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CONFRONTING TECHNOLOGY'S GREATEST CRISIS: GLOBAL CHIP SHORTAGE

DESIGN OF AN INNOVATIVE NEW SUPPLY CHAIN

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Declaro, bajo mi responsabilidad, que el Proyecto presentado con el título Confronting technology's greatest crisis: global chip shortage.

Design of an innovative new supply chain

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

This research project will present the microchip industry, the causes of its shortage crisis, and the only feasible solution under the title "Confronting technology's greatest crisis: Global chip shortage. Design of an innovative new supply chain."

Today, mankind must deal with one of the greatest technology crises of its existence. With continuously growing demand, the microchip industry has become extremely challenging in terms of technology requirements and demand satisfaction. This project will allow the reader to have a better understanding of the industry operations, the causes of the current global shortage, and the possible solution. It will explore the design of an innovative and new supply chain that would solve the global shortage in a short-medium term. This new supply chain must be realistic, feasible and profitable for the stakeholders that will take part in.

1 INTRODUCTION

The current globalized world we live in is completely surrounded by technology that makes our lives easier. Today, everyone's life strongly depends on electronic devices such as smartphones, laptops, TVs among others. Besides, not only us, end-consumers, have a strong dependency on electronic devices, in almost every industry from automotive to industrial currently electronic devices play a crucial role in machinery, equipment, vehicles, fabs, and many other elements that also use technology and electronic devices to work.

Every electronic device, technological, and data operation have something in common, Microchips. Microchips are behind every digital item since they support the operations and storage of digital information. Since microchips have become more and more relevant, the industry has developed extremely sophisticated and complex techniques to make these microchips smaller and more powerful. The microchip industry has become the most complex and most important industry in the current technological world which has a strong influence on every other industry, and basically, on the global world's functionality.

However, the industry is today suffering from a critical situation known as Global Chip Shortage that is impeding the microchip supply causing devastating effects not only for industry players but also for many other industries that strongly depend on microchips. The chip shortage is, therefore, the current global greatest crisis and must be solved as soon as possible or the negative effects could become irreversible.

Thus, the main objective of this project is first, to explore, understand and analyze the industry and every stakeholder in the supply chain to develop the right industry scope. Second, use all the information gathered to determine and expose the main causes of the global chip shortage. Finally, study the possible solutions and carry out an action plan for the most suitable solution to the shortage.

This solution must confront the global chip shortage in a way that the supply can meet the demand in the short-medium term, being realistic, feasible, and economically profitable for all stakeholders taking part in its development.

2 MICROCHIP INDUSTRY OVERVIEW

2.1 MICROCHIP BACKGROUND

Microchips are considered the most advanced and complex niche within an enormous industry: The Semiconductor Industry. To better understand microchips and their industry, it is crucial to start from the beginning of semiconductors and their evolution towards today.

The semiconductor industry can be traced back to the invention of the transistor, the first semiconductor device, in 1947. A transistor is a device used to amplify or switch electrical signals and power. It is made of a semiconductor material, silicon. Transistors revolutionized the consumer electronics industry in 1954 with the radio transistor, the first small portable radio receiver. Radio transistors became rapidly very popular thanks to prosperity post-WWII and the growing popularity of Rock’n’roll. Along with radio transistors, in 1954 was also developed the first programming language named Fortran, a very primitive not-binary programming language, the father of current programming languages, and crucial in the development of electronic devices.

These two inventions were the preceding of modern electronic devices and hence, the semiconductor explosion. The semiconductor industry grew rapidly exceeding the scale of 100 million dollars by 1957, but the industry exploded in the 1960s with the arrival of the so-called microchips, or technically, integrated circuit (IC). An IC is a set of electronic circuits on a small chip also made of silicon. Being much faster, smaller, and thinner, the IC was widely used in a variety of electric appliances becoming one of the basic requirements for informatics systems. [1]

Since the IC launch, the chip industry grew at an alarming rate due to two main reasons: technological advances, and new fields of application.

Firstly, regarding technological advances, integrated circuit developments produced more and more powerful chips by increasing the number of transistors inside each chip. This growth can be dimensioned by what Gordon Moore, co-founder of Intel Corporation, said in his well-known Moore’s Law back in 1965: “the number of transistors in a dense integrated circuit (IC) doubles about every two years". Moore's law is based on empirical observations of a historical trend as is shown below:

