R., and Lynch, D. J. (2021). Biden can't fix the chip shortage anytime soon. Here's why. . The Washington Post. https://tinyurl.com/yazdahmq.

Yamamitsu, E. and Kelly, T. (2021). Honda and Nissan to sell a quarter of a million fewer cars because of chip shortage . Reuters. https://tinyurl.com/yex89cuy.

Yang, H. (2021). Hyundai Motor Group chases local chipmakers to cut exposure to shortage . Reuters. https://tinyurl.com/ydmn779p.

Zakharov, V., Balykina, Y., Petrosian, O., and Gao, H. (2020). Cbrr model for predicting the dynamics of the covid-19 epidemic in real time. *Mathematics*, 8(10):1727.

Appendix

S.No.	Reference	Date	S.No.	Reference	Date	S.No.	Reference	Date	S.No.	Reference	Date
1	SCMP	16-Jun-21	54	Ch. D.	14-Dec-20	107	WSJ	29-Apr-21	160	Reuters	20-May-21
2	Wa. Po.	14-Jun-21	55	FT	31-Jan-21	108	FT	27-Apr-21	161	SCMP	19-May-21
3	Reuters	11-Jun-21	56	NYT	22-Apr-21	109	FT	26-Apr-21	162	FT	18-May-21
4	NYT	8-Jun-21	57	Ch. D.	12-Mar-21	110	SCMP	21-Apr-21	163	Reuters	14-May-21
5	SCMP	5-Jun-21	58	SCMP	6-Mar-21	111	SCMP	21-Apr-21	164	Reuters	13-May-21
6	ToI	5-Jun-21	59	Reuters	5-Apr-21	112	WSJ	20-Apr-21	165	WSJ	13-May-21
7	Barron's	2-Jun-21	60	FT	25-Jan-21	113	Reuters	20-Apr-21	166	Reuters	12-May-21
8	NYT	24-May-21	61	FT	26-Jan-21	114	Ch. D.	20-Apr-21	167	FT	11-May-21
9	Barron's	5-May-21	62	Reuters	18-Feb-21	115	Times	16-Apr-21	168	Reuters	7-May-21
10	SCMP	9-May-21	63	SCMP	28-Feb-21	116	Reuters	13-Apr-21	169	Times	7-May-21
11	Ch. D.	30-Apr-21	64	SCMP	26-Feb-21	117	Wa. Po.	9-Apr-21	170	Reuters	5-May-21
12	Reuters	28-May-21	65	SCMP	27-Mar-21	118	Barron's	8-Apr-21	171	FT	4-May-21
13	Ch. D.	14-May-21	66	Bus. Std.	10-Feb-21	119	Reuters	8-Apr-21	172	Bus. Ins.	29-Apr-21
14	Ch. D.	16-Apr-21	67	WSJ	18-Dec-20	120	Ch. D.	7-Apr-21	173	Ch. D.	26-Apr-21
15	Ch. D.	19-Apr-21	68	ToI	18-Jan-21	121	Reuters	6-Apr-21	174	Times	24-Apr-21
16	FT	15-May-21	69	NYT	18-Feb-21	122	FT	3-Apr-21	175	Barron's	23-Apr-21
17	Ch. D.	20-Apr-21	70	FT	15-Feb-21	123	FT	24-Mar-21	176	Times	23-Apr-21
18	WSJ	8-Apr-21	71	FT	29-Jan-21	124	Reuters	24-Mar-21	177	NYT	21-Apr-21
19	Barron's	17-May-21	72	Reuters	19-Feb-21	125	FT	22-Mar-21	178	WSJ	16-Apr-21
20	Ch. D.	31-Mar-21	73	Reuters	1-Apr-21	126	FT	21-Mar-21	179	Wa. Po.	11-Apr-21
21	WSJ	29-Apr-21	74	Reuters	11-Mar-21	127	FT	20-Mar-21	180	Reuters	8-Apr-21
22	Barron's	6-May-21	75	Reuters	2-Mar-21	128	WSJ	19-Mar-21	181	SCMP	7-Apr-21
23	Barron's	22-Apr-21	76	Reuters	9-Feb-21	129	WSJ	13-Mar-21	182	WSJ	2-Apr-21
