Review of the Effect of COVID-19 on the American Semiconductor Industry Supply Chain

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Abstract

COVID-19 has had an immense impact on supply chains, both globally and locally. The semiconductor industry has been especially hit by the challenges COVID-19 has presented to supply chains because of how globalized and lean the industry has become over time. Recently the semiconductor industry has been focusing its efforts on reducing inventory and outsourcing to keep costs low. Although proven financially successful, these methods have also led to a supply chain that is prone to risk. The supply chain has an inherent risk because of the high level of scrutinization that is required to qualify a company as a supplier. This has led to companies only being able to rely on a few suppliers for key components. In addition to risks that were already present in the industry, COVID-19 has also decreased the industry's revenue, closed borders, and shut down factories and plants. This paper aims to study the effects of COVID-19 on the semiconductor industry and analyze the reactions and results that different companies have experienced through case studies.

Keywords
Semiconductor, Supply Chain, COVID-19, Outsourcing, Qualification

1. Introduction
Since the beginning of 2020, COVID-19 has had an immense impact on the world, affecting almost every person and every company and industry. The onset of this major pandemic decimated many global supply chains and brought many companies under. The tech industry saw some of the most significant changes due to stay-at-home legislative ordinances that sparked a boost in telecommunications demand. The semiconductor industry is an integral component of all technology and experienced a considerable hit from the pandemic due to the level of globalization its supply chain has reached. With much of semiconductor material and manufacturing being done overseas, semiconductor companies in the United States of America had to take on and adapt to increased costs, lead times, and a shortage of supplies while keeping up with consumer demand.

The objective of this paper is to assess multiple American semiconductor companies varying in size in order to gather information and make industry-specific conclusions. With limited information available due to how recently the pandemic began, it is essential to analyze the impacts and reactions the American semiconductor industry experienced in order to understand the current state further and discover trends. In this study, the company size was determined by each company's respective annual revenue in 2019. This metric was used to determine size because it is indicative of how much product the company sells and, in turn, how much material they purchase and use every year. The amount of material a company goes through determines its level in the supply chain. Case studies were conducted during the week of October 12th, 2020, by hosting Zoom Meeting interviews with company stakeholders. The stakeholders were chosen based on our access to industry connections and the size of the company they work for. Each stakeholder was asked a series of questions, and their responses were documented.

2. Literature Review
Semiconductors have become increasingly popular in the 21st century, as they provide a crucial component for nearly all electronic devices. Semiconductors can be assembled in the form of diodes, transistors, and integrated circuits,

which are all devices that have wide-reaching applications in nearly every industry. The popularity of semiconductors can be attributed to their low cost, high reliability, reliant power efficiency, and ability to handle a wide range of voltages. As they are one of the most vital elements in electronic systems today, we can expect to see semiconductors used at a high frequency well into the future (Batra et al., 2018).

The semiconductor supply chain extends from the material manufacturers to the final customers, with a wide array of consumers and producers in between. The semiconductor manufacturing process starts with the collection of a semiconducting material (a material that is neither great at conducting or insulating). The most common material used is silicon, as it is easy to acquire in the form of sand along with its ability to induce an electric current through a process called doping. In the most intricate and important part of the manufacturing process, silicon wafer crystals are turned into semiconductor chips through the fabrication process (Semiconductor, 2020). The end product is most commonly an integrated circuit (I.C.) that consists of billions of capacitors and resistors. This process can take anywhere from 4-16 weeks, as the chips must be treated with the utmost level of care and caution. After the manufacturing process is completed, finished I.C.s are sent out to be further assembled and tested. With such a long and variable production process, this step of the supply chain can often lead to delays and disruptions for producers and consumers up the ladder (Kohls et al., 2020).

