CHALLENGES IN THE SEMICONDUCTOR SUPPLY CHAIN AND CHIP SUPPLY UNCERTAINTY: A GLOBAL PERSPECTIVE

PULAVENDRAN A/L VIJAYA KUMARAN

MASTER OF SCIENCE (SUPPLY CHAIN MANAGEMENT)

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PULAVENDRAN A/L VIJAYA KUMARAN

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Nama Pelajar
(Name of Student) : **Pulavendran A/L Vijaya Kumaran**

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(Name of Supervisor/Supervisors) : **Dr. Alminnourliza Noordin**

Tandatangan

Nama Penyelia/Penyelia-penyelia
(Name of Supervisor/Supervisors) : -

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ABSTRAK

Industri semikonduktor merupakan teras kepada kemajuan teknologi moden, namun ia menghadapi gangguan yang ketara akibat kelemahan dalam rantaian bekalan. Permintaan terhadap semikonduktor meningkat dengan ketara dalam pelbagai industri seperti elektronik, automotif, perubatan dan produk pengguna. Namun, bekalan semikonduktor tidak dapat memenuhi permintaan, menyebabkan berlakunya kekurangan dan kelewatan yang memberi kesan besar kepada pengeluaran global. Kajian ini menyelidik cabaran utama yang menjejaskan rantaian bekalan semikonduktor dan bagaimana cabaran-cabaran ini menyumbang kepada ketidakpastian bekalan cip. Secara khusus, kajian ini mendedahkan persepsi pakar industri terhadap kesan tiga faktor kritikal iaitu: penumpuan geografi, ketegangan geopolitik, dan kerumitan pembuatan terhadap bekalan cip global. Reka bentuk kajian kualitatif telah digunakan, melibatkan temu bual mendalam dengan tiga profesional industri dari syarikat semikonduktor yang beroperasi di Malaysia. Analisis tematik digunakan untuk mengekstrak dapatan melalui proses berstruktur iaitu pengurangan data, paparan data, dan membuat kesimpulan. Dapatan kajian menunjukkan bahawa penumpuan geografi mewujudkan titik kegagalan tunggal, terutamanya apabila operasi pembuatan atau sumber bahan mentah tertumpu di wilayah tertentu seperti China atau Taiwan. Ketegangan geopolitik, seperti konflik perdagangan antara Amerika Syarikat dan China serta sekatan eksport terhadap teknologi semikonduktor, memburukkan lagi ketidakpastian bekalan melalui pengenaan tarif dan gangguan logistik rentas sempadan. Sementara itu, kerumitan pembuatan yang dipacu oleh piawaian kualiti yang ketat, pengecilan saiz teknologi, dan kitaran pengeluaran yang panjang menyumbang kepada kelewatan dan penolakan bahan, khususnya dalam persekitaran pengeluaran cip tersuai. Kajian ini menyumbang kepada literatur sedia ada dengan menawarkan pemahaman yang fokus terhadap gangguan dalam rantaian bekalan industri semikonduktor, serta memberikan pandangan strategik kepada penggubal dasar dan pemimpin industri untuk meningkatkan daya tahan rantaian bekalan dalam menghadapi ketidakpastian global pada masa hadapan.

Kata kunci: Rantaian bekalan semikonduktor; Penumpuan geografi; Ketegangan geopolitik, Kerumitan pembuatan; Bekalan cip global

ABSTRACT

The semiconductor industry lies at the core of modern technological advancement, yet it faces significant disruptions due to supply chain vulnerabilities. The demand for semiconductors has surged across various industries, such as electronics, automotive, medical, and consumer products. However, the supply of semiconductors has not been able to keep up with the demand, resulting in shortages and delays that have had far-reaching impacts. This research investigates the key challenges affecting the global semiconductor supply chain (SSC) and how these challenges contribute to chip supply uncertainty. Specifically, the study reveals the industry expert perception of the impact of three critical factors: geographical concentration, geopolitical tensions, and manufacturing complexity on global chip supply. A qualitative research design was adopted, involving in-depth interviews with three industry professionals from semiconductor companies operating in Malaysia. Thematic analysis was used to extract insights through a structured process of data reduction, data display, and conclusion drawing. The findings reveal that geographical concentration creates single points of failure, particularly when manufacturing operations or raw material sources are centralized in specific regions such as China or Taiwan. Geopolitical tensions, such as the US-China trade conflict and export restrictions on semiconductor technologies, further exacerbate supply uncertainties by imposing tariffs and disrupting cross-border logistics. Meanwhile, manufacturing complexity driven by stringent quality standards, technological miniaturization, and long production cycles contributes to delays and material rejection, particularly in customized chip production environments. The research contributes to existing literature by offering a focused understanding of supply chain disruptions within the semiconductor industry and provides strategic insights for policymakers and industry leaders aiming to enhance supply chain resilience in the face of future global uncertainties.

Keywords: Semiconductor supply chain; Geographical concentration; Geopolitical tension; Manufacturing complexity; Global chip supply

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

The semiconductor industry, a dominant aspect of modern technology, has played a pivotal role in globalization. As the building block of most electronic applications, semiconductors have contributed to various industries including military and defense, car manufacturing, healthcare, electrotechnology, modern entertainment, and consumer electronics (Mohammad et al., 2022). The increasing demand for smart devices, automobiles, and other electronic products that are chip-enabled has gradually enhanced the importance of the semiconductor industry (Singh et al., 2024).

The World Semiconductor Trade Statistics has estimated strong growth for the global semiconductor market in 2024 and 2025. The market was valued at US$610.15 billion in 2023 and is expected to reach around US$736.40 billion by 2027, with a compound annual growth rate (CAGR) of around 6.30 % (World Semiconductor Trade Statistics, 2024). Innovation in artificial intelligence, autonomous electric vehicles, the Internet of Things (IoT), industrial automation, and 5G technologies will continue to drive growth in chip manufacturing through the next decade, strengthening the long-term market demand for semiconductors (Semiconductor Industry Association, 2024). Furthermore, the COVID-19 pandemic accelerated the transition towards teleworking, online learning, and e-commerce which led to the increase in demand for chips powering computers, laptops, cloud computing, and hardware for wireless communications. Figure 1 shows the demand drivers of the semiconductor industry.

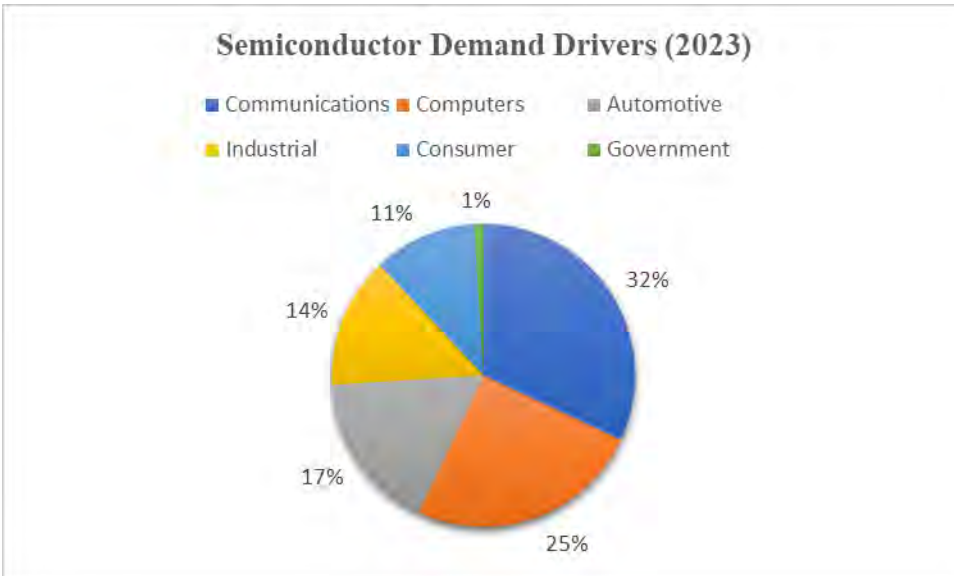

Figure 1.1 Semiconductor demand drivers in 2023 (Semiconductor Industry Association, 2024)

Figure 1.2 illustrates the semiconductor supply chain (SSC) which comprises four stages: pre-competitive research, chip design stage, front-end manufacturing which refers to wafer fabrication, and back-end manufacturing (assembly, packaging, and testing). These stages depend on a highly complex and sophisticated environment which includes specialized materials, advanced high-precision manufacturing equipment and tools, advanced electronic design automation (EDA) software, and sterile manufacturing facilities (Varas et al., 2021).

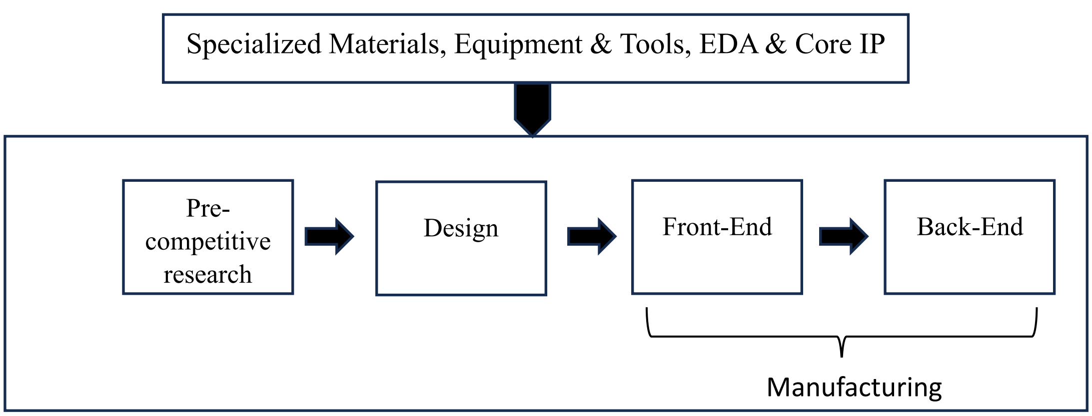

Figure 1.2 The Semiconductor Supply Chain (Varas et al., 2021)

The SSC is geographically concentrated as six major regions dominate the SSC: the US, mainland China, Taiwan, Japan, South Korea, and Europe whereby each region has a distinct role. The US is the global leader in Research and Development (R&D), EDA, core Intellectual Property (IP), and chip design. The US, Japan, and Europe specialize in producing highly advanced manufacturing equipment. As for wafer fabrication, assembly, testing, and packaging are concentrated in China, Taiwan, and other Asian countries (Varas et al., 2021). Critical raw materials to produce semiconductor chips such as silicon and germanium are largely supplied from China. According to the U.S. Geological Survey (USGS), China contributed to almost 70% of the global production of silicon materials in 2022 (Schnebele, 2023). Figure 1.3 shows that China is the largest producer of germanium in the world. As each stage of the SSC is concentrated in a specific region, the global chip supply is at risk in the event of disruption in a single region (Kumar et al., 2024).

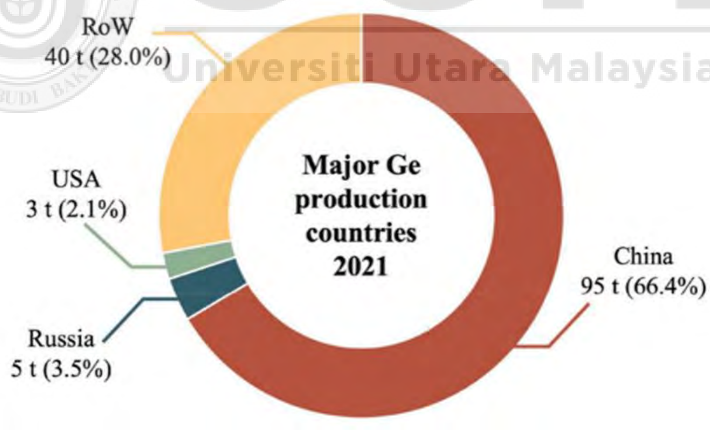

Figure 1.3 Major germanium-producing countries in 2021 (Mei et al., 2024)

The global SSC is vulnerable to significant risks due to geopolitical tensions between countries. Trade tensions between the United States and China have led to export restrictions on raw materials for semiconductor manufacturing and chip-making technology (Varas et al., 2021). Furthermore, political disputes between Japan and South Korea have also put the supply of semiconductor material at risk, especially high-purity chemicals crucial for chip production. These tensions have increased chip supply uncertainty due to limitations to operate effectively across borders (Varas et al., 2021). As highlighted by Moktadir and Ren (2024), these challenges of the SSC make it difficult for chip supply to match its rapid growth in demand.

1.2 Problem Statement

Semiconductor chip supply is uncertain with the steady increase in demand for technological advancements and poses a major challenge to the SSC. Concerns regarding single points of failure in the SSC, political conflicts, and difficulties in semiconductor fabrication have exacerbated the struggle to meet the demand. The uncertainties can be overcome by semiconductor businesses and ensure steady operations by incorporating resilience and reliability strategies during disruptions (Kumar et al., 2024). James (2024) pointed out the fact that the chip shortage issue is yet to be solved completely, even though significant development has taken place in the SSC. Therefore, ensuring a continuous supply of semiconductor chips has become an area of focus for researchers.