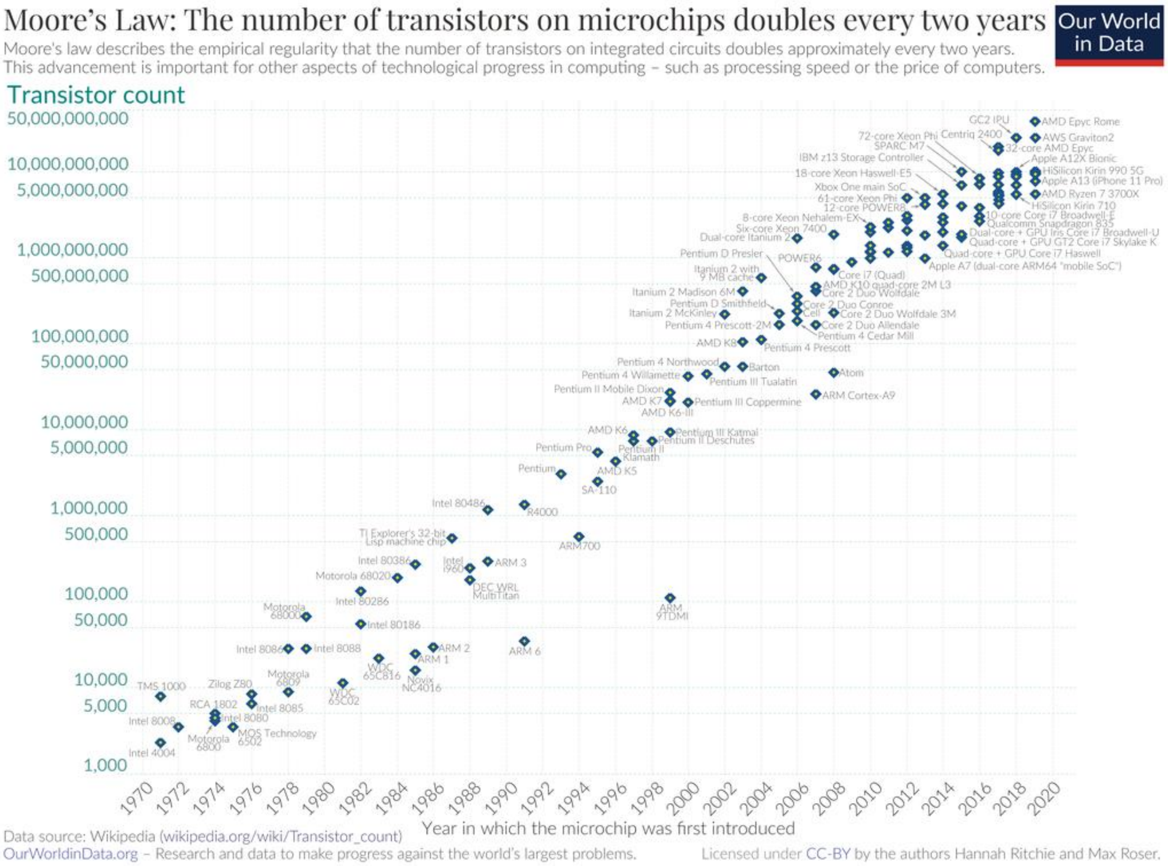


Figure 1 Moore's Law

Moore's prediction has been accomplished in the semiconductor industry until today when we are reaching physical boundaries of development. Thus, just because of technological improvements the demand for semiconductors (transistors) has increased at an annual compound growth rate of 41%. The technological advances have allowed microchips to develop from initial chips such as Intel's first commercial microprocessor chip known as the 4004 (2300 transistors) to current ones such as Intel´s Tukwila chip which contains more than 2 billion transistors and has 500,000 times as many power as 4004. Thus, the microchip industry has become one of the most advanced and complex industries in the world. For comparison, a current transistor size is 10 nanometers while a human blood cell is 7000 nanometers in diameter or a virus 14 nanometers. [2]

Secondly, as microchips progressed toward high performance and multiple functions, their field of application expanded broadly. These improvements in chip technology caused the arrival of a new world of electronic devices driven by the commonly known as the Third Industrial Revolution. The revolution began in the 1970s, it is based on the new information and communication technologies, as well as the development of renewable energies.

One of the key elements of this revolution is the personal computer (PC). Computers had already been developed since 1936, however, it wasn't until 1971 when John Blankenbaker invented what is considered the first personal computer named Kenbak-1. Ten years later, a whole new market appeared, changing our way of life forever. Companies such as IBM or a brand-new Apple started a fierce war developing their first personal computers in a technological race. PCs were just the beginning of a revolution that led to the current electronic and digital world we live in.

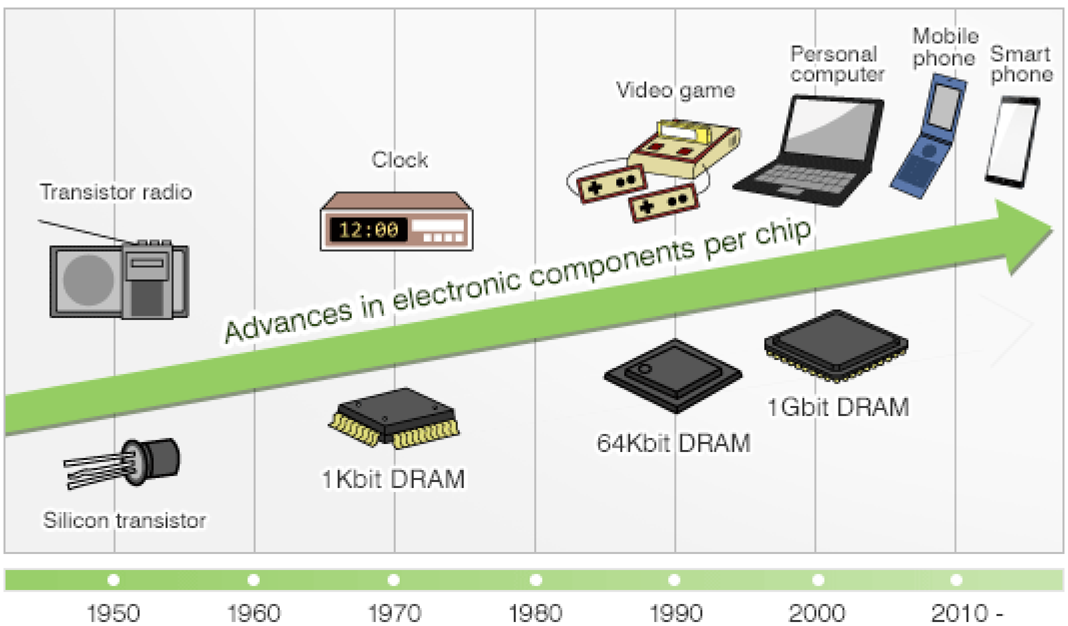


Figure 2 Advances in electronic components per chip throughout decades

This technological war has only increased in the last four decades. Today almost any item in every industry contains electronic devices. From smartphones, and computers, to vehicles, medical equipment, or furniture. Every industry you can think of has some dependency on electronic devices and therefore, ICs. Microchips are now used in every corner of our society and support everyday life.

2.2 GLOBAL MICROCHIP MARKET

The global microchip industry is one of the largest and most powerful markets. This section is divided into three parts: market size, competitive landscape, and product mix.