The majority of the semiconductor fabrication and manufacturing processes detailed above occur in China, European Union, Japan, Korea, and Taiwan; however, the United States of America has over 50% of the global market share of semiconductor production (United States Department of Commerce, 2016). This is because the American semiconductor industry currently relies heavily on outsourcing raw materials and labor. As of 2015, 48% of semiconductor manufacturing from American companies was outsourced, and this number has only grown in recent years (Yinug, 2015). Outsourcing to overseas companies is a method American companies have been using since the 1960s to reduce overhead costs. A variety of factors contribute to the lower cost associated with manufacturing offshore. They are primarily the following: significantly cheaper labor, land, rent, and taxes; less stringent government regulations; and higher automation levels. Asia, namely China and Japan, is the United States' main target for offshoring semiconductor manufacturing and, in turn, reducing overhead costs. In fact, from 1984 to 2004, the share of semiconductor sales in Asia and Japan rose from 38 to 63%, which shows how prevalent the trending of offshoring is. At this point, all three steps of the wafer manufacturing process (assembly, fabrication, and design) are predominantly outsourced. In 2003, all of the top 10 semiconductor contractors, accounting for 70% of total contracting revenue that year, were all based out of Asia (Brown & Linden, 2005). Although proven to be fiscally successful, there are also a variety of disadvantages to offshoring and outsourcing.

One disadvantage specific to outsourcing is the extensive vendor qualification process. Company outsourcing materials and components must prove to their customer that this change in supplier will not significantly affect the quality of the following steps in the process and the resulting end product. This qualification process varies from company to company, dependent upon their size, customers, and reputation. The typical supplier qualification steps include determining supplier expectations and selection criteria, qualification of the selected supplier through samples and data, testing and inspection of supplies used in manufacturing, repeated inspection, and customers' approval (SCILLC, 2019).

A study conducted by Zhang et al. (2003) determined that the top three selection criteria for suppliers are price, quality, and delivery. The manufacturing of semiconductors requires a high level of control at all steps within the process. Reliability and quality control are crucial for a manufacturer to maintain to produce a product at the level of quality required by its customers. International industry standards for quality management, such as ISO 9000 certification, currently exist (Procurement Strategy Council, 2006). Many companies ensure that they are compliant with these standards to gain a competitive advantage against other manufacturers by gaining credibility of the process and product quality. In addition to the product's quality, some companies select suppliers based on the cost of the product.

The supplier qualification process may last between six months to a year due to the amount of testing and verification of components at multiple steps in the manufacturing process. The extended duration that a supplier qualification process takes must be accounted for by a company when planning production and reaching desired lead times (SCILLC, 2010). Companies must review their processes and conduct a cost-benefit analysis to determine which manufacturing steps can benefit from outsourcing.

In addition to the qualification process, another disadvantage of outsourcing is that it makes the supply chain much more susceptible to geopolitical factors that limit the flow of goods from Asia to the United States. These geopolitical factors are most visible between the United States and China. Technological dominance is the driving force in the power struggle between the United States and China. Trade restrictions and penalties inhibiting the sharing of technology between China and the United States of America have put their common ground of Taiwan into a complicated geopolitical situation. Taiwan is the United States of America and China's main source for manufacturing silicon components. If the two nations were to disassociate completely, Taiwan might have to decide which nation to trade with (Kirk, 2020). The escalating tension between the United States of America and China may also threaten the global supply chain and be detrimental to the semiconductor industry. Restrictions being put into place for geopolitical reasons have the potential to bring down the global supply chain, causing economic loss and even slowing some technological advancements (P.R. Newswire, 2020).

Conversely, this strain between the two nations is forcing United States of America technology supply chains to evolve and have less dependence on China by increasing production of United States of America manufactured semiconductor components (FitchRatings, 2020). Increasing domestic production could raise costs while also giving the United States of America control over the entire supply chain. Domestically manufacturing semiconductor components could limit any potential geopolitical risks that could arise.

In August of 2020, the United States government banned semiconductor chips' sale to the Chinese multinational corporation Huawei. There were many unprecedented consequences in a move that was seen as a push for American consumer safety. Specifically, the action banned the sale of any semiconductor company (domestic or foreign) from selling a chip that was manufactured with U.S. technology or software. Not only did the ban prohibit U.S. companies from selling to Huawei, but it also prohibited American companies from selling chips to foreign entities that did business with Huawei. John Neuffer, President of Semiconductor Industry Association, detailed how Chinese chip sales were the driving force in the American semiconductor industry. He describes how the ban could negatively affect the American economy along with slowing industry progress and innovation (Pham, 2020). While this paper does not further delve into the effects of the ban, it is important to consider how the semiconductor industry's active state could be attributed to both COVID-19 and the Huawei ban.