Based on the facts provided in the background of the study, it can be deduced that the SSC is concentrated in specific regions, where design and manufacturing are centralized in multiple geographical areas. In conjunction with this, disruptions of a large scale can happen if there are single points of failure, such as natural disasters, fires, pandemics, labour strikes, halts in port operations, or shutdowns (Kumar et al., 2024). For example, a fire breakout was reported in 2021 at the Renesas semiconductor manufacturing facility in Naka City, Ibaraki Prefecture, Japan, which led to a halt in the production of semiconductors (Hu et al., 2024). This crisis had a severe impact on the automotive industry, forcing many companies to put their production on hold as a result of the shortage of semiconductor chips. Moreover, during the COVID-19 pandemic, the semiconductor industry faced slowdowns in manufacturing, leading to semiconductor shortages that impacted the automotive sector, leading to production interruptions and backlogs (Hu et al., 2024). Therefore, since the SSC is geographically concentrated, disruptions occurring in one region might cause bottlenecks in other countries, causing shortages in chip supply.

In the past decade, geopolitical tensions have increased globally. In July 2019, tensions between Japan and South Korea escalated as Japan enforced export restrictions on South Korea as a consequence of Korean judicial rulings against some Japanese business organizations. The restriction was a major blow for South Korea, as three critical chemicals required for the manufacturing of semiconductors were mainly imported from Japan (Mohammad et al., 2022). This impacted an estimated value of $7 billion worth of semiconductor exports per month (Varas et al., 2021).

Meanwhile, the trade war between the US and China initiated by American president Donald Trump was a major concern as tariffs were imposed on Chinese exports to the US, such as the restrictions in September 2021 on the Semiconductor Manufacturing International Corporation (SMIC), the largest semiconductor firm in China (Mohammad et al., 2022). On the other hand, the Biden administration has also put restrictions on the exports of chipmaking technologies, manufacturing equipment, and tools to China (Wong et al., 2024). Limiting China's access to advanced semiconductor chips aims to hinder China's development of supercomputers and the integration of AI in military technologies.

As the U.S., Japan, and the Netherlands impose more curbs on the sale of advanced semiconductor manufacturing equipment to China, China has reacted by taking measures to consolidate its export control system, by mandating new licensing requirements for the purchase of gallium, germanium, graphite, and other rare earth elements, which are necessary for semiconductor manufacturing

(Semiconductor Industry Association, 2024). This export restriction has created a major concern that a second chip shortage can occur anytime soon (Mei et al., 2024).

Furthermore, the SSC is considered very complex due to long fabrication cycle times, high levels of variations in chip design, and irregular manufacturing processes. This is due to the hundreds of processing steps that are involved in the manufacturing process of semiconductor chips which depends on the complexity of the chips itself leading to long cycle times (Sun & Rose, 2015). The fabrication process is also highly complex because specific inputs and equipment are required to meet precise specifications at a nanoscopic scale. Manufacturing of semiconductors is also complex as electronic components such as integrated circuits are fabricated in controlled environments or cleanrooms, designed to maintain sterile conditions to avoid contamination by pollutants in the air that could change the characteristics of the materials that form the electronic circuits (Varas et al., 2021).

In addition to being a complex process, semiconductor manufacturing is capital intensive as huge sums of R&D investments are required to develop and fabricate high-precision semiconductor manufacturing equipment. The cost of fabricating a whole wafer can go up to $10 billion due to highly expensive manufacturing equipment, each valued at up to $100 million. Expanding production capacity is costly and time-consuming. Expansion of manufacturing capacity could take up to 9 months. This complexity in SSC contributes to the semiconductor shortage (Mohammad et al., 2022).

The impact of the manufacturing complexity of semiconductors on global chip supply has been minimally studied in the present body of research. Sun and Rose (2015) have addressed the need to measure the complexity of the entire semiconductor supply chain. The impact of changes of the structure of SSC on the complexity of SSC was also studied (Sun et al., 2016). This appears to be significant and research worthy in the context of global chip supply uncertainty. Only Mohammad et al. (2022) has discussed the relationship between manufacturing complexity and global chip supply shortage. Therefore, a more comprehensive understanding of the independent variable is required. Research also predominantly focuses on the upstream of the SSC and hence more research is suggested to include the whole SSC (upstream, midstream operations, and downstream), which addresses the challenges and resilience of the SSC with a more detailed and overall viewpoint (Yu et al., 2024).

There is also a lack of study on current issues of geographical concentration and geopolitical risks of the SSC and its effect on the supply of global chips. This is supported by the view of Zhang & Zhu (2023) who cited that research on the global chip supply chain has reduced after the year 2020 even though tensions particularly between China and the US and its impact on uncertainty of chip supply have been extensively studied by scholars (Wong et al., 2024; Zhang & Zhu, 2023; Tse et al., 2024). A very limited number of scholars have dissected and discussed the geographical concentration of the SSC apart from Grimes and Du (2022) and Varas et al. (2021). Nevertheless, there are still more insights to be added to the pool of knowledge on the link between geopolitical conflict and geographical concentration with the semiconductor chip supply. Therefore, an investigation of these challenges is important to validate the effect on global chip supply and open a pathway to the creation of a more robust and resilient SSC.

1.3 Research Questions

Upon reviewing the related literature, the following three main research questions were addressed in this study:

1) How do industry experts in the semiconductor industry perceive the impact of geographical concentration of chip manufacturing on global chip supply?

2) How do stakeholders in the semiconductor industry perceive the influence of geopolitical tensions on the global chip supply?
3) How do professionals in the semiconductor industry perceive the impact of manufacturing complexity of semiconductors on global chip supply?

1.4 Research Objectives

The research addresses the following objectives by answering the research questions in the previous subsection.

1) To reveal the impact of geographical concentration of the SSC on global chip supply.
2) To find out the influence of geopolitical tensions on global chip supply.
3) To reveal the impact of the complexity of semiconductor manufacturing on global chip supply.

1.5 Significance of Study

From a theoretical point of view, the research is expected to shed more light on how the manufacturing complexity of semiconductors affects the global chip supply as a minimal study has been carried out by researchers on the effects of manufacturing complexity on the semiconductor supply chain. Sun and Rose (2015) highlighted the need to establish complexity measurement metrics for the whole semiconductor supply chain. The impact of manufacturing complexity on semiconductor shortage has only been highlighted by Mohammad et al. (2022). Thus, this study will be a valuable addition to the existing literature on semiconductor chip shortage as influenced by manufacturing complexity.

This study also aims to provide further insights into the contemporary issues of geopolitical tensions and the geographical concentration of the SSC and how it will affect the global chip supply which is corroborated by the view of (Zhang & Zhu, 2023) who suggested that research on the global chip industry network is lacking since the year 2020. Geopolitical tension especially between the US and China has been associated with global chip supply uncertainty and extensive study has been done by scholars (Wong et al.,2024; Zhang & Zhu, 2023; Tse et al., 2024). However, there is still more to learn from the relationship between geopolitical conflict and semiconductor chip supply. Therefore, this study will contribute to the knowledge and literature about chip shortage and its dependency on political trade tensions between countries.

From a practical perspective, this study will give organizations in the semiconductor industry some valuable insights into the effect of geographical concentration, geopolitical tension, and semiconductor manufacturing complexity on the global chip supply. The findings of this study will assist organizations in designing a resilient and reliable supply chain by leading to the proposal of recommendations to mitigate the challenges and ensure the continuous supply and availability of semiconductor chips. As a result of this, the increasing demand for IoT, artificial intelligence systems, robotic industrial automation procedures, 5G networks, laptops, tablets, smartphones, and other consumer electronics products can always be fulfilled and delivered on time by preventing component shortages and other supply challenges.

The information obtained from the study will help government agencies in re-evaluating and designing trade policies appropriately and intensify resource allocation and investment efforts to increase their semiconductor manufacturing capacity to prevent future disruptions. Additionally, the findings are expected to increase semiconductor research and development funding to reduce the manufacturing complexity of semiconductor chips.

1.6 Scope of Study

As the demand for semiconductor chips continues to surge, the risk of chip shortage has become a major global concern for firms in the SSC. The advancement in technology across all sectors has created the need to address the issues faced by the SSC and minimize disruptions in global chip supply.

One of the key challenges that leads to uncertainty in global chip supply is the high geographic concentration of the SSC, whereby the expertise, source of raw materials and manufacturing capacity of semiconductors are centralized in different parts of the world. This has threatened the resilience of the SSC, in the event of unforeseen circumstances such as natural disasters or shutdowns. Thus, one of the focuses of this study is to determine the impact of the SSC's geographical concentration on global chip supply.

Another construct that is associated with global chip supply is geopolitical tension. Rising conflicts between countries in the last decade has presented a risk to the SSC. Trade restrictions between countries especially the US and China could disrupt the production of microelectronic products (Varas et al., 2021). These restrictions stem from the US' strategy to protect their own foreign policy interests and remain ahead of China in terms of technology advancement in military and defense functions. Dispute between other countries such as Japan and South Korea could also lead to inconsistencies in global chip supply, as Japan produces three chemicals key to semiconductor manufacturing: hydrogen fluoride, fluorinated polyamide and photoresists (Varas et al., 2021). Therefore, the scope of this study is to reveal the influence of geopolitical disputes between nations on global chip supply.

Finally, this study also analyzes the impact of manufacturing complexity of semiconductors on global chip supply. Intricate manufacturing processes, requirements for highly specialized inputs and equipment, and a controlled environment for wafer fabrication not only leads to longer lead times but also makes the production of chips extremely capital intensive (Mohammad et al., 2022).

Thus, the scope of the study is to validate the effect of the complexities in semiconductor manufacturing on the supply of chips.

Through this study, the respondents were requested to provide their perception of geographical concentration, geopolitical tension, and the manufacturing complexity of semiconductors to understand the uncertainty in global chip supply. The study was conducted on employees in managerial roles of the semiconductor industry in Malaysia. Malaysia holds 13% of the global assembly, testing, and packaging services of semiconductors and is the sixth-largest semiconductor exporter in the world (Said & Tan, 2024). Therefore, Malaysia was selected as it is a key player in the semiconductor value chain.

The respondents of this study are qualified professionals with vast experience in the semiconductor industry. Their roles are closely related to SSC as they serve a diverse category of business functions of the semiconductor industry, including inventory management, warehouse management, supplier performance assessment, and new product implementation. This research employed a qualitative method whereby interviews were conducted for data collection.

1.7 Definition of Key Terms

In this section, some of the key terms used in this study were explained.

1.7.1. Semiconductor Supply Chain

The semiconductor supply chain is the network of business organizations involved in the design, manufacturing, testing, packaging, and distribution of semiconductor products (Hayes, 2024).

1.7.2. Electronic Design Automation

Electronic Design Automation (EDA) refers to a group of multiple tools, techniques and services that employ computer-enabled design to develop and validate electronic systems (Marinova & Bitri, 2021).

1.7.3. Wafer Fabrication

Wafer fabrication is the process of producing wafers (thin and flat slices of semiconductor material), used as the foundation for the creation of microelectronic components, such as integrated circuits (ICs). The wafer fabrication process includes wafer cleaning, photolithography, etching, and doping.

1.7.4. Core IP

Core Intellectual Property (IP) is the basic element in the design of semiconductor chips such as integrated circuits (ICs). The design components that are pre-designed and pre-verified smoothen the development of chips by providing access to the reuse of existing functional elements such as units of logic or circuit layout design, thus accelerating design processes and allowing designers to focus on product innovation. Core IPs can be owned and used by one party or licensed to another party for a fee (Yan, 2024).

1.7.5. Geographical Concentration

Geographical concentration refers to the tendency to focus on individual activities, business operations, and economic activities within a specific geographic area.

1.7.6. Geopolitical Tension

Conflicts between countries due to economic, political, or territorial disagreements are referred to as geopolitical tension (Datta & Satghare, 2024).

1.7.7. Lithography

Lithography is part of the microchip manufacturing process. The process utilizes light to create patterns onto a silicon surface (Mack, 2006).

1.7.8. Etching

Etching refers to the selective removal of material from surface of wafer performed via ionic sputtering or by using chemicals (Romano, 2025).

1.8. Chapter Summary

Chapter one introduces the research by forming a comprehensive outline of the study and acts as the foundation for the subsequent sections of this thesis. It provides a detailed background of the study followed by the statement of the problem, research questions, and research objectives. The significance of the study, which includes both theoretical and practical perspectives, the scope of the study, the definitions of the key terms, and the arrangement of the thesis follows accordingly.

CHAPTER 2

LITERATURE REVIEW

2.1. Introduction

This chapter examines the concept, definition, and previous research findings and determines the gaps in the present knowledge pool to develop a theoretical model of this research. The first section of this chapter discusses the global chip supply, whereby the second section focuses on the geographical concentration of the SSC. The third section of this chapter discusses the impact of geopolitical tensions on global chip supply followed by the fourth section that describes the manufacturing complexity of semiconductors. The fifth section highlights the gaps in literature, whereby the sixth section demonstrates the development of theoretical framework of this study based on literature findings. In the final section, the chapter is summarized to pave way for research methodology in the next chapter.

2.2. Global Chip Supply

Modern developments in technology, such as increasing utilization of artificial intelligence, manufacturing of autonomous vehicles, and industrial automation, are expected to lead to a significant growth in demand for semiconductor chips. Hence, the semiconductor industry is anticipated to be worth a trillion dollars by 2030, with a yearly projection of 6-8% growth in demand (Moktadir & Ren, 2024). Microchips' elevated demand and disruptions in the SSC are questioning the resilience and sustainability of the SSC in the long run. Furthermore, geopolitical tensions, supply chain complexity, war between Russia and Ukraine, trade war between the US and China, and environmental concerns are exacerbating the challenges of the global SSC (Moktadir & Ren, 2024).