2.2.1 Market Size

Looking at the demand, the global microchip market has been growing extremely fast in recent years. As mentioned in the previous section, technological advances and increased use allowed the market to expand rapidly.

In 1987 global industry revenues were just $33B while in 2021 sales were $553B. Revenues are expected to increase at a high rate in the following years. In 2022, the global market is projected to post moderate growth of 8.8% to reach $601.5 billion in annual sales. [3]

The graphs below represent the demand variation throughout the years. The area shows the global revenues since 1987. The line shows the global growth rate by year.

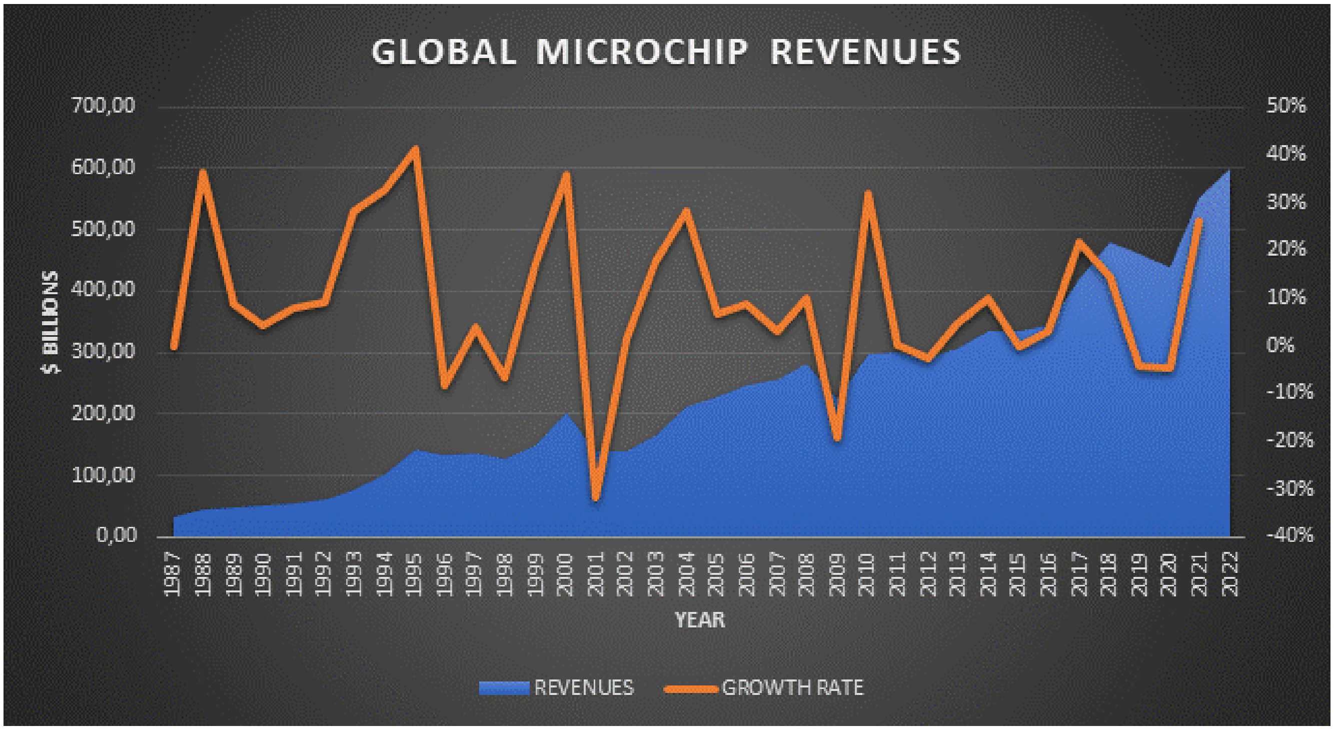


Figure 3 Global Microchip Revenue

Analyzing these graphs one can notice that from the 1990s to the 2000s the microchip expansion was astonishing. On average, the revenue growth rate was over 16%. As expected, this growth rate did not keep that pace for the 2000s reducing to 5% annually. However, since 2010, especially in recent years, the microchip market has experimented a second boom thanks to smartphones, web and online services such as social media (Twitter, Facebook…) or media platforms (Netflix, HBO, Dazn…), and cryptocurrency mining. [4]

2.2.2 Competitive Landscape

The largest companies that operate with microchips are in total 79 which have an approximated market cap of $4500 trillion. This number could be more impressive if one compares this industry to others. For instance, the automotive industry just has a global market cap of $2500 trillion. Besides, looking into the largest companies by market cap in the world, there are two (TSCM & NVIDIA) in the top 10 and five in the top 40 (Samsung, ASML, Broadcom).

AS the table below shows there are very large companies in the microchip industry. It is important to point out that not every company on this list operates in the same way. Thus, companies such as Samsung are mainly B2C businesses, so their revenues do not come from selling microchips themselves but from devices that include microchips (computers, smartphones). However, NVIDIA, Intel, or AMD are B2B companies whose revenues indeed come from microchip sales and others such as TSMC, Qualcomm, or Applied Materials are suppliers. These differences will be deeply analyzed in **Chapter 2: Microchip Supply Chain.**

Hence, the top 10 companies in the microchip industry are the following [5]:

NAME	MARKET CAP ($B)	COUNTRY	OPERATIONS
TSMC	642.44	TAIWAN	Taiwan Semiconductor Manufacturing Co. is one of the world's largest dedicated independent pure-play semiconductor foundries. They only fabricate integrated circuits and do not have design capabilities.
NVIDIA	619.28	USA	Nvidia is best known for its line of consumer and high-end video graphics cards found in computers. These GPUs are popular among computer gamers, digital artists and the company also received a boost in business from crypto mining, where GPUs have been found to be more efficient at mining digital currencies.
SAMSUNG	425.22	SOUTH KOREA	Samsung is one of the world's largest producers of electronic devices. Samsung specializes in the production of a wide variety of consumer and industry electronics, including appliances, digital media devices, semiconductors, memory chips, and integrated systems.
ASML	263.86	NETHERLANDS	ASML is one of the world's leading manufacturers of chip-making equipment. Their customers are companies such as Intel
BROADCOM	242.60	USA	Broadcom manufactures digital and analog semiconductors and provides interfaces for computers' Bluetooth connectivity, routers, switches, processors, and fiber optics.
INTEL	198.06	USA	Intel is an integrated device manufacturer that designs and manufactures motherboard chipsets, including the world's first metal oxide semiconductor.
QUALCOMM	191.98	USA	Qualcomm is a global semiconductor and telecommunications company that designs and markets wireless communications products and services.
TEXAS INSTRUMENTS	155.59	USA	Texas Instruments designs and fabricates semiconductors for manufacturers worldwide. The company is a major manufacturer of chips for mobile devices, digital signal processors.
AMD	142.62	USA	AMD specializes in manufacturing semiconductor devices used in computer processing. The company also produces flash memories, graphics processors, and a variety of components used in consumer electronics goods.
APPLIED MATERIALS	122.15	USA	Applied Materials is the leader in materials engineering solutions used to produce virtually every new chip and advanced display in the world.

Figure 4 Top 10 Industry Companies in the world

2.2.3 Product Mix

This last section describes the several types of microchips and their specific use allowing one to have a big picture of what is currently considered a microchip and its different operations. Microchips can be divided into two types: logic and memory chips.

Logic chips represent the “brain” of an electronic device that processes information to complete a task. Among logic chips 3 are highlighted:

- **CPU:** The first logic chip is the central processing unit (CPU). Invented in 1964, performs basic arithmetic, logic, controlling, and input/output (I/O) operations specified by the instructions in the program. Every electronic device needs a CPU to work.
- **GPU:** graphical processing unit is a specialized chip used to accelerate the creation and visualization of images in the display device. Hence, they are widely used in electronic devices that require visualizations such as mobile phones, PCs, workstations, or crypto mining
- **NPU:** neural processing units. Designed for deep and machine learning applications, NPUs are mainly used in IA and robots.

Memory chips are designed to store information. There are two types of memory chips:

- **DRAM:** Dynamic Random-Access Memory is the “working memory” chip that only saves data while the device’s power is turned on. Every device must include a DRAM to operate.
- **NAND:** Also known as flash memory is a chip that saves data even after the device is turned off. Currently, almost every device has also a flash memory to store data. [1]

3 MICROCHIP SUPPLY CHAIN

This chapter exposes the microchip supply chain from raw materials to final customers' products. It is divided into two sections. The first section explains the production process of a microchip which allows having a better understanding of what is needed to fabricate the chips and how they are fabricated. Then, the second section explores the supply chain of the production process. It analyzes step by step each part of the chain providing real information about companies, their location, and their role in the supply chain. This chapter is extremely important for understanding the causes of the chip shortage.

3.1 PRODUCTION PROCESS

The production process of microchips is crucial for understanding their supply chain. In this section the process from sand to end-microchip is explained in the following steps [6]:

The process begins with raw materials. As mentioned in the first chapter, microchips are made of silicon 99.99%. Silicon is a semiconductor material that is not obtained directly from nature. Although is the second most abundant element in the earth's crust, silicon is mainly hidden in the sand as silicon oxide, SiO_2.

The second step is silicon purification at foundries. It is obtained pure silicon throughout several foundries at 1500-2000 ºC following the chemical reaction:

$$SiO_2 + C \rightarrow Si + CO_2$$

The obtained silicon is 99% pure but it still contained other metals such as Fe, Al, etc. Therefore, it is needed to be purified.

In the same foundries, other chemical reactions are required to obtained pure single-crystal silicon ingots are obtained. First solar silicon or purified silicon is produced by reacting Silicon with HCL at 300ºC:

$$Si + 3HCl \rightarrow SiHCl_3 + H_2$$

Finally, the solar silicon reacts with H_2 for 200-300h at 1100ºC to obtained pure single-crystal silicon ingots:

$$SiHCl_3 + H_2 \rightarrow Si + 3\,HCl$$

Once the ingots are formed in the foundries, the third step is carried out in manufacturing plants with the following treatment process. It is very important to distinguish between silicon foundries and semiconductor foundries. Silicon foundries are the mentioned above, semiconductors foundries are also called semiconductor manufacturing plants or fabs and are the plants where chips are made as follows: [7]

The ingots are sliced with saws into extremely thick wafers of several inches in diameter. Then, these wafers are cleaned and polished in a "cleaned room" environment to prevent contamination.

Once the wafer is cleaned and polished the wafer is treated to create several chips:

First, a SiO_2 layer is deposited on the surface, and ultraviolet light is used to create a 3-D landscape on the chip that replicates the circuit which has been previously designed.

Second, the photolithography and etching process is used to create conducting paths with a thin layer of aluminum creating thousands of chips from each wafer.

Once these chips are fabricated, they are tested for correct performance and separated from the other chips of the wafer by saw. Finally, these chips are packaged and distributed from chip manufacturers such as Intel or AMD to electronic products manufacturers who include these chips in their own products and sell them to final customers.