Due to the globally distributed supply chain and the extensive qualification process, COVID-19 has had an immense impact on the semiconductor industry's supply chain both globally and within the United States. To understand the pandemic's impact, KPMG surveyed 22 senior executives and board members from global semiconductor companies. More than 2/3rds of the companies surveyed said that they "have experienced supply chain shortages due to COVID-19" (Clark & Jones, 2020). Of the companies that replied that they had experienced supply chain shortages as a result of the pandemic, half responded that these supply chain shortages had impacted their sales. Therefore, it can be concluded that the pandemic has significantly affected the supply chain of the global semiconductor industry and has also had a massive financial impact on the industry. According to Accenture's review of the semiconductor industry during COVID-19, the revenue projection and annual growth projection for the semiconductor industry had both dropped (Accenture, 2020). This information, coupled with companies replying to KPMG that COVID-19 supply shortages have affected their order fulfillment, shows the extent of the fiscal impact it has had on the semiconductor industry. In addition to fiscal impact, the consumer demand for the industry has also been impacted.

The demand for major semiconductor components has seen significant shifts due to the COVID-19 pandemic. As a whole, the semiconductor industry faced a decline of 5-15% compared to the previous year. However, when broken down into different markets, the demand shifts varied depending upon the market. Some markets faced a steep decline, while others saw a gain in their market demand. Due to the delay of planned hardware upgrades and other long-term mitigation projects, the personal computer (P.C.) market in the semiconductor industry could decline to 9% in 2020. Conversely, the semiconductor market for servers could see an increase in demand of up to 7% through late 2020 due to the increase in video conferencing and streaming (Bauer et al., 2020). Wired communication could also increase demand by up to 11% due to various factors like higher internet traffic, the rise in video streaming, and more security upgrades. For the semiconductors utilized in wireless communication, demand could fall up to 26%. Mobile phone sales contribute most to this decrease in demand since sales notoriously align with the GDP. Less expensive phones are also anticipated to be the focus of consumers, which negatively impacts the semiconductor industry as well.

Similarly, consumer electronics demand is expected to drop up to 12%, as consumers' purchasing habits are aligned with the GDP. The change in demand that COVID-19 also inspired manufacturing efforts to change among semiconductor companies. There was a general trend in shifting manufacturing focus away from future development (i.e., 5G) and towards older or legacy products (Perlow, 2020). The curtailment of personal expenses on technology caused many tech companies to hold on to their legacy products for a much more extended period than expected. The severity of the impact and change in demand forced companies to react promptly and make company-wide changes for the long and short-term.

The semiconductor industry has frequently utilized Crisis-management and safety stock strategies in the past. However, the abrupt onset of COVID-19 introduced an entirely new form of crisis that most of the industry could not have predicted or prepared for ahead of time. It forced quick and strategic reactions from all of the semiconductor industry. During the pandemic, semiconductor companies have focused their efforts on protecting employees, securing supply chains, and addressing other pressing concerns. In general, common reactions were reducing capital expenditures and sending most employees to work from home (Clark & Jones, 2020). Companies have been stockpiling funds and inventory if they experience a sharp decrease in revenue during this time of crisis. Besides, companies have started to diversify their supply chains to break dependencies on specific countries. A common practice in the industry is single-source supplying. This proved to be a risky practice with the onset of COVID-19 when suppliers were unable to produce, therefore, severing single-sourced supply chains. Companies are now pushing away from single source supplying and towards qualifying new suppliers in multiple geographic areas to broaden their supply chains. In addition to adding sources for supply, companies are moving their manufacturing facilities to other countries to create a more geographically flexible supply chain. It is predicted that around 200 companies in the U.S. plan to move their manufacturing base from China to India post the general elections (Bombe, 2020). They have also started to explore alternative revenue streams in case of large shutdowns and decreases in demand. They have also expanded their demand forecasting efforts and investment in smart manufacturing capabilities (Accenture, 2020).