For example, the COVID-19 pandemic caused a shortage in chip supply, whereby the automotive sector alone suffered a potential loss of sales worth $210 billion (Moktadir & Ren, 2024). Mohammad et al. (2022) revealed that these disruptions in global supply are due to the forced shutdown of chip-producing facilities during pandemic-induced lockdowns, leading to reduced semiconductor manufacturing and stock on hand. Disruptions were also contributed to by delays in the shipment of chips during the pandemic, as the number of flights was reduced and airports were closed. Consequently, manufacturers globally faced difficulties in satisfying the demand for new cars because of the chip shortage for vehicle safety systems (James, 2024). This clearly shows the bottlenecks of sustaining a balance between microchip supply shortage and the increasing demand in the event of disruptions (Moktadir & Ren, 2024).

There are also complex scenarios in other industries. Sectors with high demand, such as high-end computing and manufacturing of consumer electronics, are struggling, especially with the cutting-edge and highly specialized chips. While manufacturing capacity is growing worldwide, with state-of-the-art facilities being built, the complete solution to the chip supply shortage relies on managing multiple issues, such as political unrest and supply chain gaps. Therefore, the global chip supply shortage is not fully resolved, even though significant development has taken place (James, 2024).

Beginning in 2025, the incorporation and improvement of AI for personal computers and smartphones might need extra capacity for memory, hence the market is predicted to encounter a critical supply shortage. A 11% decrease in supply for High Bandwidth Memory (HBM) chips and a 23% reduction of Dynamic Random Access Memory (DRAM) chips is projected (Stanley, 2024).

2.3. Geographical Concentration

2.3.1. Concept and Definition of Geographical Concentration

The geographical concentration of businesses is defined as the clustering of organizations within a particular industry in a specific region. This concentration is usually described as the agglomeration of businesses, specific suppliers of highly specialized inputs such as machines, components, and services, skilled professionals, and facilities that form a network leveraging the exchange of resources and knowledge (Porter, 2000).

2.3.2. Geographical Concentration and Global Chip Supply

The SSC is widely dispersed across different geographic regions and jurisdictions. However, wafer fabrication and back-end manufacturing are relatively centralized in specific areas of the world. The concentration is due to several reasons such as incentives from the government and labor outsourcing. For instance, 75% of the global wafer-producing foundries are in Taiwan (TSMC) and South Korea (Samsung), the two most influential chip manufacturers. Meanwhile, more than 60% of global back-end manufacturing is accounted for by China and Taiwan (Semiconductor Industry Association, 2024). Additionally, 100% of the global capacity in advanced semiconductor chip manufacturing such as 7- and 5-nanometer nodes is located in East Asia, mainly Taiwan whereby TSMC can manufacture logic chips in advanced nodes (10 nanometers and below) that are required to produce application processors, CPUs, GPUs and FPGAs for smartphones, PCs, data center servers, and autonomous vehicles (Varas et al., 2021).

On the other hand, the United States is the global leader in EDA, core IP, and semiconductor manufacturing equipment which is highly R&D intensive. It accounts for 74% of EDA and core IP worldwide whereas Europe holds 20% of the R&D-driven layer of the supply chain (Varas et al., 2021). In semiconductor manufacturing equipment, the US, Japan, and Europe collectively combine for a staggering 91% of the global market share (Varas et al., 2021). US companies account for half of the critical manufacturing process equipment produced worldwide (deposition tools, dry/wet etch and cleaning, doping equipment, process control, and testers). Similarly, 90% of the photoresist processing market is owned by Japan, which is crucial equipment for the lithography process (Varas et al., 2021). Furthermore, ASML, which is a European company has a global market share of approximately 100% in the production of Extreme Ultra-Violet (EUV) lithography machines which are involved in the manufacturing of advanced nodes below 7 nanometers (Varas et al., 2021).

As per the above facts, it can be deduced that the SSC is geographically concentrated, where design is focused in one area and manufacturing is centralized in another area. This increases the risk of supply chain disruptions. Large-scale supply interruptions can possibly occur if there is a single point of failure in the unforeseen event of natural disasters such as earthquakes, hurricanes, tsunamis, floods, pandemics lock-downs and even threats caused by humans such as fires, labor strikes, acts of terrorism, cyberattacks and halts in port operations (Kumar et al., 2024). Semiconductor organizations will be exposed to potential financial and operational challenges that lead to a shortage in global chip supply.

For example, a massive earthquake hit Japan in 2011, followed by a tsunami. The unprecedented natural disaster negatively impacted 25% of silicon wafer fabrication globally and 75% of the global hydrogen peroxide supply (Varas et al., 2021). Several wafer manufacturing facilities were also forced to stop operations and shut down for several months (Varas et al., 2021). Furthermore, the semiconductor industry faced slowdowns in production during the COVID-19 pandemic that affected automobile manufacturers, leading to production halts and backlogs (Hu et al., 2024).

A fire breakout was reported in 2021 at the Renesas semiconductor manufacturing facility in Naka City, Ibaraki Prefecture, Japan which led to a halt in the production of semiconductors (Hu et al., 2024). This crisis had a severe impact on the automotive industry, forcing many companies to put their production on hold as a result of the shortage of semiconductor chips (Hu et al., 2024). At the beginning of the same year, a cold wave struck Texas in the southern United States, causing the closure of factories owned by NXP semiconductors in the Netherlands and Germany's Infineon Technology. NXP Semiconductor announced that production will be disrupted for approximately a month in its facilities in Texas (Hu et al., 2024).

The supply of certain materials used for wafer fabrication is also geographically concentrated such as silicon wafers, substrates for packaging, specialty gases, and photoresist. Even though these specialized materials account for a very small part of the industry's value chain, they are a mandatory requirement for the fabrication of semiconductors. For example, C4F6, a crucial type of process gas, is used to produce several advanced logic chips and 3D NAND memory chips (Varas et al., 2021). It is a vital component for the etching process during wafer fabrication, which reduces the etching process time by 30% compared to the closest substitute of C4F6 (Varas et al., 2021). Additionally, once a manufacturing facility is configured to use C4F6, it cannot be changed. In 2019, total sales of C4F6 were about $250 million, where Japan, Russia, and South Korea accounted for 88% of the global supply (Varas et al., 2021). In the event of any disruptions, there will be a loss of C4F6 supplies worth $60-100 million, which may cause a loss of revenue of approximately $10-18 billion for 3D NAND chips only (Varas et al., 2021). Permanent effects of such disruptions will constrain the manufacturing output of NAND chips for 2-3 years till new locations are identified to cater for the large-scale production of chips (Varas et al., 2021). With the supply of key materials concentrated in East Asia and China, front-end manufacturing dominated by Taiwan and South Korea, and fabrication of manufacturing equipment spearheaded by the US, Europe, and Japan, the SSC is vulnerable to major disruptions.

2.4. Geopolitical Tension

2.4.1. Concept and Definition of Geopolitical Tension

Geopolitical tensions have been on the rise in supply networks lately and have impacted supply chain operations massively. Geopolitical risk comprises the threat, occurrence, and increase of geopolitical incidents like tensions, terrorism, and even wars between different countries, jeopardizing the smooth relationship (Tse et al., 2024). Geopolitical tensions have had negative consequences on the economy, particularly on employment and investment, and a greater financial risk for business organizations. The challenges caused by these scenarios have exposed risks to the global supply chain stability of multinational companies. According to Tse et al., 2024, risks exist in multiple aspects:

(i) Geopolitical tensions often lead to the enforcement of trade restrictions and tariffs. These approaches can destabilize supply chains, restrict the movement of goods and materials across international borders and, subsequently, affecting businesses' supply networks;

(ii) Regions facing political unrest are vulnerable to social unease and government policy changes. Such circumstances hamper transportation systems, create inconsistencies in the business landscape, and disrupt and delay the manufacturing and supply of goods;

(iii) Geopolitical tensions can possibly reduce access to critical raw materials. Trade restrictions or sanctions, for example, can limit the opportunity to acquire essential resources, which negatively impacts production processes and disrupts raw material supply chains.

2.4.2. Geopolitical Tension and Global Chip Supply

In July 2019, tensions between Japan and South Korea escalated as Japan enforced export restrictions on South Korea as a consequence of Korean judicial rulings against some Japanese business organizations. The restriction was a major blow for South Korea, as three critical chemicals required for the manufacturing of semiconductors were mainly imported from Japan (Mohammad et al., 2022). This impacted an estimated value of $7 billion worth of semiconductor exports per month (Varas et al., 2021).

Increasing tensions between two world superpowers, the US and China have created a major concern regarding the future of the semiconductor value chain. As semiconductors are a significant element in most industries and play a key role in national security, both countries want to dominate this sector (Grimes & Du, 2022). This policy change has created the possibility of disconnecting the links of technology development between the two countries, which will have a massive impact on the future transformation of the SSC and on China's aspirations to build its self-sufficient semiconductor sector. Therefore, restrictions in technology transfer, sanctions, and tariffs against China are the US strategy to keep China at bay with technological advancements, deter its progress towards the upstream of the value chain, and limit China's role up to low value-added operations such as assembly, packaging, and testing only (Grimes & Du, 2022).

The trade war between the US and China initiated by American president Donald Trump was a major concern as tariffs were imposed on Chinese exports to the US, such as the restrictions in September 2021 on the Semiconductor Manufacturing International Corporation (SMIC), the largest semiconductor firm in China (Mohammad et al., 2022). The Biden administration has also put restrictions on the exports of chipmaking technologies including chip design software, manufacturing equipment, and tools to China (Wong et al., 2024). Limiting China's access to advanced semiconductor chips aims to hinder China's access to the development of supercomputers and the integration of AI in military technologies such as missiles, fighter jets, and other advanced smart equipment and tools thereby halting its rise in technological and market power (Varas et al., 2021).

These US restrictions also apply to other ally countries, such as ASML and Tokyo Electron located in the Netherlands and Japan respectively, which have employed US proprietary technologies in the fabrication of their advanced semiconductor manufacturing equipment to be exported to China (Wong et al., 2024). This includes lithography, etching, cleaning, chemical vapor deposition, and other machines used in wafer fabrication processes. In addition to this stringent control of technology export, the US also forbids American citizens and its permanent residents to work for semiconductor companies in China. This particular ban has caused many experienced managers and engineers to leave their jobs in China's firms. The ban also forced foreign semiconductor equipment organizations in China such as ASML, Applied Materials, and Lam Research to prohibit their American employees from giving services to domestic customers. Consequently, many local semiconductor firms in China have been dealing with an alarming shortage of skilled professionals to sustain large-scale manufacturing of chips (Wong et al., 2024).

As the U.S., Japan, and the Netherlands impose more curbs on the sale of advanced semiconductor manufacturing equipment to China, China has reacted by taking measures to consolidate its export control system, by mandating new licensing requirements for the purchase of gallium, germanium, graphite, and other rare earth elements, which are necessary for semiconductor manufacturing (Semiconductor Industry Association, 2024). This export restriction has created a major concern that a second chip shortage can occur anytime soon (Mei et al., 2024).

Likewise, Ying Kei Tse (2024) highlighted the impact of Huawei's supply chain operations due to extended trade tensions with the US and the sanctions imposed. A study conducted by Jacobs et al. (2022) confirmed the negative consequences of the U.S. government's trade restriction on ZTE and subsequently on its supply chain stakeholders, particularly Tier 1 and Tier 2 suppliers and clients in various countries.

China's initiative to establish memory chip manufacturing has been severely affected by US sanctions. The supply of materials or components from US firms to Fujian Jinhua Integrated Circuit Co. (JHICC), a key DRAM facility in China, was banned after IP theft accusations from Micron Technology were made on JHICC and its R&D stakeholder United Microelectronics Corp (UMC), from Taiwan (Grimes & Du, 2022). Before that, Tsinghua/XMC, the other Chinese counterpart, was unsuccessful in forming a licensing agreement with Micron, and subsequently, failed to acquire a USD23 billion bid (Grimes & Du, 2022). Similar to other semiconductor companies in the world that depend on suppliers from the US, UMC has stopped its collaboration with JHICC, and therefore its DRAM development program had to be shut down (Grimes & Du, 2022).

The technological war between China and the US not only has an impact on the two superpowers but also affects the sustainable growth of the semiconductor sector worldwide. There are unprecedented risks in the sustainable development of the SSC as a result of the practical problems highlighted above, which not only lead to the semiconductor chip shortage in China but also affect the supply of chips in other countries (Zhang & Zhu, 2023).

On the other hand, the tensions between Russia and Ukraine have aggravated shortages in chip supply. The USA and Western Europe have enforced sanctions on Russia leading to additional disruption of supply chain networks, impacting demand, supply, and transportation (Kumar et al., 2024). The supply of raw materials such as noble gases from Ukrainian firms has reduced. They are an essential requirement for lasers in the photolithography process in chip production. For example, Ukraine acquires about half the global market share for neon, which is the most significant noble gas (Rapp & Moebert, 2022). Unfortunately, the invasion of Russia in 2014 has caused a sharp spike in the prices of noble gases. Palladium is another example of a critical raw material for chip manufacturing, whereby the U.S. sources 35% of palladium from Russia (Rapp & Moebert, 2022). Palladium is largely used to form multilayer metallization structures in microchips (Rapp & Moebert, 2022).

2.5. Manufacturing Complexity

2.5.1. Concept and Definition of Manufacturing Complexity

Manufacturing complexity involves the multiple levels of difficulties and intricacies in the manufacturing of goods, which affects the operational efficiency of a production system and its adaptability to demand fluctuations and product design changes. Complexity in manufacturing can be classified into two main aspects: process complexity and product complexity. Process complexity refers to the quantity and variations in operations, together with the relationships between different process steps in manufacturing whereby product complexity is linked to the differences in parts, modification, and the requirement for comprehensive specifications in modern products (Bozarth et al., 2009).