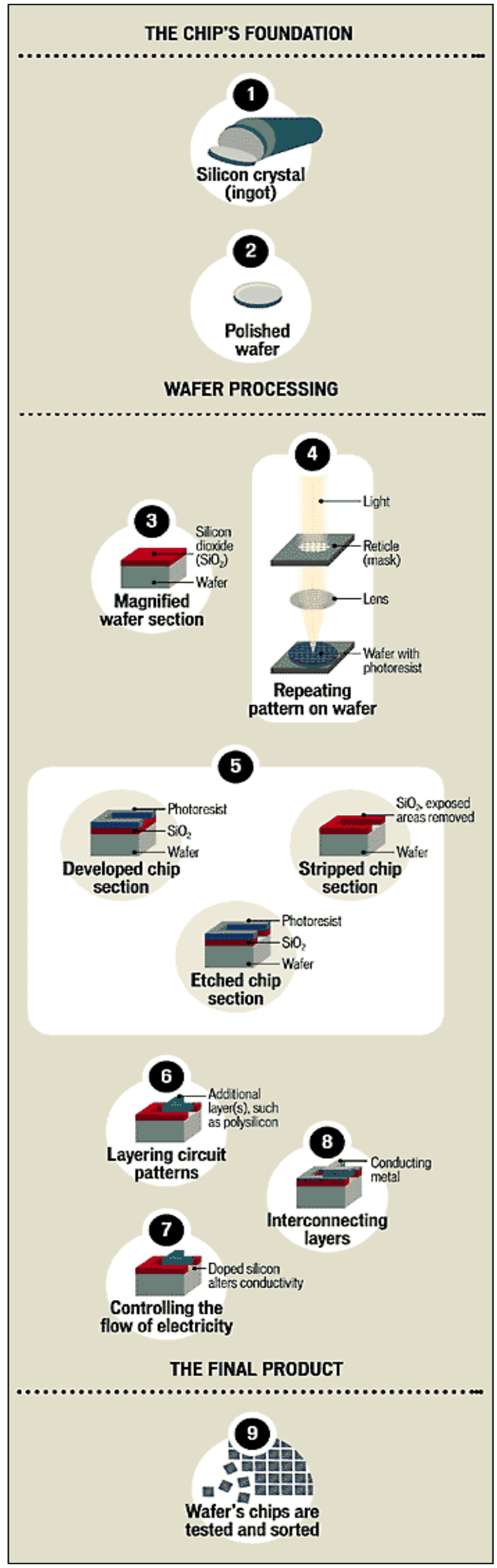


Figure 5 Chip Production Process

3.2 INDUSTRY STAKEHOLDERS IN THE SUPPLY CHAIN

This section is focused on analyzing the elements, processes and, organizations intervening in the microchips industry. This section let the reader see the big picture of the microchip industry and all the players taking part in it.

The industry can be divided into 7 elements. These elements are 1st Raw materials, 2nd Design, 3rd Machinery, 4th Front-end fabrication, 5 th Back-end assembly test & packaging, 6 th Electronic devices manufacturing, and 7 th End-users. The following image summarizes these steps that will be deeply analyzed later. [8]

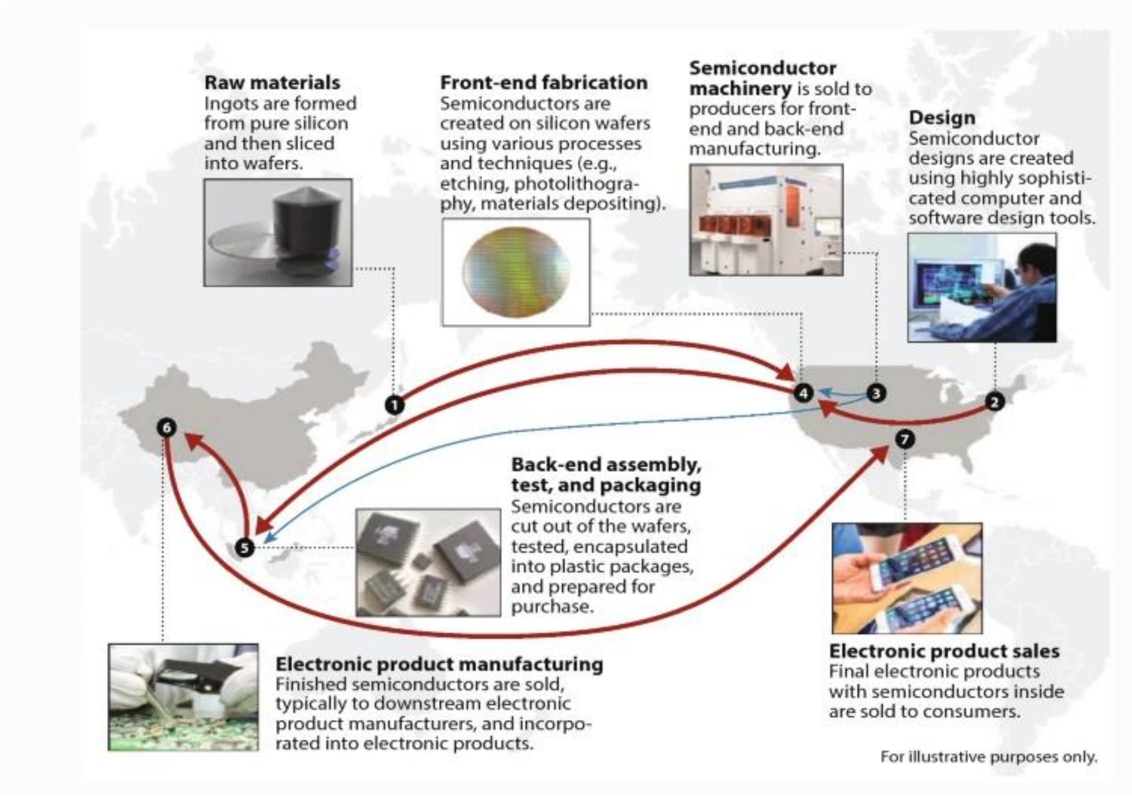


Figure 6 Industry Stakeholders' main elements

3.2.1 Raw materials: From Sand to Silicon

The first element in the industry is raw materials. As mentioned previously, chips are made of silicon that is obtained from specific sand. This sand is called silica sand which contains approximately 28% of silicon. Countries such as the United States (71B tons) the Netherlands (51B tons) and Spain (34B tons) are the largest sand producers in the world.