3. Methodology

In order to understand the effect of COVID-19 on the semiconductor industry, we acquired data through the collection of case studies. We decided to utilize case studies because they can help detect trends across industries, provide qualitative and quantitative data, and compare responses between companies. Case studies are also a valuable form of primary source data; coming from the source, we can ensure quality and accurate data. To compare the data, we drafted up a series of questions that were distributed in interview style to each company representative. Companies varying in employee size, revenue, and level of supply chain were targeted to ensure diversification in the responses. The questions remained precisely the same from stakeholder to stakeholder, but they were encouraged to share and explain as much information as possible. In total, four case studies from different sized American semiconductor companies were compiled; they can be found below.

4. Data Collection

Case Study A:

Company A is a small American hardware company that was founded and is currently based in Southern California. Company A focuses on finding solutions for broadband communications applications through the use of mixed-signal semiconductors and highly integrated radio frequency (R.F.) devices. The company has a worldwide reach, as it actively operates research and development centers in the US, Israel, China, and India. Company A is located near the top of the semiconductor supply chain, as they get their semiconductor chips manufactured from foundries all over Asia. Their biggest supplier has its main foundries in Taiwan and Singapore.

The onset of COVID-19 has had a fairly large impact on Company A. The shutdown of China's border led to factories closing/limiting production, an increase in shipping costs, and additional capacity constraints. For Company A, they felt the effects of this through extended lead times and shortages of supplies. Orders were often fulfilled to only 50% of expected, which is still causing problems for the company today. In May and June of 2020 specifically, Company A often had to wait an additional eight weeks to receive their orders. This has had a significant impact on their capacity handling, as they are going to lack the desired inventory for the next 6-8 months. Company A has also had to combat the issue of increased demand during COVID-19. As more people are working from home, there is a higher demand for internet modems and tech products, causing demand to skyrocket. The company will not be able to fulfil the increase in demand, which will undoubtedly impact their future sales and growth.

In response to COVID-19, Company A was able to find part-time solutions. Their first thought was to utilize the safety stock held by the company, but the quantity was not sufficient to last them through the pandemic. Company A had to find additional suppliers to fulfill their inventory requirements. This is a long process that usually takes 3-6 months, as the suppliers have to prove reliable and have sufficient product. Company A will take advantage of their new suppliers and actually begin to move forward with them in the future. Having additional suppliers will allow them to negotiate to price, use more leveraging, and outsource all their inventory items.

Case Study B:

Company B is a small manufacturing company for the semiconductor industry headquartered in Oregon. They are key manufacturers and suppliers of high-purity Silicon Carbide (SiC) Ceramics, Chemical Mechanical Polishing (CMP) Slurries**,** and Extreme Ultraviolet Lithography (EUV) Blanks. Company B sells its products to chip fabricators located all around the world and source raw materials exclusively from Japanese distributors who source from China. Company B is high up in the global supply chain because it sources from Japan and sells their products to fabricators in the semiconductor industry globally.

COVID-19 affected Company B, but not drastically. The biggest impact the company experienced was a massive increase in the freight cost. The abrupt ban on flights from China to America caused the freight cost of deliveries to triple. Although ordering costs skyrocketed, causing company revenue to decrease, Company B never experienced an increase in lead time. Other factors contributing minute changes in lead time were based on the company's buying patterns. As a company, they buy materials in blanket orders with scheduled receive dates. These blanket orders were placed months in advance and were honored by suppliers despite the strike of the pandemic. This allowed them to continue providing to their customers as per usual. COVID-19 caused shortages in personal protection equipment (PPE; face masks/shields, sanitizing supplies, etc.) but not in raw materials for Company B. Besides minimal shortage in HPW (highly purified water), Company B saw little to no effect on procurement of the raw materials necessary for their manufacturing. The shortage in PPE was a hassle for the company but did not prevent orders from being fulfilled. In terms of change in market demand, Company B experienced significant change both from a supplier and customer point of view. As a supplier, Company B saw a decline in demand from their automotive customers and in next-generation products. In direct correlation to next-generation product demand decreasing, an increase in demand for legacy products (older product versions) was noticed. Also, Company B saw an overall demand increase due to the steep increase in telecommunication and cloud computing demand caused by the shift to at-home working.