2.5.2. Manufacturing Complexity and Global Chip Supply

The design and manufacturing of semiconductor products is very complex. Producing a single chip takes up to 1400 process steps based on the complexity of the chip itself (Mohammad et al., 2022). The degree of complexity is also on the rise due to the elevated demands in terms of functions, size, and number of electronic devices (El Jamal et al., 2023).

During wafer fabrication, some of the steps are repeated hundreds of times which include etching, doping, oxidation, coating, and lithography. Therefore, on average, the manufacturing cycle time of a semiconductor can go up to a duration of 26 weeks. Around 12 weeks are needed for wafer fabrication alone, however, this might require as long as 20 weeks for advanced chips. The wafers are then sent to back-end manufacturing facilities for assembly, testing, and packaging which requires up to 6 weeks. Consequently, the lead time between the purchase order from the customer and final product delivery takes 26 weeks on average (Mohammad et al., 2022).

The design stage of semiconductors involves the contribution of EDA companies who provide sophisticated software and technical support to facilitate the design. State-of-the-art EDA tools are essential to design modern semiconductors that are competitive. Highly specialized semiconductor manufacturing and testing equipment are also provided for each process step in wafer fabrication by specific suppliers. Equipment for precise measurement and inspection is also critical for the manufacturing process of semiconductors. This is due to long manufacturing cycle times and hundreds of process steps involved and if any defects occur the entire build will be jeopardized (Wong et al., 2024). Therefore, the strict employment of specialized equipment for metrology and inspection processes at critical stages of semiconductor fabrication is vital to ensure high yields and prevent loss of output (El Jamal et al., 2023).

In the present semiconductor manufacturing environment, metrology is an essential element that helps to maintain the standards of quality and performance of products, which in turn ensures high yields of wafers. Metrology comprises multiple methods of measurement, various specifications and measurement units, tools and equipment for data collection, and process parameters inspection such as the functionality of products, thickness of the wafer, alignment accuracy, the composition of the material, and electrical characteristics (Orji et al., 2018). The market for equipment used for semiconductor measurement and inspection includes equipment for defect inspection of pattern and non-pattern wafers, mask inspection, 3D shapes, thickness of semiconductor film, overlay precision, and equipment for mask measurement. Process control is the most significant purpose of metrology in the manufacturing of semiconductors, and metrology also plays a key role in sustaining the profitability of the semiconductor industry (Orji et al., 2018). For example, more than a hundred pairs of layers are used in 3D NAND devices where the wafer structure is double stacked. Therefore, a combination of challenges such as high variation in topography, opacity of material, and wafer stress presents difficulties in measurement feasibility. On the other hand, the continuous evolution of dynamic random-access memory (DRAM) chip production towards smaller nodes of design, leads to more stringent specifications for overlay error (Maitra et al., 2024).

Nevertheless, the demand for high-performance electronic devices has not decreased. It is expected that future semiconductor processes, including advanced packaging, will be much more complex. With the reduction in size of devices and by becoming more 3D in shape, the requirement and significance of metrology in semiconductor production increases. Several products require measurement, testing, and inspection for more than 50% of the fabrication process steps (Maitra et al., 2024). Studies by Orji et al. (2018) state that the semiconductor industry is driving towards the goal of determining every atom's type and position within an electronic device, which further increasing manufacturing complexity. In some semiconductor product packaging, the degree of connectivity has increased more than 100 times within the last decade, and the minimum units of measurement are applied currently in sub-micron (Maitra et al., 2024). Hence, this particular trend of increasing density and complexity of systems is expected to proceed in the future, presenting crucial challenges in both the design and processing of semiconductor chips. The robustness and testing of semiconductor processes in the future is one of the most dominant issues (Maitra et al., 2024).

Multiple dies are used in most semiconductor devices, with a variety of functions such as micro-electro-mechanical systems (MEMS), units of logic, units of power, and a range of different sensors which are formed using numerous steps of manufacturing, which consequently demand unique testing requirements. Each component's testing procedures are distinctive, and the vast range of resources needed to cater to the testing capabilities may incur high costs (Maitra et al., 2024). Furthermore, the minute size of the interconnection pitch will also increase the risk of cost issues (Maitra et al., 2024).

Moreover, the structure of future testers to be used in future semiconductor manufacturing will have to be modular to comply with the testing requirements for a wide range of applications with significantly enhanced performance. Therefore, more innovation and technical reinforcements are needed in the present technologies of metrology, adding to the complexity of future chip production (Maitra et al., 2024).

Accomplishing the objective of the whole inspection of partially finished goods and finished products during the manufacturing of semiconductors requires excessive machines for metrology and may take significantly long periods. The semiconductor industry at present utilizes random sampling and inspection techniques to monitor and assure quality which greatly conserves the resources of companies. However, this approach does not always meet robust quality standards or ensure high yields of production. Sampling during distinct processing steps and measurement at individual metrology stations are part of the metrology methods used currently which also extend processing time unnecessarily (Maitra et al., 2024).

The integration of multiple components and subsystems with designated functionality into semiconductor manufacturing equipment also shows that the production of chips is highly complex. Hundreds of specialized vendors are involved in providing these parts and systems (Varas et al., 2021).

Apart from that, semiconductor manufacturing also requires specific raw materials for front-end and back-end processes that are procured from specialized materials. Materials such as polysilicon, photoresist, dopants, dry-etchants, and encapsulation resins are produced using advanced technology. For example, polysilicon is required to have ultra-refined purity levels (1000 times more than the purity level needed for solar panels) to be suitable for wafer fabrication and is mainly provided by only four firms globally, with a collective market share of above 90% (Varas et al., 2021). Additionally, semiconductor chips such as integrated circuits are fabricated in facilities that are highly specialized, known as cleanrooms, that are specifically designed to maintain sterile conditions to avoid contamination by pollutants in the air that could change the characteristics of the materials that form the electronic circuits at a nanoscopic scale (Varas et al., 2021).

Semiconductor manufacturing also requires a huge amount of capital, especially for wafer fabrication. Construction of a modern wafer fabrication facility requires approximately USD 20 billion of capital, comprising complex equipment, buildings, and land. Besides, huge sums of R&D investments are required to develop and fabricate high-precision semiconductor manufacturing equipment. Tools and equipment for lithography also account for one of the largest percentage of the capital expenditures which determines how advanced of a chip a facility can manufacture. For example, a single state-of-the-art EUV lithography machine from ASML can cost USD 175 million (Mohammad et al., 2022). Expanding production capacity is also costly and time-consuming which could take up to 9 months. This complexity in semiconductor manufacturing contributes to the semiconductor shortage (Mohammad et al., 2022).

2.6. Theoretical Framework

A thorough assessment of the relevant literature and identifying the research variables have led to the development of a theoretical framework. The framework was developed through detailed reviews of the literature and determining the knowledge gap of the variables of this study namely geographical concentration, geopolitical tension, manufacturing complexity of semiconductors, and global chip supply. The framework demonstrating the impact of geographical concentration, geopolitical tension and semiconductor manufacturing complexity on global chip supply is shown in Figure 2.1.

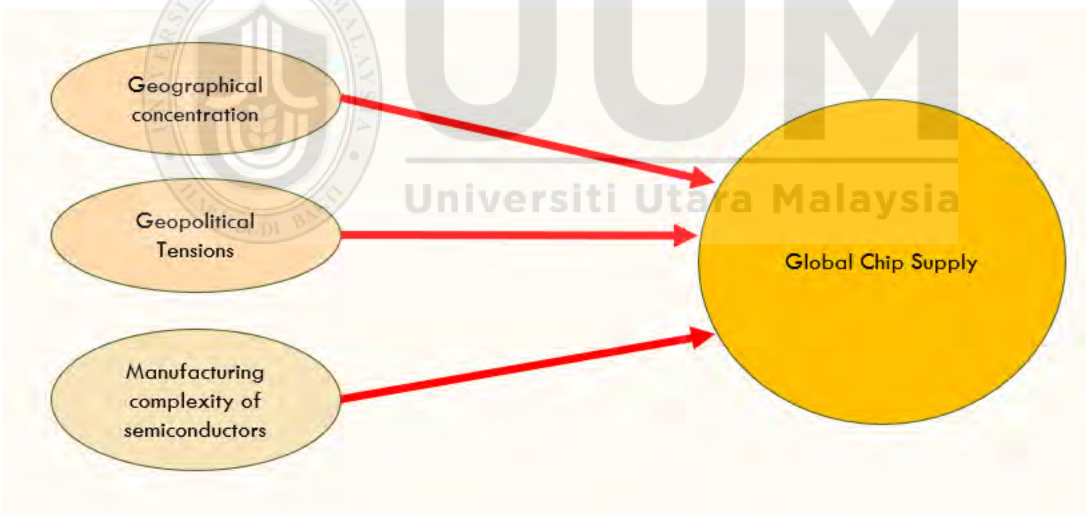

Figure 2.1 Theoretical Framework

2.7. Chapter Summary

The literature review on geographical concentration, geopolitical tension, and semiconductor manufacturing complexity has provided thoughtful and comprehensive knowledge on the past research of these variables, uncovering the gaps in the body of knowledge, in addition to improving the intellectual content of this study.

The geographical concentration of the SSC, geopolitical tensions, and the complexity of semiconductor chip manufacturing are identified as the most prominent factors that affect global chip supply. Therefore, they have been selected as the independent variables of this study as they are broadly documented in academic journals and semiconductor industry analysis reports, discussing their significant roles in forming a resilient and stable SSC.

CHAPTER 3

METHODOLOGY

3.1. Introduction

This chapter discussed the research methodology in detail, and the research design was identified. The first section of the methodology chapter includes research design. The following sections of this chapter describe the population of the study, sample size, sampling techniques, instrumentation of this study, data collection strategy, and data analysis strategy used in this research.

3.2. Research Design

Research design refers to an established framework that provides direction for data collection, measurement, and analysis. It acts as a foundation that ensures the problem statement of the study is addressed efficiently. A research design identifies the approach of determining the answer to the research questions, highlighting the specific methods, procedures, and instruments to be used while considering limitations such as resources and time. It ensures consistency between the research objectives and methods employed (Kothari & Garg, 2019).

The research design aims to give an organized framework as a reference to carrying out the research process efficiently and align the research objectives with suitable research methodologies. It functions as a guide for the collection of data, analysis, and data interpretation while validating the reliability of the research outcomes. The research design also makes sure that the selected methods correspond to the research questions, letting the approach be quantitative, qualitative, or mixed methods. It defines how data collection will be done, measured, and analyzed to provide answers to the research questions (Creswell & Creswell, 2023). In conjunction with the qualitative method to be employed in this study, the research questions were answered via data collection from interviews.

3.3. Population of Study

As discussed in the scope of the study, the research was conducted in Malaysia, a key player in the semiconductor industry. According to the Malaysia Semiconductor Industry Association, 590,000 Malaysians are employed by semiconductor manufacturers in Malaysia (Malaysia Semiconductor Industry Association, 2023). The industry contributes to 7% of Malaysia's Gross Domestic Product (GDP) (Malaysia Semiconductor Industry Association, 2023). Employees in the managerial roles of semiconductor companies are the target population of this study.

3.4. Sample Size

Qualitative research focuses on getting dense and comprehensive insights compared to producing statistically generalized results. Therefore, smaller sample sizes are selected, emphasizing the depth of details provided by the respondents. The selection of one vastly experienced and knowledgeable professional employee from each company will be able to ensure that the research incorporates different points of view across multiple organizations (Maarop, 2017).

In general, for interviews that are conducted individually, a sample size of 5 to 15 respondents is sufficient to get an adequate range of views and experiences, until the 'data saturation' level is achieved, whereby no important or new details are provided (Reid & Mash, 2014). The background and diversity of the interviewees have to be seriously taken into consideration, as it is essential to select key professionals who have the role and experience required to get an in-depth understanding of a whole scenario or issue (Reid & Mash, 2014). This research employed a sample of 3 respondents, which is lower than the minimum sample size of 5 specified by Reid & Mash (2014). A smaller number of respondents were interviewed mainly due to the highly specific criteria and the struggle to secure interviews with professionals in leadership roles in the semiconductor industry. Even though additional efforts were put into reaching potential respondents, several rejected the request to participate, and some were not able to dedicate their time for interviews due to tight schedules.

3.5. Sampling Techniques

An efficient technique of sampling includes steps that allow the researcher to make conclusions according to the sample measurement. It ought to generate outcomes that can be generalized to the whole population. The two important categories of sampling designs are probability sampling and non-probability sampling (Sekaran & Bougie, 2010).

In this research, employees in managerial roles of the semiconductor industry in Malaysia are chosen as the target population. The samples were selected from three multinational companies using purposive sampling. Purposive sampling is limited to a specific group of respondents who are the only ones who can provide the required details. They are expected to be knowledgeable, as they are experienced and may have the ability to provide reliable data to the researcher (Sekaran & Bougie, 2010).

Three different organizations were selected for this research that includes On Semiconductor (M) Sdn. Bhd., Silterra Sdn. Bhd., and Lam Research Sdn. Bhd. as they are strategically positioned in the global SSC. On Semiconductor (Malaysia) is part of the downstream of the SSC that specializes in device assembly, test and packaging which belongs to a multinational organization headquartered in the US known for its worldwide operations. Silterra is a wafer fabrication foundry based in Malaysia, which is a crucial stage of chip manufacturing. Lam Research is a subsidiary of a dominant corporation in the US that provides the technologies and tools needed to produce the equipment for wafer fabrication.