However, these countries allocate more than 80% of their sand resources to the construction industry. In fact, the US only assigns 2% of its resources to the electronic industry. These countries are not interested in dedicating their silica to the electronic industry since the following industry elements are located far away, especially in Asia. As the vast majority of silicon producers are located mainly in China, countries from Europe and especially the US (great rivals in commercial terms), prefer to allocate silica resources to other industries within their countries more profitable.

Therefore, the silica sand used for the electronic industry is mainly obtained from Asia and Africa. The main producers of silica sand for the electronic industry are Japan, South Korea, and Malaysia. These top producers have a competitive advantage thanks to the very cheap workforce.

The second element in the industry is the foundation of the sand to obtain pure silicon. Pure silicon is obtained in foundries mainly located in Asia. China is by far, the largest silicon producer with 5.4B tons per year, approximately 70% of global production. The following graph shows the largest silicon producers in the world [9]:

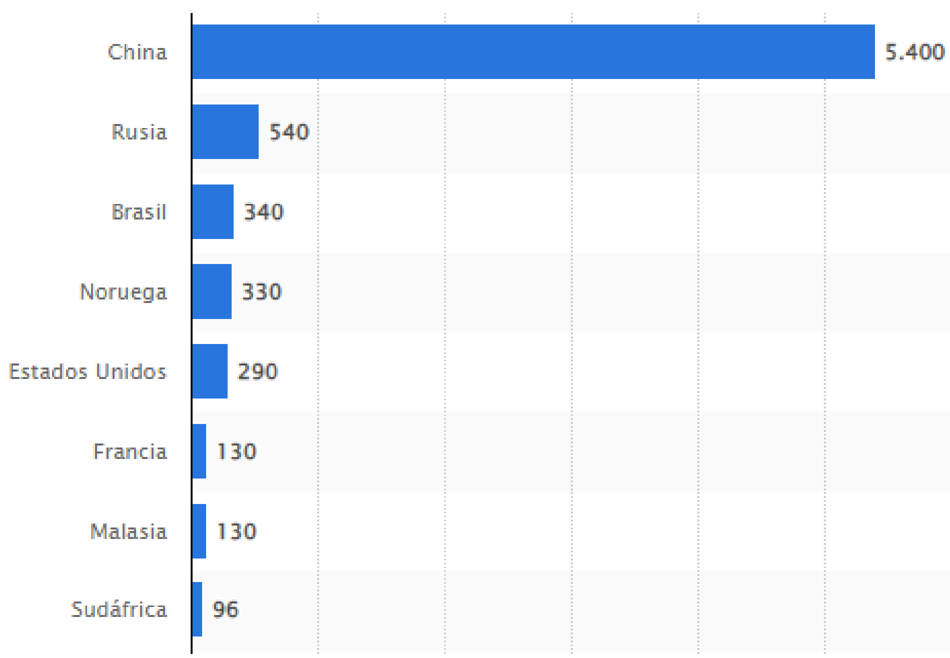


Figure 7 Largest silicon producers in the world

China has a competitive advantage in dominating the silicon industry. First, China's potential is enormous with more than 1300 million population, they have become in the last 50 years the second world potential. A cheap workforce, specific government policies with large investments in industrial production, and very permissive with environmental contamination led to a competitive advantage having no real competitors in the sector.

From silicon wafers, the industry will advance to front-end fabrication in semiconductors foundries, however, two side elements in the industry are crucial. These elements are Design and Semiconductor Foundry Equipment:

3.2.2 Design

The chip design is carried out by chip manufacturers in their headquarters. Chip design is the main activity of manufacturing companies as the industry is becoming extremely complex. Customer's criteria keep increasing, and their expectations for chip's performance are incredibly high and require a lot of effort from designers to keep up the pace of previous decades. As mentioned in the first chapter, Moore's law is harder and harder until eventually, it will become impossible to follow.

Thus, chip designs are the most valued asset of integrated device manufacturers. Today, one transistor is 10nm in diameter and each IC has between 5B to 50B transistors. Therefore, IC manufacturers use highly sophisticated computers and software design tools (VHDL). The manufacturing companies will be analyzed in the 6^{th} element.

3.2.3 Semiconductor Foundry Machinery

The other side industry element is the Semiconductor Foundry Equipment. Chip manufacturing requires extremely complex and powerful machinery to fabricate these 10-nm-in-diameter chips. There are mainly two types of machines needed to chip fabrication: Lithography machines and Metrology and inspections machines.

The lithography systems are the machines that make chips a reality. They use the highest ultraviolet resolution to print the tiny features that form the basis of a microchip. The metrology and inspection systems cover all solutions to measure the quality of the patterns on the wafer.

This machinery is the costliest and most relevant in a semiconductor fab. A semiconductor plant has much more machinery required as the production process has many more steps that we are not getting into detail.

This section of the industry is mainly dominated by ASML. It is a Dutch company specified in lithography and metrology systems for Semiconductor foundries. Each of these machines is estimated at USD 120M. Currently is the largest supplier with a bast network of more than 4600 tier 1 suppliers. Its headquarters are in the Netherlands, but it already expanded having offices in most of the countries where customers operate. ASML plays a very important role in chip fabrication as they have very few competitors. Its market share is currently over 85%, while the remaining 15% was split among Applied Materials, Nikon, and Canon. [2]

3.2.4 Semiconductor Foundry. Front-end fabrication

Once it has been analyzed the side industry elements, it is time to return to the microchip's production process. The first link of the industry ended in the production of silicon wafers. These silicon wafers are transported to semiconductor foundries where the microchip fabrication and assembly take place.

The front-end fabrication is probably the most important element in the industry. As mentioned above, chip fabrication requires the most complex techniques and machinery, so very few companies have the ability to produce IC. Besides, a semiconductor foundry requires enormous investments which makes it very difficult for possible new entrants to succeed.