The onset of COVID-19 was unpredictable, abrupt, and motivated quick company-wide action for Company B. As a company, material, process, and vendor requirements were reevaluated. Historically, single sourcing for materials was practiced. However, once factories were shut down and the shortage was experienced globally, second, third, and even fourth source suppliers were pursued in an attempt to broaden the existing supply chain and keep up with demand. These measures have not proven successful yet, due to the extensive qualification requirements for adding new suppliers. On average, it takes Company B around six to twelve months to qualify new company suppliers, so they have not officially added all of the vendors they desire. However, consolidation is nearly achieved and is predicted to be very successful in the following few months. In addition, a pandemic response and preparedness plan were created and implemented that includes a large increase in safety stock (up to 4 months) for all raw materials as well as a requirement to keep all of the added vendors as a means of keeping their supply chain broadened. The challenge Company B expects to face in the future is fulfilling supplier buying requirements to keep the newly added vendors as official suppliers.

Case Study C:

Company C is a large semiconductor company based in Silicon Valley. Company C employs over 110K people and is the world's largest and highest-valued chip manufacturer by revenue. In the semiconductor industry in the United States, Company C's processes are often used as a benchmark for other companies to compare their quality and processes to. Company C is located towards the top of the semiconductor supply chain and produces many products for the biggest names in computer system manufacturers such as Apple, Lenovo, H.P., and Dell.

Pre-COVID-19, Company C sourced 100% of its materials from outside the United States of America**.** The majority of the components came from China, with Taiwan supplying the second most. This proved to be a considerable risk

for Company C as at the beginning of the global pandemic, everything in China shut down for two weeks. This contributed to a supply chain analyst at Company C answering the question "how severely has COVID affected your company's supply chain on a scale of 1-10", with an 8. Company C saw a shortage from its component suppliers in Asia. The shortage was the worst between March and May of 2020. Fortunately for Company C, lead times from suppliers were not affected too drastically, although it did vary from company to company. The most typical lead time change from Company C's suppliers was a 2-3 week increase that was attributed to shortages, freight shipping changes, and a restructuring of the supply chain. In addition to COVID-19 impacting Company C's suppliers, it also affected the demand for what Company C produced. Overall the company experienced a 30% decrease in demand. However, the solid-state drive (SSD) group had an increase in demand for serial advanced technology attachments (SATA). Legacy products increased in demand while development halted. Company C wants to extend its legacy products longer due to higher inventory to sell more.

Company C has done a lot in response to the global pandemic to make its supply chain and company more resilient. One effort to make their supply chain hardier to pandemic and geopolitical factors is qualifying suppliers in the United States of America. Qualifying a supplier in the semiconductor industry is a lengthy and expensive process, so companies typically will avoid doing this unless absolutely necessary. All companies were allowed to bid to be qualified, but Company C was highly selective due to the requirements for qualifying a new supplier. Additionally, Company C has a high inventory hold to ensure products are available. Overall, companies have understood the lack of variety that they are currently able to supply. These short-term changes will have long term effects on Company C's supply chain. If a supplier is qualified, they will place orders from them at least every six months to ensure they stay qualified. Company C will also continue to order from these newly qualified suppliers in the long term because it is such an expensive process to qualify suppliers in the first place.

Case Study D:

Company D is an American semiconductor company with over nine thousand employees. The company is headquartered in Southern California, where they manufacture semiconductors for use in radio frequency and mobile communication. Company D's primary goal is to empower the wireless network revolution by innovating high-performance analog semiconductors. Assembling 10 million multi-chip modules per day and testing and shipping 20 million products per day, Company D utilizes its various manufacturing locations in California, Massachusetts, Japan, Singapore, and Baja California. Being a global organization, Company D has an impressive supply chain network. The company employs a tier-one supply chain, spanning 17 countries with 20 subcontracted product facilities and 131 finished goods materials suppliers.