The incorporation of the three firms enabled the research to gain viewpoints across multiple stages of the SSC, providing a more detailed perspective of the bottlenecks and uncertainties impacting the semiconductor industry. Moreover, all three firms have international footprints, making them suitable to demonstrate the worldwide dimensions of the SSC.

The main criterion for respondents is that they must be in a leadership or managerial position at the organizations mentioned in Table 3.1. Secondly, they must have a strong educational background with at least a bachelor's degree. Thirdly, they must have broad experience in a role that is closely related to the SSC's operations to be able to provide reliable information.

Table 3.1 shows the details of the organizations and the data of purposive sampling.

Company Name	**No. of Employees**
On Semiconductor (M) Sdn. Bhd.	1
Silterra Sdn. Bhd.	1
Lam Research Sdn. Bhd.	1
Total	3

Table 3.1 Sampling fraction

3.6. Unit of Analysis

The person or object from which data is collected by the researcher is known as the unit of analysis. The queries of 'what' and 'who' are analyzed and answered by the unit of analysis. It comprises individuals, groups, organizations, geographical units, technologies, and objects that are the target of the study (Kumar, 2018).

The research aims to analyze the global chip supply as influenced by geographical concentration, geopolitical tension, and manufacturing complexity. Since the analysis of every company's perspective has to be performed to understand the impact of the independent variables on global chip supply, the unit of analysis employed in this research is the organization.

3.7. Instrumentation and Measurement of Variable

The study's main objective is global chip supply. Based on the research framework, the global chip supply is influenced by geographical concentration, geopolitical tension, and semiconductor manufacturing complexity. To perform a qualitative analysis, a list of interview questions was prepared. A total of 13 different questions were presented to the interviewees. The interview questions were structured in such a way that it began with getting to know the interviewees and their roles in the firms followed by revealing their perspective on the critical challenges affecting the global chip supply. Then each factor, namely geographical concentration, geopolitical tension, and semiconductor manufacturing complexity were diagnosed individually to understand their impact on global chip supply, impact on their respective companies, and ways to mitigate each of the challenges. The final two questions were about the best strategy to manage chip supply issues and future challenges of the SSC.

3.8. Data Collection

Sufficient data collection is a significant element in ensuring the reliability of research outcomes, as the researcher's results and inferences will be supported by this data. As a qualitative method was employed in this study, data collection was performed via interviews. Interviewing respondents is one of the methods of data collection to get information on a particular area of interest. An interview is an effective data collection strategy, particularly when the research is at the exploratory stage (Sekaran & Bougie, 2010).

3.8.1 Structured Interviews

Structured interviews are carried out when the type of information required is known. The interviewer prepared a list of prearranged questions to be directed to the respondents face-to-face, via telephone, or via personal computer. As the respondents answer the questions, the researcher takes notes. Every respondent will be asked the same questions in the same way. At times, however, depending on the situation, a researcher who is experienced may go a step further from the respondents' views and ask other related questions that are not on the list. By doing this, new insights may be determined, leading to a comprehensive grasp of the topic discussed. However, to identify a possible response, the interviewer must understand the objective of each question (Sekaran & Bougie, 2010).

After conducting a substantial number of structured interviews, sufficient information has been collected to understand and validate the significant variables, the researcher concludes the interviews. The details are then tabulated, and data analysis is performed. This enables the researcher to achieve his objective, which includes the description or quantification of the scenario, determining a particular issue, and the emergence of a theory of variables that affects the problem, or finding answers to the research objectives (Sekaran & Bougie, 2010).

3.8.1.1 Taking Notes

During interviews, the researcher should keep in mind that taking notes is a crucial step as the interview progresses, or right at the end of the interview. The researcher should not depend on memory due to inaccuracies. Moreover, if multiple interviews are planned in a day, more information will have to be collected, which increases the possibility of errors from recalling. Information derived from memory alone creates bias. The researcher can record the interview as long as the respondents do not object. However, recorded interviews might also create bias in responses as the respondents are aware that their voice or video is being recorded, which does not guarantee complete anonymity. Therefore, the researcher should ensure that the information obtained is free from bias (Sekaran & Bougie, 2010). Hence, before each interview, the respondents were briefed about the research's objectives, given confidentiality assurance, and reminded that their identity will not be revealed in any form. In addition, consent was given by the interviewees to record their voices only to reduce discomfort and maintain a certain level of anonymity.

3.9. Data Analysis Strategy

Data analysis is an organized approach of systematically performing data interpretation and synthesis to draw beneficial inputs and provide answers to the research questions. The objective is to determine the relationships between variables and trends to draw conclusions that are evidence-based (Taherdoost, 2020).

Qualitative data are deduced in terms of words. Notes taken during interviews, video recording transcriptions, and sharing product experiences online are some examples of qualitative data. Qualitative data can be obtained from a vast range of sources, which include individuals, organizational records, publications by the government, and online sources. The objective of qualitative data analysis is to justify the inferences made from the enormous amount of data collected (Sekaran & Bougie, 2010).

Qualitative data analysis is usually performed in three steps, comprising data reduction, data display, and the drawing of conclusions. Data reduction is the first step, which consists of data selection, coding and categorization of data. Data display is the second step, which refers to the presentation of data. Quotes selection and graphical illustrations may assist the researcher and the reader to better comprehend the data. By doing this, data displays lead to the drawing of conclusions based on trends of the reduced dataset (Sekaran & Bougie, 2010).

The data analysis sequence of this study is explained briefly in the following sections.

3.9.1 Data Reduction

Data collection via a qualitative approach generates enormous amounts of data. Therefore, data analysis will begin with data reduction via coding and categorization. Coding refers to an analytical step in which qualitative data that is collected by the researcher is simplified, reorganized, and integrated to construct a theory. The objective of coding is to assist the researcher in drawing purposeful conclusions regarding the data. Codes are identifications provided to text units that are transformed into categories. Coding is usually a repetitive process, where the researcher must refer to the data collected multiple times, to better comprehend the data, including pattern recognition, the link between data, and the coherent arrangement of data into categories.

The analytic process of qualitative data can be performed using different types of coding units, which include words (the smallest unit), sentences, paragraphs, and themes. The theme generally provides a much more beneficial context as it reflects on how an idea is expressed. Therefore, any size of text unit can be assigned a code as long as the text unit symbolizes a single theme or scenario.

On the other hand, categorization refers to the organization, arrangement, and classification of coding units. An inductive and deductive approach can be used to develop codes and categories. In case no theory can be identified, the researcher has to produce codes and categories empirically from the data, which is then known as grounded theory (Sekaran & Bougie, 2010).

Grounded theory is defined as a structured set of approaches to construct a theory that is inferentially derived from the data. The key aspects of grounded theory are theoretical sampling, coding, and consistently comparing the data. Theoretical sampling refers to the data collection steps that lead to the generation of theory, as the researcher collectively gathers, codes, and performs data analysis, and makes decisions on the type of data to be collected next and where to locate them, to develop his theory. Constant comparison refers to data comparison from one interview to another. When a theory has been deduced from this approach, it is then compared with findings from new data. In the event of contradiction between data (interviews) or between the theory developed and the data, modifications must be made to the categories and theories until they align with the data.

As the data is grouped into multiple themes or categories, trends or links between data can be identified. Therefore, during data analysis, there is a possibility of a shift in the list of categories. For example, new categories might be determined, descriptions of categories may be modified, or a detailed breakdown of categories into sub-categories may be done. This shows that qualitative data analysis is an iterative process (Sekaran & Bougie, 2010).

The data obtained via interviews were analyzed using an online tool, DELVE which was used to perform coding and thematic analysis. The interview transcripts were uploaded individually into DELVE, then codes were assigned to develop themes for each of the hypotheses to be tested.

3.9.2 Data Display

Data display refers to the second crucial process that a researcher has to perform during qualitative data analysis. Data display requires the reduced data to be well-organized and compact when displayed. Illustrative tools such as graphs, charts, diagrams, matrices, or drawings might assist the researcher in arranging the data in such a way that it is able to determine patterns and links between data to enable the deduction of conclusions (Sekaran & Bougie, 2010).

3.9.3 Drawing Conclusions

The drawing of conclusions is the last step in qualitative data analysis. This is where the researcher can answer his research questions by deducing the representation of identified themes, by providing explanations and clarifications for noticed trends and relationships, or via comparisons (Sekaran & Bougie, 2010).

3.10. Summary

This chapter has discussed the methodologies of this research, comprising the theoretical framework, hypotheses development, research design, population of the study, sample size, sampling techniques, the unit of analysis, instrumentation, measurement of variables, data collection, and data analysis strategy to answer the research questions. By employing the methodology stated above, the data analysis was performed and discussed in the following chapter.

CHAPTER 4

RESULTS

4.1. Introduction

This chapter shows the results of analysis of qualitative research data. The first section of this chapter describes the background of interviewees. Three best industry experts were identified to support the data collection of this research, due to their in-depth knowledge and vast experience in the semiconductor supply chain. All three interviewees are currently in a managerial role at their respective organizations. The second section illustrates the findings of data analysis via DELVE as mentioned in Chapter 3. Codes were identified and categorized into themes, and each theme is discussed based on supporting evidence extracted from the interview responses. The final section of this chapter summarizes the findings of the qualitative data analysis.

4.2 Background of Respondents

From the targeted companies mentioned in Chapter 3, three best industrial experts were selected as they were able to provide insightful perspectives about the SSC, and they met all the criteria set by the researcher. Table 4.1 shows the background of the respondents.

Interviewee	Company	Role	Location	Headquarters
Mr Sekaran	On Semiconductor	Senior Section Head (Supply Chain)	Senawang, Negeri Sembilan	Phoenix, Arizona, United States
Mr Mano	Silterra	Section Head (New Product Introduction)	Kulim, Kedah	Kulim, Kedah, Malaysia
Mr Bernard	Lam Research	Supply Line Business Manager	Batu Kawan, Penang	Fremont, California, United States

Table 4.1 Background of Respondents

The first respondent was Mr Sekaran from On Semiconductor Sdn, Bhd., a company that produces semiconductor products. He is a Senior Section Head of Supply Chain who oversees raw material supply and the warehouse operations of On Semiconductor. Mr Sekaran has served the semiconductor industry for more than 2 decades, having been in the supply chain role for the past 15 years.

The second respondent was Mr Mano from Silterra Malaysia which is a wafer fabrication facility located in Kulim, Kedah. Mr Mano is a Section Head of New Product Introduction (NPI), where he is responsible for addressing customer enquiries to understand process requirements, performing design verifications, followed by reticle purchasing, prototype development, product testing and delivery to customers for evaluation. After due assessment by the customer, the prototype will be transferred to the manufacturing department for mass production.

The third respondent was Mr Bernard from Lam Research which is also a wafer fabrication equipment facility located in Batu Kawan, Penang. Mr Bernard works as a Supply Line Business Manager whereby his role is to mainly focus on supplier performance. He works closely with the Supply Chain Commodity Manager to manage Lam Research's suppliers. Mr Bernard prioritizes supplier delivery performance while the commodity manager, on the other hand, focuses more on pricing and supplier contracts.

4.3 Critical Challenges in Global Chip Supply

A thematic analysis of the qualitative data was performed by assigning codes to excerpts of the interview using DELVE. This analysis emerged four different themes which resemble the categories of critical challenges that have an impact on global chip supply. Table 4.2 below shows the summary of themes and their corresponding codes.

Theme	Codes
Geopolitical Risks	Geopolitical tensions; Risk of trade wars; Effect of war on supply chain
Raw Material Supply Disruptions and Supply Chain Delays	Pandemic disruption; Risk of manufacturing shutdown; Demand volatility; Raw material shortage; Lead time extension
Rigidness of Supply Chain and Strict Compliance	Tight requalification standards and procedures; Stringent supplier change process
Impact on Business Operations and Financial Performance	Business sustainability risk; Production shutdown risk; Increased product cost

Table 4.2 Themes and Corresponding Codes on Critical Challenges in Global Chip Supply

4.3.1 Geopolitical Risks

Risks due to geopolitical tensions were one of the themes identified by the respondents. Mr Sekaran highlighted the concerns regarding tariffs and tensions between countries as the critical challenges affecting global chip supply. He added that the impact due to geopolitical tensions is gradual and provides adequate timeframe to counter the consequences, unlike the COVID-19 pandemic that instantly disrupted supply chains. On the other hand, Mr Bernard expressed his perspective which backed Mr Sekaran’s response, mentioning the risk of trade wars (US-China) and war between countries (Russia-Ukraine) as prime examples that can hamper global supply chains.

4.3.2 Raw material Supply Disruptions and Supply Chain Delays

Another major theme determined is disruptions in raw material supply and lead time extensions. Mr Sekaran pointed out the issue of copper supply shortage, a critical raw material needed for lead frame production that forms the base of chips. He further elaborated that On Semiconductor struggled to maintain its copper inventory due to longer lead times. He also highlighted that unprecedented fluctuations in customer demand jeopardized procurement strategies and material planning.

4.3.3 Rigidness of Supply Chain and Strict Compliance

Mr Mano representing Silterra emphasized the stringent specification for semiconductor products. He was deeply concerned about the difficulties changing suppliers due to the need to strictly comply with customer requirements. Any modification or changes in materials or vendors must go through multiple stages of screening and approval comprising, Material Review Board (MRB), Quality Review Board (QRB), and Technology Review Board (TRB) consent. Furthermore, process change requests must be formally informed to customers, whereby complete reassessment, reliability test, and customer conformance ought to be performed. This whole process might take years to complete.