24	ET	23-Apr-21	77	Reuters	19-Feb-21	130	Reuters	11-Mar-21	183	Barron's	1-Apr-21
25	WSJ	22-Apr-21	78	Reuters	10-Feb-21	131	Reuters	3-Mar-21	184	Bus. Ins.	30-Mar-21
26	WSJ	9-Apr-21	79	Reuters	19-Feb-21	132	FT	1-Mar-21	185	Barron's	26-Mar-21
27	Reuters	19-Apr-21	80	Reuters	4-Dec-20	133	Times	26-Feb-21	186	FT	17-Mar-21
28	Reuters	16-Apr-21	81	Reuters	12-Jan-21	134	FT	25-Feb-21	187	Reuters	16-Mar-21
29	Reuters	28-Apr-21	82	Reuters	24-Jan-21	135	NYT	25-Feb-21	188	FT	15-Mar-21
30	Reuters	3-May-21	83	Times	6-May-21	136	Times	25-Feb-21	189	FT	10-Mar-21
31	Barron's	5-May-21	84	Reuters	16-Jun-21	137	Times	20-Feb-21	190	Reuters	9-Mar-21
32	Reuters	11-May-21	85	ET	20-Jun-21	138	Reuters	18-Feb-21	191	WSJ	4-Mar-21
33	Reuters	11-May-21	86	Wa. Po.	15-Jun-21	139	FT	17-Feb-21	192	FT	24-Feb-21
34	Ch. D.	19-Apr-21	87	Barron's	14-Jun-21	140	FT	16-Feb-21	193	WSJ	22-Feb-21
35	Reuters	3-May-21	88	WSJ	12-Jun-21	141	FT	13-Feb-21	194	Reuters	15-Feb-21
36	Bus. Ins.	25-Feb-21	89	SCMP	9-Jun-21	142	WSJ	12-Feb-21	195	Bus. Ins.	14-Feb-21
37	SCMP	25-Feb-21	90	Bus. Ins.	9-Jun-21	143	Barron's	10-Feb-21	196	WSJ	11-Feb-21
38	Barron's	17-Mar-21	91	Forbes	8-Jun-21	144	WSJ	10-Feb-21	197	Bus. Ins.	10-Feb-21
39	Barron's	23-Mar-21	92	SCMP	3-Jun-21	145	FT	5-Feb-21	198	WSJ	9-Feb-21
40	Barron's	23-Apr-21	93	Barron's	1-Jun-21	146	Reuters	3-Feb-21	199	Reuters	8-Feb-21
41	Ch. D.	1-Mar-21	94	Bus. Std.	21-May-21	147	Reuters	28-Jan-21	200	WSJ	4-Feb-21
42	Reuters	25-Feb-21	95	Barron's	18-May-21	148	Times	14-Jan-21	201	NYT	3-Feb-21
43	Wa.Po.	2-Mar-21	96	Wa. Po.	14-May-21	149	WSJ	10-Jan-21	202	FT	28-Jan-21
44	FT	8-Feb-21	97	Reuters	13-May-21	150	Reuters	22-Jun-21	203	FT	27-Jan-21
45	Wa. Po.	10-Apr-21	98	Reuters	12-May-21	151	Barron's	16-Jun-21	204	FT	19-Jan-21
46	FT	24-Mar-21	99	SCMP	12-May-21	152	Reuters	7-Jun-21	205	FT	18-Jan-21
47	Reuters	10-Feb-21	100	Reuters	11-May-21	153	Barron's	1-Jun-21	206	NYT	14-Jan-21
48	Ch. D.	29-Mar-21	101	Bus. Ins.	10-May-21	154	SCMP	1-Jun-21	207	Barron's	13-Jan-21
49	Barron's	23-Apr-21	102	ST	9-May-21	155	Barron's	31-May-21	208	Ch. D.	8-Dec-20
50	Bus. Std.	24-Mar-21	103	WSJ	6-May-21	156	Reuters	28-May-21	209	WSJ	12-Feb-21
51	Bus. Std.	23-Mar-21	104	NYT	5-May-21	157	WSJ	28-May-21			
52	WSJ	3-Mar-21	105	Barron's	4-May-21	158	Mail On.	27-May-21			
53	Bus. Ins.	3-Mar-21	106	FT	29-Apr-21	159	WSJ	21-May-21			

Table A1: Abbreviated references used in thematic analysis; see **supplementary file** for details