The height of the Covid-19 pandemic hit in spring, impacting Company D only moderately. Seeing as their slow season is after Christmas, Company D was able to consume the remainder of their inventory. However, with the implementation of the lock-down period, the company's supply chain was at risk since shipping lanes were either shut down or severely restricted. The pandemic also brought significant material shortages and increased lead times along with it. Many components were in very short supply due to the implementation of hoarding strategies from future uncertainty and manufacturers wanting as much supply in their inventory as possible. On average, lead times increased from 50-100% on typical components and finished good products due to a combination of factors. Factories being required to run at a reduced capacity, and international border restrictions slowed down transportation and logistics. Additionally, the change in demand and ordering patterns also led to an increase in overall lead times. Older legacy products saw an increase in demand, while high-end product demand slowed. Products in support of working from home, remote learning, and telemedicine also saw a significant increase in demand.

Fortunately for Company D, they had a decent amount of safety stock during the onset of COVID-19. This acted as a buffer from the company running out of supply completely so that end products could still be produced. Nevertheless, Company D had to take action in response to the pandemic and make specific changes. The company swiftly ramped up orders with alternate suppliers, as their manufacturing strategy is to source components from multiple providers. This choice in strategy is not generally highly regarded by hi-tech customers, as it requires them to spend time and resources qualifying additional vendors. However, with the pandemic well underway, all customers agreed to this strategy to ensure the receipt of their supply.

Many changes that were introduced to mitigate issues brought on from the pandemic may be implemented in the long term since customers are now demanding a secure and stable supply. Previously the Company D business model was

designed with 80% of daily volume to be manufactured in-house with only 20% offshore. With the onset of COVID-19, it was observed that a single supplier's factory could severely impact the entire business. Thus, Company D has altered its original business plan to expand its offshore manufacturing footprint so that more than 20% of their end products are built at various offshore locations. By diversifying their supply chain, they hope to reduce the risk of factory shutdowns hindering their ability to achieve revenue targets.

5. Results and Discussion

5.1 Case Study Results

Table 1 summarizes the numeric data collected from each case study. The summary is broken into six major categories, including each case study's respective impact rating, lead time increase, raw material shortage, transportation fee increase, the shift in overall demand, and order fulfillment failure. The cells containing non-numeric values indicate that the interviewee could not provide specific quantitative data, only qualitative.

Table 1: Summary of Case Study Results

Company	Impact Rating	Lead Time Increase	Raw Material Shortage	Transportation Fee Increase	Shift in Overall Demand	Order Fulfillment Failure
A	5/10	8 weeks	6-8 Months	Yes	Sharp Increase	50%
B	3/10	No	No	Triple	Increase	No
C	8/10	2-3 weeks	Yes	Yes	30% Decrease	Yes
D	4/10	50-100%	Yes	Yes	Increase	No

Table 2: Summary of Impact Experienced per Case Study

	Company A	Company B	Company C	Company D
Impact Rating (1: No impact to 10: Company-wide failure)	5	3	8	4
Lead Time Increase	X		X	X
Raw Material Shortage	X		X	X
Shift in Overall Demand	Increase	Increase	Decrease	Increase
Transportation Fee Increase	X	X	X	
Order Fulfillment Failure	X		X	

Table 2 summarizes the level of impact each case study experienced and how the impact was measured. The table is effective for quickly and easily analyzing similarities and differences in how COVID-19 impacted each company. As seen above, all but company B experienced lead time increase and raw material shortage. Also, all but company D

experienced transportation fee increases. It is important to note that only half of the four companies experienced failure in order fulfillment despite the heavy impact.