4.3.4 Impact on Business Operations and Financial Performance

The final theme refers to the impact on business functions because of disruptions in supply. Mr Mano explained how the shortages in chips supply a direct consequence on production activities has, whereby in some cases manufacturing lines are shut down completely. He also stressed the fact that price of finished goods skyrockets due to shortage in chip supply, creating financial risks in companies and eventually challenging the long-term sustainability of business, workforce layoffs or ceasing of operations.

4.4 Geographical Concentration and Global Chip Supply

An analysis on the impact of geographical concentration on global chip supply has emerged one single theme which encapsulates multiple associated codes. Table 4.3 below shows the theme and its corresponding codes.

Theme	Codes
Risks of supplier concentration in a single region	Overreliance on China for raw material; Extended lead times; Natural disaster/pandemic induced disruption; Risk of securing material in advance; Risk of supplier shutdown in a single region; Competition for limited suppliers

Table 4.3 Theme and Corresponding Codes on Geographical Concentration and Global Chip Supply

4.4.1 Risks of Supplier Concentration in a Single Region

The interview respondents shared a similar point of view on the risks of geographical concentration of the semiconductor supply chain. All three interviewees stated that overdependence on a single country for raw materials critically affects the supply of chips worldwide especially in the event of crisis.

Mr Sekaran stated that On Semiconductor gets its copper supply from its suppliers in China, and when their operations are disrupted by natural disasters or pandemics, there will be significant delays in delivery of copper. He highlighted,

> *"Lead times initially promised at 3 months are stretched up to 6 months and even up to 1 year for unique products."*

The sole reliance on suppliers from China compelled On Semiconductor to acquire its copper supplies a year in advance, whereby demand uncertainties posed financial risks due to increase in inventory holding costs of material not utilized for manufacturing.

Likewise, Mr Mano cautioned that overly relying on one region is not an appropriate strategy. He mentioned, *"When a particular area is impacted by war or natural disaster, the impact is huge and may even result in the closure of a particular semiconductor company."*

He stated that suppliers closing their operations due to major crisis such as natural disasters had formerly affected Silterra's supply chain.

Mr Bernard also emphasized the overreliance of Lam Research on suppliers from China. He stated,

"Most of our suppliers are from China, whereby a lot of parts required by Lam Research is also supplied by firms from China."

He discussed the massive impact of the COVID-19 pandemic on Lam Research's operations, as China was affected first. Widespread lockdowns and transport restrictions around the globe limited Lam Research's access to materials whereby they were forced to compete for suppliers and struggled to satisfy customer demand.

4.5 Geopolitical Tensions and Global Chip Supply

An analysis on the impact of geopolitical tensions on global chip supply has emerged one single theme which encapsulates multiple associated codes. Table 4.4 below shows the theme and its corresponding codes.

Theme	Codes
Risks of geopolitical tension and trade war	US-China trade war; Impact of tariff on supply chain; Transfer of inventory between countries; Increase in holding costs due to shifting of inventory; Tariff induced raw material price hike; Drop in demand due to price imbalance; Impact of tariffs on suppliers; Minimum impact due to strong American presence

Table 4.4 Theme and Corresponding Codes on Geopolitical Tensions and Global Chip Supply

4.5.1 Risks of Geopolitical Tensions and Trade War

Geopolitical tension between countries and trade war also creates risk in the semiconductor supply chain, especially the political unrest between the United States and China. Based on the interview transcripts, it can be observed that the direct impact of these tensions differs on each organization, all respondents agreed that tariffs and trade restrictions could restructure the flow of global chip supply.

Mr Sekaran stated that On Semiconductor's existing routes of supply were affected by trade policies during President Trump's administration.

> *"Before Trump, the U.S. got chips directly from China. But during Trump's administration, trade restrictions forced On Semi Malaysia to produce and ship extra stock to cover for what couldn't come from the China plant anymore."*

He mentioned that tensions as such forced his organization to alter its trade routes by transferring inventory to plants in other countries, at the expense of increase in holding costs during demand fluctuations. He added,

"The transfer of inventory to other plants has caused an increase in holding costs."

Mr Mano explained the impact of tariffs on raw material price hikes, delaying new order placement by customers:

"Our customer may hold on to issuing POs or new orders till the price is stable."

This proves that the risks of geopolitical tensions disrupt semiconductor supply chains and also reduce market demand due to price instability.

Apart from that, Mr Bernard further elaborated that Lam Research was minimally affected due to its dominant position in the United States, having the privilege of tax exemptions. However, he specified that their suppliers who depend on firms from China are more vulnerable to the risks of trade wars:

"Some of our suppliers depend heavily on the China market which is subject to high tariffs. Therefore, the suppliers are still operating as normal for now, but the impact is on them."

This shows that the suppliers may face disruptions in the event of elevated tariff enforcements, caused by raw material price increase as also specified by Mr Mano.

4.6 Manufacturing Complexity and Global Chip Supply

Manufacturing complexity also leads to challenges in global chip supply, even though industry expert opinion varies. An analysis on the impact of manufacturing complexity on global chip supply has emerged a single theme which encapsulates multiple associated codes. Table 4.5 below shows the theme and its corresponding codes.

Theme	Codes
Tight customer compliance and manufacturing bottlenecks	Strict customer requirement; Changes in customer requirement; Quality, supply and sourcing concerns due to supplier relocation; Challenges in vendor requalification; Complex chips in military/medical; Mass production challenges of new products; Cycle time increase; Manufacturing shutdown due to electricity disruption; Delay in delivery due to non-conformance; Challenges in quality improvement

Table 4.5 Themes and Corresponding Codes on Manufacturing Complexity and Global Chip Supply

4.6.1 Tight Customer Compliance and Manufacturing Bottlenecks

Mr Sekaran recounted the significant challenges faced by On Semiconductor in complying with strict specifications of products expected by customers. He further described that even though qualification steps for new products are performed comprehensively, challenges emerge during mass production, which leads to extended lead times and eventually are unable to fulfill customer demand:

> *"These issues in manufacturing have caused delay in supply of chips to customers, and consequently unable to fulfill customer demand."*

He highlighted that increasing complexity of products, due to changes in customer needs and advancements in technology, has necessitated the requirement for continuous improvement efforts in quality of manufacturing. More sophisticated needs by customers increase complexity in chip design, which leads to difficulties in maintaining high quality standards.

Mr Mano from Silterra also shared his experience where manufacturing slowdowns often arise due to the unavailability of required parts or materials. He noted that power outages further lead to production shutdowns, rejection of products, and reassessment of tools prior to resuming production. He also acknowledged that highly complex chips come with stringent acceptance criteria which also makes it very profitable with high price margins. Therefore, the possibility of product reject is high due to tight specifications, in which non-compliance will extend delivery lead times:

> *"An increase in the complexity of chip design is good as it generates more ASP (average selling price), but it comes with certain risks where the supplier needs to meet tight acceptance criteria by our IQA (incoming) and OQA (outgoing). When materials are rejected due to non-acceptance, it will lead to a delay in delivery"*

On the contrary, Mr Bernard did not see the complexity of chip design as a critical issue for Lam Research. He elaborated that most of the firm's products already have complex specifications, and complexity only surfaces when there is a need for customization:

> *"For us, I don't think complexity of chip design is a big problem because a lot of our products that we manufacture for our customers, mostly have complex design all the while. Complexity arises only if there is a special customization demand from the customer"*

Nevertheless, Mr Bernard stated that the relocation of manufacturing facilities by suppliers leads to supply issues. This is because relocation disrupts the established vendor networks, and the suppliers are forced to seek unapproved vendors in a new region, that might not fulfill the required standards of quality. He continued:

"Apple to apple sourcing cannot be done and we won't get parts the way we actually want when we try to source locally."

4.7 Chapter Summary

Chapter 4 has provided a thematic analysis of three different responses from industry experts. With the help of DELVE, an online tool for coding and analysis of qualitative data, four key themes were identified that discussed the critical issues faced by the global chip supply chain. It can be summarized from the findings that the SSC is at a great risk and exposed to a combination of geographical, geopolitical and technical bottlenecks. Therefore, strategic mitigation steps are essential to overcome the impact of these risks on global chip supply.

CHAPTER 5

DISCUSSION AND RECOMMENDATION

5.1. Introduction

The findings from industry experts highlighted in Chapter 4 were analyzed and discussed in Chapter 5 to reveal the impact of geographical concentration, geopolitical tensions, and manufacturing complexity on global chip supply. The discussion also aligned with existing literature, thereby leading to purposeful conclusions. Recommendations were also provided to mitigate each critical challenge affecting the global chip supply.

5.2. Geographical Concentration and Global Chip Supply

Based on the response from the industry experts, it can be deduced that all three of them agree with the fact that geographical concentration increases the risk and vulnerability of the SSC, and therefore disrupts global chip supply. Mr Sekaran emphasized the supply disruptions of copper from China, an essential raw material required to produce its semiconductor products. He mentioned that when their suppliers in China are forced to shut down their operations, manufacturing of chips at On Semiconductor was delayed. Mr. Mano, representing Silterra, resonated with similar concerns and warned that single supplier dependence puts companies at greater risk of disruption. Mr. Bernard specified Lam Research's huge dependence on Chinese suppliers before the COVID-19 pandemic. During the pandemic, supplier concentration in China proved to be a huge blow for Lam Research's operations, whereby Lam was forced to relocate production capacities to other countries. He highlighted that the settling of the entire business operations in one region led to a single point of failure.

These findings align with the previous literature citing the impact of geographical concentration on global chip supply. As stated by Varas et al. (2021), the SSC is focused primarily on East Asian countries, whereby 75% of the world's wafer fabrication is done in Taiwan and South Korea, with back-end manufacturing mainly dominated by China. Kumar et al. (2024) also highlighted the risk of single points of failure due to heightened vulnerability towards natural disasters and pandemics. Furthermore, multiple disruptive events including the 2011 tsunami and earthquake in Japan, 2021 Texas cold waves, and the fire breakout at the Renesas facility in Japan further showcased the bottlenecks of concentrated manufacturing facilities in a single region (Hu et al., 2024)

Crucial raw materials required for semiconductor manufacturing such as silicon, germanium and noble gases are also geographically concentrated, thereby elevating the vulnerability of the SSC (Schnebele, 2023). For example, the C4F6 gas, a chemical critical for wafer fabrication is predominantly supplied by Japan, South Korea, and Russia (Varas et al., 2021). Chip manufacturing will be significantly delayed in the event of disruption in any of these regions.

5.2.1 Mitigation of Geographical Concentration

To mitigate the impact of geographical concentration on chip supply, all three organizations have taken the strategy of supply chain diversification. On Semiconductor ensures that its procurement team sources its raw materials from a few different regions to maintain a consistent supply to support its manufacturing plan if a single country or region is negatively impacted. On Semiconductor also qualifies at least 2 manufacturing plants for unique products to prevent supply breakdowns and fulfill customer demand. For example, On Semiconductor has a total of 7 qualified plants, 3 in China, 2 in the Philippines, and one each in Vietnam and Malaysia. Some of these plants produce products of the same specifications to mitigate the risk of disruption at a single site. This is due to the possibility of supply disruptions caused by natural disasters and global pandemics. It has also qualified a few suppliers who are able to supply the equipment required to support its manufacturing operations.

Silterra also qualifies more suppliers, and it does not depend on one or two suppliers for a particular product. Lam Research has also relocated all its manufacturing plants from China to other regions such as Malaysia, Korea, America, Mexico and India. Lam Research then prioritizes the strengthening of domestic supply chains. Each of the region will take an equal amount of manufacturing capacity. Therefore, the impact will not be as severe in the event of a disruption.

Mr Sekaran also specified that On Semiconductor continuously updates and reviews its Business Continuity Plan (BCP), to navigate through the impact of supplier concentration in a single region.

5.3 Geopolitical Tension and Global Chip Supply

A common stance on the impact of geopolitical tensions on global chip supply was expressed by the interviewees as they viewed it as a critical external threat. Mr. Sekaran explained how the enforcement of tariffs by President Trump necessitated On Semiconductor to restructure its supply chain routes and manufacturing had to be shifted from China to Malaysia as an alternative production site. This aligns with the view of Wong et al. (2024) whereby sanctions imposed on China's Semiconductor Manufacturing International Corporation (SMIC) and the banning of exports from ASML to China has hampered China's chip production. Disruption of global supply chains due to tensions induced export control on semiconductor production technologies and equipment was quoted by Tse et al. (2024) and Zhang and Zhu (2023). Mr Sekaran further mentioned that political unrest between countries often causes uncertainty in the long run, leading to spikes in inventory holding costs as firms store additional inventory as buffers to navigate through demand instability.

Mr Mano noted that the imposing of tariffs and geopolitical tensions directly affect the price of raw materials, which consequently delays their procurement. He noticed that customers hesitate to submit purchase orders during trade conflicts often waiting for the market to stabilize. Mr Bernard on the other hand had a contrary view due to Lam Research's protection from the direct effects of trade tensions at it is primarily based in the U.S. However, the implications of trade restrictions will be borne by suppliers, particularly those who heavily depend on China. He specified the ongoing tensions between US and China, and the Russia-Ukraine war can potentially disrupt supply chains via sanctions and tariffs. This corroborates with the view of Rapp and Moebert (2022), whereby the war between these two countries (Russia-Ukraine), has disrupted the supply of critical raw materials such as neon and palladium, that are required to produce semiconductor chips. Intervention by the Chinese government to impose restrictions through the licensing of the export of gallium and germanium, has further heightened the concerns of chip supply uncertainty (Mei et al., 2024). All these findings support the fact that geopolitical tensions negatively impact the global chip supply.