This section analyzes first, the scope of the global semiconductor market and then what is required to develop a microchip plant in every region which will explain the market behavior.

Regarding the semiconductor foundry market, it has 5 players dominating the whole market. These companies are TSMC, Samsung, United Microelectronics Corporation (UMC), GlobalFoundries, and China's Semiconductor Manufacturing International Corporation (SMIC) [10] [11].

1. **TSMC (Taiwan)**: is by far, the largest semiconductor company dominating 55% of the market share. They chose not to design, manufacture, or market semiconductor products avoiding competing against their customers. TSMC produces chips for prestigious companies such as AMD, NVIDIA, Apple, and Qualcomm. TSMC is today the most

valuable company in the industry, the company reported 2020 a revenue of $45.5 billion. They are planning to invest $100 billion over the next three years to increase plant capacity.

2. **Samsung (South Korea):** Samsung is the second-largest company in the semiconductor market. Unlike TSMC, Samsung mainly produces microchips for its products. Besides, Samsung is producing the most advanced chips for the latest NVIDIA GPUs. The South Korean giant established in the foundry business in 2005, currently dominates the 16% market share, far from TSMC but still has a strong position in the market. Samsung announced an investment of $151 billion in the Foundry business through 2030.
3. **UMC (Taiwan):** UMC is the third-largest company in the market. UMC follows TSMC's business strategy focused on chip production rather than manufacturing, designing, etc. The Taiwanese company dominates the 8% market share operating 12 fabs strategy located mainly in Asia with total revenue of $6.2 billion.
4. **GlobalFoundries (U.S):** The US company is the fourth-largest company dominating around 7% of the market share. Following UMC's business strategy its 8 fabs produce chips for Qualcomm and AMD. Is important to mention that GlobalFoundries is the only occident company in the semiconductor foundry market.
5. **SMIC (China):** SMIC is the largest and most advanced foundry in Mainland China. The company provides IC foundry and technology, and it is currently dominating just 5% of the market share. However, its advanced technology and investment efforts allowed it to increase its revenues by 25% in 2020 ($3.9 billion). Broadcom, Qualcomm, Texas Instruments along with the Chinese military companies are some of its customers. They are planning to open new fabs in the following years to fiercely against the Taiwanese companies for dominating the industry.

In addition, mention that Intel has several semiconductor fabs but only for internal chip production, and therefore, it has not been included in the previous analysis. In March 2021, Intel announced $90 billion in new fabs launching the Intel Foundries Services company which will offer intel manufacturing to external customers so they will soon be an important player in the semiconductor industry.

One can realize that most of these companies have their headquarters in Asia. Hence, the next step of the analysis is to understand why the industry is mainly positioned in Asia and how it affects the industry. The following map gathered not only the companies' headquarters but also their foundries' locations.

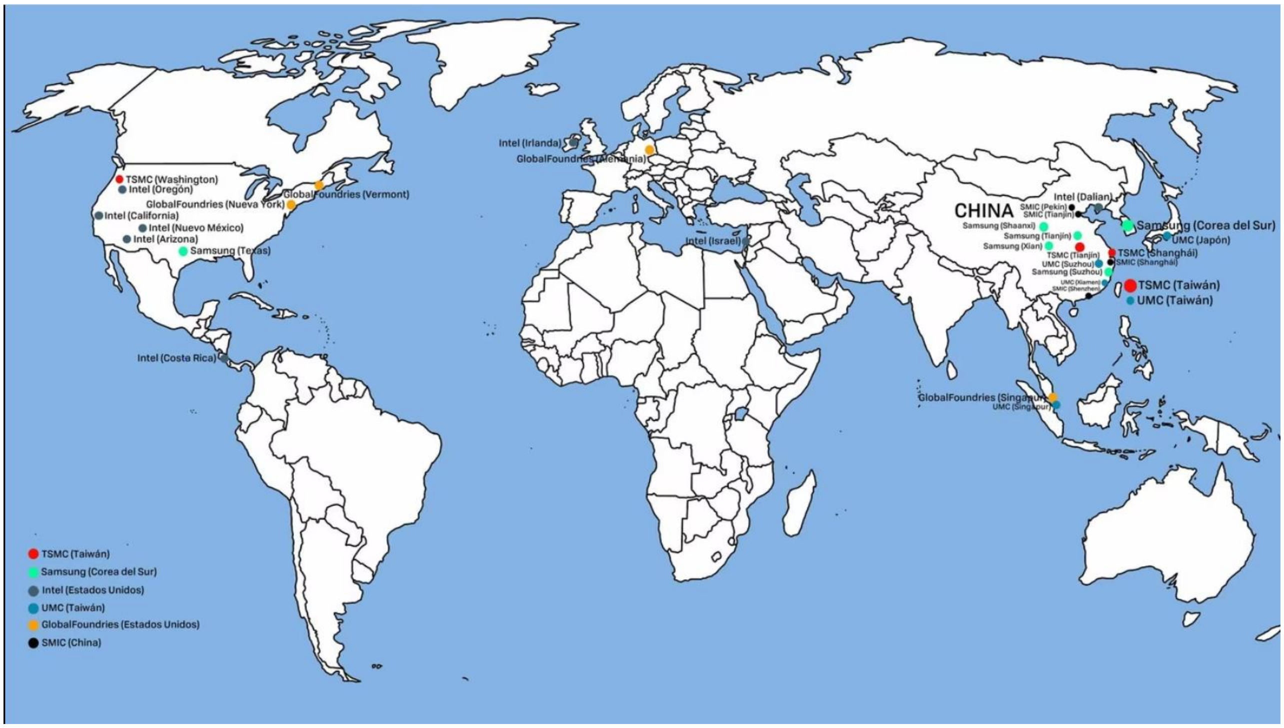


Figure 8 Main Foundries Locations

As expected, the map shows that foundries are concentrated in China, Taiwan, South Korea, and Japan combining for roughly 87% of the global foundry market. There are also a few foundries from Intel, GlobalFoundries, and TSMC in the US. However, South America, Europe, and Russia barely have foundries allocated. There are two reasons which explain the dominance of Taiwan and Asian countries:

The first reason is the strategic position that these companies have in the industry. Three arguments support the strategic position of Asian countries.