Table 3: Summary of Reactions per Case Study

	Company A	Company B	Company C	Company D
Utilization of Safety Stock	X			X
Addition of Overseas Suppliers	X	X	X	X
Addition of U.S. Suppliers			X	X
Reevaluation of Supplier Requirements*		X		
Pandemic Response and Preparedness Plan		X		

Table 3 summarizes the actions each company took in response to the pandemic. This table is useful for quickly and easily analyzing similarities and differences in how companies reacted to COVID-19. As seen above, 100% of the companies reacted by adding overseas suppliers while only half added suppliers to the United States of America. Only half of the companies utilized safety stock, and only company B started developing a pandemic response plan and reevaluated its supplier requirements for qualification.

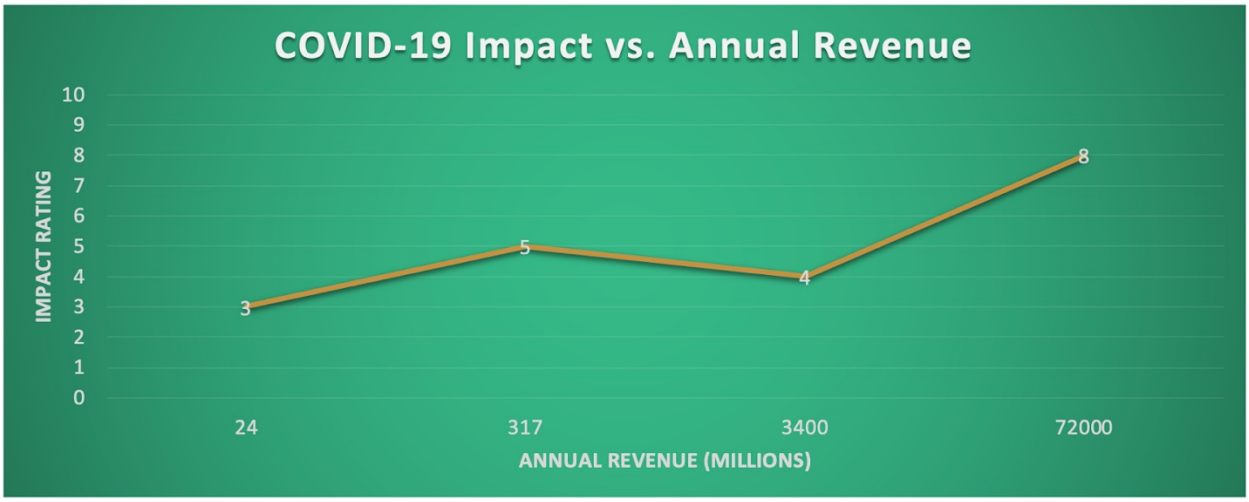

Figure 1: COVID-19 Impact Rating vs. Annual Revenue

Figure 1 shows a relationship between the level of impact and annual revenue. As seen above, the rating out of ten that each company assigned to the level of impact they experienced increased as the company's size increased. Although there were only four data points, this general trend is critical to consider because it shows that bigger companies are more susceptible to broader impacts from supply chain disruptions.

5.2 Validation

To validate our study, we compared our data findings to the results found in similar studies conducted by KPMG and Accenture.

A KPMG study determined that 63% of companies surveyed said their companies had had supply chain shortages (Clark, 2020). Our case studies had ¾ or 75% responded that they experienced supply chain shortages. An Accenture study proposed that the industry could expect a decrease in demand (Accenture, 2020). This was not resonated in our case study findings, with 75% of companies saying they experienced an increase in overall demand. The KMPG study found a common reaction to increasing the quantity and diversity of their suppliers (Clark, 2020), which was fortified by all four of the companies in our case study.

Due to the pandemic's recency, there is not an abundance of studies and to compare our results with. However, based on the studies we were able to compare with, we noticed similarities indicative of our study being significant.

6. Conclusion

In analyzing the report's results section, we can see that all research objectives have been met. We successfully assessed a variety of different sized American semiconductor companies to pinpoint industry-specific COVID-19 impacts and responses. To ensure accuracy and reliability in our findings, we acquired data through the collection of case studies. The case studies proved to be very beneficial in detecting American semiconductor companies' trends, providing qualitative and quantitative data, and comparing responses between companies. We were able to determine some commonalities between companies in their response to COVID-19, such as qualifying additional suppliers and pursuing in-house fabrication. We also quantified the pandemic's impact on each respective company and noticed a positive correlation between company size and level of impact. While most companies endured increased lead times and transportation costs, there was no significant impact on their ability to meet the shift in market demand.