5.3.1 Mitigation of Geopolitical Tension

According to Mr Sekaran, government policies play a critical role in protecting the interests of the semiconductor industry by enabling foreign investments. He highlighted the Malaysian government's massive support for the semiconductor industry and the good relationship it maintains with the semiconductor organizations in Malaysia. He commended Malaysia's neutral approach with all the countries in the world to avoid biased relationships and to prevent any impact such as supply uncertainty. Therefore, Malaysia always maintains a good relationship with other countries especially with the two superpowers, the US and China. Mr Mano also shared the same view, as he stressed the importance of maintaining good relationships with all countries to avoid trade embargo and restriction on the sales of chips. He also suggested that improving the robustness and flexibility of domestic supply chains will reduce dependence on foreign countries. Mr Bernard on the other hand explained the significance of policy making, which he believes completely depends on the highest level of leadership of each country. Lam Research also urges its suppliers to diversify instead of relying on a single country or region.

5.4 Manufacturing Complexity and Global Chip Supply

Mr Sekaran discussed the increasing complexity of product specifications due to complex chip design driven by rapid changes in customer requirements. He added that customer specifications are stringent for complex product designs. Furthermore, unexpected issues arise frequently during mass production of new products, even though robust evaluation is done during the qualification stages of NPI, leading to delays in chip supply.

Mr Mano offered a similar view, stating that more complex chips must fulfill tighter requirements by Incoming Quality Assurance (IQA). Rejection of materials during the inspection by IQA causes delays in manufacturing and delivery of chips. In contrast, Mr Bernard dismissed production complexity as a major challenge. He explained that Lam Research is well equipped to produce complex chips, however challenges arise only when unique modifications are demanded by customers.

The findings substantiate with the observations of Mohammad et al. (2022), who discussed the complexities in semiconductor manufacturing, highlighting the requirement of lengthy production processes which take up to 26 weeks. Additionally, Orji et al. (2018) and El Jamal et al. (2023) stated the continuous reduction of size in semiconductor chips and multiple layer designs of chips elevate the complexity of manufacturing processes and requires unique measurement and inspection machinery that eventually leads to extended production lead times.

5.4.1 Mitigation of Manufacturing Complexity

On Semi's strategy to combat manufacturing complexity is by ensuring that the workforce in the factory is well trained and is completely aware of customer expectations and quality concerns. Therefore, On Semiconductor continuously urges its employees to learn new skills and strengthen the grasp of the manufacturing processes to support any improvement plan as required by customers. Furthermore, the hiring of skilled and experienced experts to lead specific business functions and drive product quality also helps On Semiconductor to navigate through production complexities. Moreover, the implementation of on-site six sigma programs by On Semiconductor, educates engineers on how to meet customer standards through six sigma.

Mr Mano emphasized the importance of efficient inventory management systems to prevent manufacturing bottlenecks due to parts or materials unavailability. Lam Research has access to highly capable vendors to fulfil their highly sophisticated manufacturing requirements and therefore maintains a good relationship with them as finding a similar alternative is extremely difficult.

5.5 Contribution of Study

This research has contributed theoretically by further clarifying and adding new knowledge to the limited availability of literature on the impact of geographical concentration of the SSC, geopolitical tensions and manufacturing complexity of semiconductors on global chip supply. This is because previous research has prioritized the economic and technical sides of the SSC, however only a few of them have explored the SSC's challenges and how it leads to shortages in chip supply. This study also further extends the pool of academic insights with the inclusion of a qualitative point of view gained from industrial experts from multiple stages of the supply chain, focusing on various types of disruptions in the SSC. Furthermore, the research findings corroborate with the recommendations of Sun and Rose (2015) to evaluate the complexities in chip manufacturing and supports the views of Mohammad et al. (2022) on the crucial challenges of the SSC.

From a practical perspective, firms within the SSC can utilize the findings to identify the key weaknesses across their respective supply chains. This research also provides information for policymakers and key stakeholders to enhance the resilience of the SSC. The results help to streamline decision-making at the corporate level, formulate robust policies, and design industry-wide planning in terms of risk management, thereby ensuring a highly secure ecosystem of chip supply that can meet the rapid growth in demand driven by technological developments.

5.6 Limitation of Study

The research was conducted with a smaller pool of respondents leading to a constrained amount of data generated to be analyzed. Only 3 experts from the semiconductor industry were willing to share their valuable insights due to difficulties in scheduling. Even though each interviewee had vast industrial experience, played a key role in their respective companies, and provided a detailed input, a bigger sample size may have revealed new viewpoints and experiences.

Secondly, all three respondents also belonged to semiconductor companies located in Malaysia, thereby not completely representing the key players in other regions such as Europe, South Korea or Taiwan. Although On Semiconductor (M) Sdn. Bhd., Silterra Sdn. Bhd., and Lam Research Sdn. Bhd. have international connections; the analysis of results mainly reveals insights based on a regional perspective. This geographical limitation may not have completely uncovered the worldwide differences of the SSC landscape.

Third, the research findings are based on contemporary issues faced by the SSC and present market conditions as when the interviews were conducted. The semiconductor industry continues to evolve rapidly. Development in technology such as AI, tensions between countries, trade wars and policy making can shift quickly which may minimize the research's applicability over time due to outdated findings.

Fourth, the research's industrial scope is narrow as the organizations selected are from specific stages of the SSC; front-end manufacturing, back-end manufacturing and equipment fabrication. This limited the participation of other critical stakeholders such as EDA firms, raw material suppliers, and downstream integrated device manufacturers. Consequently, this limited the findings' generalizability to the wider perspective of the SSC.

Fifth, limited access to employees in higher management level roles or decision-makers may have reduced the data's robustness due to lack of strategic insights. The viewpoints provided might not have completely captured corporate level actions and decision-making steps. Finally, the research also lacks a quantitative approach of data collection and analysis, that could provide statistical validation of the findings.

5.7 Recommendation for Future Research

Future research is recommended to incorporate a bigger sample size from multiple regions around the world to improve the robustness of the results. Moreover, respondents from diverse stages of the SSC, such as suppliers of logistics, raw materials and EDA engineers should be included that can provide a more comprehensive understanding of the challenges affecting global chip supply. Furthermore, future research methodologies may employ a mixed-method strategy whereby qualitative interviews are combined with quantitative surveys to enhance the credibility of the findings. The scope of the research can also be further extended to include other critical challenges affecting the SSC beyond geographical concentration, geopolitical tension and manufacturing complexity of semiconductors and also study the impact of upcoming technologies, like blockchain and AI, to strengthen the resilience of the SSC.

5.8 Conclusion

The research explored the crucial challenges affecting the SSC, in the context of rapid growth in semiconductor demand and chip supply uncertainty. Through detailed inputs from industry experts from On Semiconductor, Silterra and Lam Research, this study has demonstrated how geographical concentration, geopolitical tensions and manufacturing complexity threaten the supply of chips worldwide.

The research affirmed the views of semiconductor industry experts that geographical concentration poses a risk of single point of failure. Raw material supply and manufacturing are concentrated in a particular region or country whereby a disruption at one location can impact the worldwide network of chip supply. As the SSC is considered fragile, it is of utmost importance to diversify operations geographically, expand regional capacity, and improve the strength of domestic supply chains.

Next, geopolitical tensions also exacerbate the uncertainty of chip supply. From trade tensions between the US and China to cross-border restrictions of technology and semiconductor equipment have hampered the SSC. Apart from that, the research also points out the political unrest between Russia and Ukraine and Japan-South Korea conflict, that has disrupted the supply of critical raw materials such as neon and palladium. These conflicts raise unpredictability in the SSC and require robust government policies to protect the interest of the semiconductor industry.

Third, the manufacturing complexity of semiconductors also negatively impacts the SSC, as it poses difficulties for rapid scale-up and further extends lead times due to stringent specifications. A highly sophisticated chip manufacturing environment and strict requirements for testing and quality, shows that minor hiccups during production eventually leads to massive delays. This complexity necessitates the need for polishing the knowledge and skills to understand customer requirement and have in-depth understanding of manufacturing processes. Strengthening collaboration with suppliers to navigate complexity is also crucial.

In conclusion, the research offers a thorough analysis and discussion of the critical challenges within the SSC and their effect on global chip supply. A qualitative approach was essential, as the theoretical framework was validated with concise and detailed inputs from industry experts. The findings did not only contribute to the academic field but also provides a guideline for policy makers, strategic decision making, and international partnerships. As countries continue to strive to secure semiconductor supplies amidst rising demand, the findings of the study will also help firms to develop a risk management framework to build a more resilient SSC.

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APPENDIX

Interview 1: Mr Sekaran (On Semiconductor)

1. What is your role at your current organization, and please describe your experience in the semiconductor supply chain?

My name is Sekaran, and I work for On Semiconductor as a Senior Section Head of Supply Chain (in charge of raw material supply and warehouse operations). I have been in the semiconductor industry for the past 21 years. I was in a manufacturing role during my early days, but for the past 15 years, I have been in the supply chain role, specializing in material planning and warehouse operations. Based on my experience in the semiconductor industry for the past 2 decades, there have been fluctuations in chip demand due to economic shifts and disruptions such as COVID-19. The global pandemic was the major supply chain disruption for the semiconductor industry compared to other factors, where the company faced multiple uncertainties, such as factory shutdowns and supplier shutdowns. After the unprecedented event, many contingency plans were designed to mitigate the supply chain risks.

2. From your perspective, what are the critical issues affecting global chip supply?

Raw material supply for chip production is one of the critical issues. For example, On Semiconductor faces difficulties in copper supply, which is a raw material required to produce lead frames, which are the core bodies of the chips. An increase in prices, rapid changes in customer demand, supply shortages, and long supplier lead times are some of the critical issues affecting the global chip supply. Supplier lead times are extended from 3 months to 6 months and even up to 1 year. COVID-19 was a challenging situation that we did not expect, and the company was not prepared to encounter the risks brought by the global pandemic, whereby the global chip supply was greatly affected. Other issues include geopolitical tensions and political unrest, such as tariffs. However, there is sufficient time to mitigate the risks due to tensions between countries compared to disruptions such as COVID-19.

3. What is the impact of the geographical concentration of the semiconductor supply chain on global chip availability?

Raw material supply intended to support the chip manufacturing plan will be affected if a single country or region is affected, where it is unable to supply due to various reasons, such as natural disasters or global pandemics. This will reduce the availability of chips globally.

4. Has there been any impact on your supply chain due to a disruption in a single region or country?

We have experienced a shortage in copper supply due to disruptions at our supplier in China. Copper supply is also allocated more for other industries, such as the mobile phone industry, which also leads to limitations in the supply of copper. Therefore, there will be an increase in lead time for copper when the order is placed. For example, in the event of a disruption, lead times initially promised at 3 months are stretched up to 6 months and even up to 1 year for unique products. Consequently, we were not able to fulfill customer demand due to a copper supply shortage in the past. Therefore, On Semiconductor has to secure the material 1 year in advance. The semiconductor business is very volatile, whereby demand turnarounds are very common. In some cases, copper supply that is secured in advance will not be utilized for manufacturing due to a decrease in demand, which becomes a liability due to an increase in holding costs. Therefore, On Semiconductor has taken the approach of securing copper supply at an optimum level, to satisfy customer demand and at the same time avoid financial risks as a result of securing copper supply in advance.

5. What mitigation steps has your organization planned or taken to diversify its supply chain geographically?

On Semiconductor's mitigation step is to ensure that its procurement team sources its raw materials from a few different regions to maintain a consistent supply to support its manufacturing plan in the event that a single country or region is negatively impacted. This is due to the possibility of supply disruptions caused by natural disasters and global pandemic. Additionally, the Business Continuity Plan (BCP) will be continuously updated and reviewed by On Semiconductor. However, equipment purchase in the BCP will not be reviewed on a regular basis, as it entirely depends on the introduction of new products or a totally new technology. This is because On Semiconductor already has a well-equipped factory, which only requires minor modifications instead of major equipment purchases. We have also qualified a few suppliers who are able to supply the equipment to support our manufacturing operations. Our customers also require us to have more than one plant to supply the same product for them. In that case, On Semiconductor will qualify at least 2 plants for unique products to prevent supply breakdowns and fulfill customer demand. For example, On Semiconductor has a total of 7 plants, 3 in China, 2 in the Philippines, and one each in Vietnam and Malaysia. Some of these plants produce products of the same specifications to mitigate the risk of disruption at a single site. Customers also demand and challenge us to improve the BCP continuously.

6. How have the current geopolitical conflicts or trade wars impacted your sourcing of chips? Any delays or price fluctuations?

Geopolitical tensions between the two superpowers of the world are very common. After the inauguration of President Trump, new trade policies are being introduced and imposed. As far as the recent tariffs are concerned, we did not see any impact because it has not been fully implemented. However, we might have some disruption in the supply of chips after full implementation of the tariffs. Before Trump, the U.S. got chips directly from China. But during Trump's administration, trade restrictions forced On Semi Malaysia to produce and ship extra stock to cover for what couldn't come from the China plant anymore. Our corporate division will make decisions on how to deal with situations like these. Inventory will be shifted from one country to another to avoid risks due to geopolitical tensions. In the event of extreme fluctuations in demand, the transfer of inventory to other plants has caused an increase in holding costs.

7. What is your view on the importance of government policies to address global chip supply uncertainty?

Government policies play a huge role to protect the interests of the semiconductor industry by enabling foreign investments. From my point of view and based on my experience, the Malaysian government is very supportive towards the semiconductor industry and maintains a good relationship with the semiconductor organizations in Malaysia. Malaysia also practices a neutral approach with all the countries in the world to ensure there is no bias to any countries and to ensure that there is no impact such as supply uncertainty. Therefore, Malaysia always maintains a good relationship with other countries especially the two superpowers, the US and China.

8. What is the contingency plan if your company faces supply issues due to geopolitical risks in the semiconductor supply chain?

I have no experience in the design of contingency plan as it is mostly done by the corporate management.

9. What semiconductor manufacturing issues has your company encountered?

We are facing a lot of challenges in terms of manufacturing, mainly due to very stringent specifications and requirements from customers. Customers are expecting there should be no failures when our products are assembled or applied into their products. Apart from that, during the qualification of new products, a robust assessment is done, however there will still be some unsolved issues during mass production, which shows that there is still room for improvement. These issues in manufacturing has caused delay in supply of chips to customers, and consequently unable to fulfill customer demand. Furthermore, the continuous effort to improve product quality is also a challenge for us.

10. In your view, does the increase in complexity of chip design and manufacturing lead to supply uncertainty? How?

This complexity is led by the complexity of the current product design for the customer applications itself. Due to the continuous improvement in technology, customer requirements also changes together, and therefore leading to increase in product complexity. Consequently, our manufacturing department faces a lot of challenges to comply all the specifications of the complex product design and achieve high standards in terms of quality. Therefore, I agree that complexity contribute to major supply issue.

11. How does your company mitigate chip supply issues due to the manufacturing complexity of semiconductors?

On Semi's strategy is to ensure that the workforce in the factory is fully trained, and is fully aware of customer expectations and quality concerns. Therefore, we continuously advise our employees to learn new skills and get a deep understanding of the manufacturing processes to support any improvement plan as required by customers. Apart from that, at the corporate level we will hire an expert in each business function, to manage a particular department or product to drive product quality. Furthermore, we also have six sigma program in our factory, to train all our engineers on how to meet customer standards through six sigma.

12. In your experience, what is the best strategy that a company has taken to manage chip supply issues?

One of the best strategy we have implemented is by having a sales agreement or supply contract with our raw material supplier to ensure material is continuously supplied based on the demand forecast given. In the event the supplier is unable to fulfill the orders, therefore they are subject to a penalty to be paid to On Semi. This type of agreement or contract in the upstream and also downstream of the semiconductor supply chain will ensure consistent supply of chips in the future.

13. In the next 3-5 years, what would be the most critical challenge in the semiconductor supply chain?

In the automotive industry, technological changes are happening drastically. Currently, there are cars that run on petrol, battery and a combination of both. Investors are continuously looking for other alternatives for future automobile products. This is an ongoing process, which results in frequent changes in technological requirements, pushing a burden on semiconductor chip suppliers to keep up with the changes. Chip suppliers will face challenges in terms of demand forecasting, where to invest, and evaluation or qualification of new products to support their customers. This is a major challenge that we are already facing now, but this will be more critical in the next 3-5 years. Therefore, companies which are ready to handle this type of situations in the future, will lead the semiconductor industry. If the corporate division does not implement and execute any strategy to handle these challenges, the company will face difficulty to survive in the future.

Interview 2: Mr Mano (Silterra)

1. What is your role at your current organization, and please describe your experience in the semiconductor supply chain?

I am involved in NPI - New Product Introduction, where I am responsible for addressing all customers' enquiries in understanding the process requirement, carrying out design rules check, and once ok, proceed to reticle ordering, running prototype, test, and ship to customers for further evaluation. Once the device performance meets customer requirements, turn the prototype to production mode and hand it over to manufacturing for volume production.

2. From your perspective, what are the critical issues affecting global chip supply?

From my perspective, issues that may arise if there are disruptions to the global chip supply are as below:-

a. Cause the line to shut down if any chip or material is part of the finished product

b. Price increase in the finished product due to a shortage of chip supply

c. Company stream down their workforce or shut down as they are not able to sustain in biz.

d. Not able to go for 2nd supply as a lot of semiconductor companies are producing chips for military, aerospace, medical, etc, which requires stringent control. Any change of supply chain requires the following:-

i) Material Review Board (MRB) approval

ii) Quality Review Board (QRB) approval

iii) Technology Review Board (TRB) approval

iv) Process Change Intent Notification (PCIN), where the customer needs to be notified

v) Internal Process qualification

vi) Customer needs to redo device qualification, reliability test, end customer acceptance test, etc

All the above might even take years to complete.

3. What is the impact of the geographical concentration of the semiconductor supply chain on global chip availability?

Heavy reliance on a particular geographical concentration is not a good approach, as when a particular area is impacted by war or natural disaster, the impact is huge and may even result in the closure of a particular semiconductor company.

4. Has there been any impact on your supply chain due to a disruption in a single region or country?

Yes, due to several factors like a particular supplier ceasing operation, natural disaster, etc

5. What mitigation steps has your organization planned or taken to diversify its supply chain geographically?

We qualify more suppliers and do not rely on 1 or 2.

6. How have the current geopolitical conflicts or trade wars impacted your sourcing of chips? Any delays or price fluctuations?

Yes, an increase in tariffs or other reasons will cause the raw materials price to increase. As a result, our customer may hold on issuing POs or new orders till the price is stable.

7. What is your view on the importance of government policies to address global chip supply uncertainty?

It's very important for the government to have good relationships with all countries to avoid any trade embargo, restriction on selling chips of vital importance that are part of our process.

8. What is the contingency plan if your company faces supply issues due to geopolitical risks in the semiconductor supply chain?

Ensure all supply chains can be sourced domestically instead of relying on foreign countries as a source.

9. What semiconductor manufacturing issues has your company encountered?

Increase in cycle time due to the unavailability of parts, tools, and materials to run our production. Electricity disruption that causes line shutdown, product scrap, replacement of tool parts, requalifying the tools back to production mode, etc.

10. In your view, does the increase in complexity of chip design and manufacturing lead to supply uncertainty? How?

An increase in the complexity of chip design is good as it generates more ASP (average selling price), but it comes with certain risk where the supplier needs to meet tight acceptance criteria by our IQA (incoming OQA). When materials are rejected due to non-acceptance, it will lead to a delay in delivery.

11. How does your company mitigate chip supply issues due to the manufacturing complexity of semiconductors?

We have adequate backup inventories of materials and parts to ensure the line is not disrupted due to unavailability or waiting for parts and materials.

12. In your experience, what is the best strategy that a company has taken to manage chip supply issues?

Automation and the use of an inventory management system, where there will be a triggering point when supplies are below the critical level.

13. In the next 3-5 years, what would be the most critical challenge in the semiconductor supply chain?

Government policies change, ease of doing business, tariffs, and any other potential retaliation from supplying countries are imposed due to the government's stand on certain international issues.

Interview 3: Mr Bernard (Lam Research)

1) What is your role at your current organisation? And please describe your experience in the semiconductor supply chain.

Currently, I am working for Lam Research as a supply line business manager. My role is mainly to focus on supplier performance. My department focuses mainly on the commercial side of the business, especially on delivery. I also work closely with the supply chain commodity manager to manage suppliers. The commodity manager, on the other hand, focuses more on pricing and supplier contracts, whereas I will prioritize supplier delivery performance.

2) From your perspective, what are the critical issues that is affecting the global chip supply?

The main issue affecting global chip supply is the trade war. The potential of trade wars between two of the biggest economies, the US and China, continues to increase. This will hurt our supply chain. Apart from that, war between countries will have an impact on global chip supply, such as the Russia-Ukraine war.

3) What is the impact of geographical concentration of the semiconductor supply chain on global chip availability?

In recent years, most industries were focused in China regardless of medical or even other industries. Most of our suppliers are from China, whereby a lot of parts required by Lam Research is also supplied by firms from China. Tensions between countries may also induce potential tariffs, which may result in supply disruptions. Therefore, geographical concentration is not a good thing for the semiconductor supply chain.

4) Has there been any impact on your supply chain particularly due to a disruption in a single region or country?

Our supply chain was massively disrupted by the COVID-19 pandemic because China was the first country to be affected. Subsequently, a lot of governments around the world began to shut down business operations and imposed restrictions on moveability. We had to compete for suppliers with our competitors and our manufacturing was disrupted. We had to continuously fight for material allocation for our production. Orders have been committed to, therefore, it was a very difficult time for us to fulfil customer demand.

5) What mitigation steps has your organisation planned or taken to diversify its supply chain geographically?

Lam Research used to have a dominant presence in China. However due to the reasons I mentioned previously, we actually relocated all our manufacturing plants from China to other regions such as Malaysia, Korea, America, Mexico and India. We no longer have manufacturing sites in China anymore. We decided not to put all eggs in one basket, as we did before. Each of the region mentioned above will take an equal amount of manufacturing capacity. We have started to diversify by moving away from China. We also started to look for suppliers in other regions as we began to move away from China based suppliers and focus on localizing the supply chain. In Malaysia, we rely more on local suppliers. The same goes for our facilities in other regions such as India, Korea, Japan and the US. A lot of other companies are into diversification and prioritize local sourcing. Therefore the impact will not be as severe in the event of a disruption. These are the mitigation steps taken to diversify our supply chain geographically.

6) How have the current geopolitical conflicts or trade wars impacted your sourcing of chips? Was there any delay or price fluctuations?

There is less impact of geopolitical conflicts or trade wars on Lam Research. However, there is more impact due to this on our suppliers. Since we have a huge presence in America, therefore most of our products are not very affected by the trade wars. We will be exempted from a lot of tariffs, but on the other hand, our suppliers will have to bare the impact of tariffs to supply their products/parts to us. This is because some of our suppliers depend heavily on China market which is subject to high tariffs. Since the tariffs have not been fully implemented we have not felt the impact yet. Therefore, the suppliers are still operating as normal for now.

7) What is your view on the importance of government policies to address global chip supply uncertainty?

Different countries have different policies on how to address trade tariffs. It is completely out of our control because we can't dictate the direction of policy making in each country. Policy making in most countries is also mostly influenced by the action of the US government. Therefore, government policies may help to address global chip supply uncertainty however it completely depends on the leaders of each country. Hence, we can just say that it helps a lot, but we can't dictate how the US government or government of other countries are going to operate in future.

8) What is the contingency plan if your company faces supply issues due to geopolitical risks in the semiconductor supply chain?

Since the geopolitical risks affect some of our suppliers, we advise them to diversify their market, instead of depending on a single country as they have all this while. This is a challenge, as the changes cannot be done overnight, therefore we are guiding our suppliers to navigate through. We also have the capability to offload production plan to our manufacturers in other countries due to our diversified manufacturing options, in the event of disruptions caused by tensions between countries. We also have multiple plants producing the same type of product for our customers.

9) What semiconductor manufacturing issues has your company encountered?

Due to the global supply chain requirement, some of our suppliers have moved their plants to different regions. Consequently, they will be disconnected from their usual vendors and sources which results in quality and supply issues of their products. This is one of the main issues that we are working on. This is a common issue when our suppliers diversify or relocate to a different region, whereby new vendors are unable to meet the required standards and specifications. They also find it difficult to find a proper replacement for their existing vendors. Apple to apple sourcing cannot be done and we won't get parts the way we actually want when we try to source locally.

10) In your view, does the increase in complexity of chip design and manufacturing lead to supply uncertainty? Now.

For us, I don't think it's a big problem because a lot of our products that we manufacture for our customers, mostly have complex design all the while. Complexity arises only if there is like a special customization demand from the customer. Other than that, we do not face issues due to complexity in chip design. Based on my experience, the most complex chips are used in the medical industry because it involves human lives. Apart from that, chips used for military applications are also very complex. A lot of our customers are actually from the semiconductor industry itself and therefore we do not face this issue.

11) How does your company mitigate chip supply issues due to the manufacturing complexity of semiconductors?

For now we do have a list of suppliers who can handle very high technology request or support high-tech manufacturing. If we do not have options, or if we don't find better options, we will stick to our original supplier even if they are located very far away. Because it is very hard to find a replacement for the kind of supplier that can support our needs. But if the supplier belongs to a Tier 2 or Tier 3 category which is replaceable, then yes, we will probably go for local sourcing and that's how the strategy works.

12) In your experience, what is the best strategy that the company has taken to manage chip supply issues?

Supplier diversification regardless of which tier the supplier is. All of them should be diversified. You shouldn't rely on a single source, especially for key components. For every single tier, we have a few hundred suppliers. Geographical diversification will also help, because when you go for different regions, you will start to look for local suppliers and you start to develop your supplier or grow your supplier towards that capability. So that is some of the strategy that we are implementing. Probability if we see that the supplier has this potential that we can actually get along with this supplier, but are not up to the standard required yet, we will go there and help them to improve. Diversify your supplies and diversify your manufacturing location. We categorise our suppliers. So based on the category, we will determine the kind of effort that we are going to put to develop them.

13) In the next three to five years, what would be the most critical challenge in the semiconductor supply chain?

So the first thing that came to my mind is trade wars. In the event of any potential trade war, no matter how well you prepare, you will still have an impact. No matter how big or how small the trade war is, it will still have an effect on the semiconductor supply chain. The second thing is unprecedented events like COVID that will also potentially affect the supply chain and also unpredictability. Another challenge is on the supply versus demand and also how we keep up with technology development. That is also one of the challenges as well.