In comparing our case study results with findings from our literature review, we found several similarities. The study conducted by KPMG detailed a similar percentage of companies that reported an increase in lead times and a general shortage of supplies. Another similarity we found was an expectation of the industry to trend towards diversifying and adding more suppliers, which is precisely what all of our case studies found. On the other hand, our early research indicated that we could see a decrease in demand; however, three out of the four companies that we interviewed mentioned they saw an increase in demand. To reiterate, we found that our academic literature research found mixed results relating to our data findings. This can potentially be explained by the broader nature of the studies conducted by these third-party companies.

Due to our research's minimal reach, it is important to expand upon this research to get the most accurate understanding of COVID-19's impact on the semiconductor industry. To further develop our study, we suggest expanding upon the case studies within this paper. This can be done by interviewing an increased variety of stakeholders at the companies. By interviewing more employees, the researchers can better understand which departments of a company were affected the most by this pandemic. It is important to note that since the COVID-19 pandemic is still going on globally, this study did not get to observe the long-term effects of the actions put in place by the companies. Expanding the study's time period would allow for the level of success from company reactions to be assessed and measured. There is also room for additional case studies that span a wider range of company size and level in the supply chain. The study would be more comprehensive of the industry if the case studies were extended past American companies to include overseas companies. These metrics would provide improvements and the most effective reactions to be suggested for future severe disturbances in the industry's supply chain.

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Biographies

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Jacob Hrbek is an Industrial and Manufacturing Engineering (IME) student at Cal Poly. Besides pursuing a B.S. in Industrial Engineering, he is also pursuing an M.S. in Engineering Management. Jacob was born and raised in Tarrytown, NY, where his passion for engineering began.

Malia Hickey is an Industrial and Manufacturing Engineering (IME) student at Cal Poly. Malia was born and raised in Kauai, Hawaii, where she enjoyed going to the beach and spending time outdoors. Malia originally began pursuing a degree in Computer Engineering but found her passion for problem-solving and efficiency aligned with Industrial Engineering.

Trevor Howell is an Industrial and Manufacturing Engineering (IME) student at Cal Poly. He is currently pursuing his bachelor's degree and plans to graduate in the Spring of 2021. He was born and raised on the Central Coast of California in San Luis Obispo, where he now is attending college. He has been recognized as Vice President of Cal Poly Systems Optimization Club, where he manages the outreach and acquisition of engineering consulting projects that are offered to fellow Cal Poly Industrial Engineers to prepare students for their professional careers. His interests include construction management, process engineering, automation, logistics planning, and supply chain management.

Natali Markowitz is an Industrial and Manufacturing Engineering (IME) student at Cal Poly. Besides pursuing her undergraduate degree in Industrial Engineering, she is currently working towards her M.S. in Engineering Management. Natali was born and raised in South Florida and chose to move to the west coast to get her engineering degree through Cal Poly's "Learn by Doing" methodology. Natali has always had a passion for problem solving and efficiency, making Industrial Engineering a perfect fit. Her interests and professional goals include consulting, project management, process improvement, and supply chain and logistics management.

Mohamed Awwad is an Assistant Professor in the Department of Industrial and Manufacturing Engineering at California Polytechnic State University (Cal Poly), San Luis Obispo, CA. He received his Ph.D. and M.S. degrees in Industrial Engineering from the University of Central Florida, Orlando, FL, USA. Additionally, he holds M.S. and B.S. degrees in Mechanical Engineering from Cairo University, Egypt. Before joining Cal Poly, San Luis Obispo, Dr. Awwad held several teaching and research positions at the State University of New York at Buffalo (SUNY Buffalo), the University of Missouri, Florida Polytechnic University, and the University of Central Florida. His research and teaching interests include applied operations research, logistics & supply chain, blockchain technology, distribution center design, unconventional logistics systems design, and OR applications in healthcare and the military.