- First, foundries' upstream suppliers are silicon producers. As mentioned in the first element of the industry, China produces 70% of global silicon which provide all Asian countries a competitive advantage in raw materials acquisition.

- In addition, it is well known that the workforce is times cheaper in these countries than in developed ones such as the U.S.
- Finally, semiconductor foundries require tons of water, a natural resource extremely cheap in Asian countries.

These three arguments imply that it is between 20-40% more costly to operate a semiconductor foundry in Europe or the US compared to Asian countries. Besides, putting a fab in operation costs around $10 billion per fab. All together make the business feasible for very few enterprises as it supposes investments of over $100 billion. [12]

The second reason is time. Semiconductor foundries are extremely complex and require years of research in addition to billions of investments. The technology used and the complexity of arranging all the elements and machinery needed for producing chips makes the industry almost impossible for new entrants. TSMC for example has been making chips since 1978, dedicating years of research to produce the most advanced microchips today. This explains for example why companies such as SMIC, which is investing hundreds of billions still is not able to compete against Taiwanese companies. In this industry, time and engineering research is even more important than money. Thus, the industry panorama is not expected to dramatically change for at least the following 5-10 years.

3.2.5 Back-end assembly, test & packaging

The next industry element is the back-end assembly. This element has no real importance in the industry. It sometimes can be carried out in the foundry itself, or transported downstream, being chip manufacturers the ones in charge of testing the products. In general, the first option is chosen by most manufacturing companies allowing them to reduce costs.

3.2.6 Electronic product manufacturing

Going downstream one finally reaches the famous and prestigious companies that actually sell microchips. When thinking about microchips, one only imagines this element in the industry. The main manufacturing companies are the well-known INTEL, AMD, SK Hynix, Broadcom, Qualcomm, Texas Instruments, and in less extent ARM. These companies, named IDMs (Integrated Device Manufacturers), take care of designing the most sophisticated microchips to meet customers' performance criteria and sell them worldwide to all technology companies and electronic device sellers. IDMs are segmented into two types of microchips: Logic and memory chips.

Regarding logic chips, Intel, AMD, and ARM are microprocessor manufacturers, in other words, CPU manufacturers for major technology enterprises. Their CPUs are in every laptop or computer currently used. Intel and AMD have a fierce rivalry for producing the strongest microchip as they both sell to the same companies. However, ARM produces microchips exclusive to Apple.

Intel leads this sector with $79.07 billion in revenues followed by AMD with $4.8 billion and in last place ARM with total revenue of $1.5 billion. However, the difference in revenue between Intel and AMD is not fair in terms of that Intel also produces GPUs and memory chips. AMD is becoming a serious competitor developing what currently is the most powerful CPU. Still, Intel dominates the market with 72% of the market share against 23% of AMD. Intel and AMD headquarters are in the U.S while ARM is in Great Britain.

In addition, NVIDIA is the largest GPU manufacturer with almost no real competitors in the sector. The U.S company's total revenue in 2021 was $16.7 billion. AMD, Intel, and Asus also produce GPUs.

Regarding memory chips, Samsung, Intel, and SK Hynix are the largest manufacturer. These memory chips have several major consumers, including Apple, Asus, Dell, and HP. This sector of the market is very segmented as the leading company's market share, Samsung, is not above 30%.

The overview of the IDM market shows that, unlike upstream suppliers, most of the companies' headquarters operate in the U.S or Europe. The IDM industry is more fragmented than in previous links with certain domination from the U.S. The following chart better shows how fragmented is the IDM industry. [4]

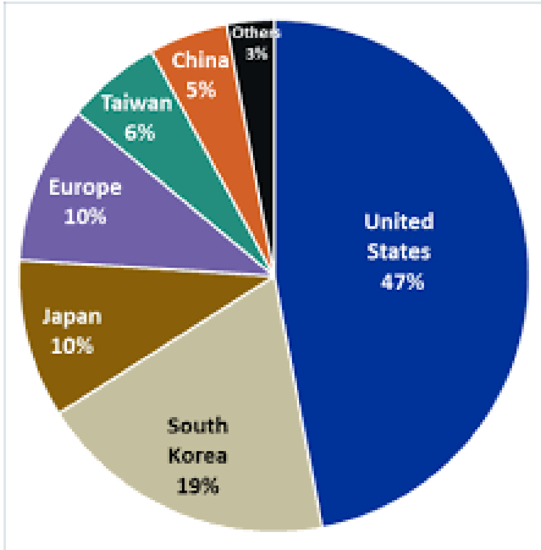


Figure 9 IDM market share by region

3.2.7 Electronic product sales (End-users)

The last element of the industry is electronic product companies. Semiconductors are used for a wide variety of products, from cars, and industrial equipment to computers and smartphones. The industry is segmented into the following end-use categories. Some examples are added to understand what involves each category:

a. Automotive: vehicles
b. Computer: pc/laptops
c. Communication: smartphones
d. Government: Military
e. Industrial: Fabs
f. Consumer: Wi-Fi, IoT

The figures below show the six major semiconductor end applications by sales and percent share of total semiconductor end sales [13]:

Table 1 End-use Market Share 2021

End-Use Category	Annual Growth	Total Value ($ billion)
Automotive	18,6%	89,12
Computer	15,5%	252,50
Communication	15,3%	243,90
Government	14,6%	7,82
Industrial	12,8%	93,81
Consumer	2,8%	93,81
Total	13,3%	781,73

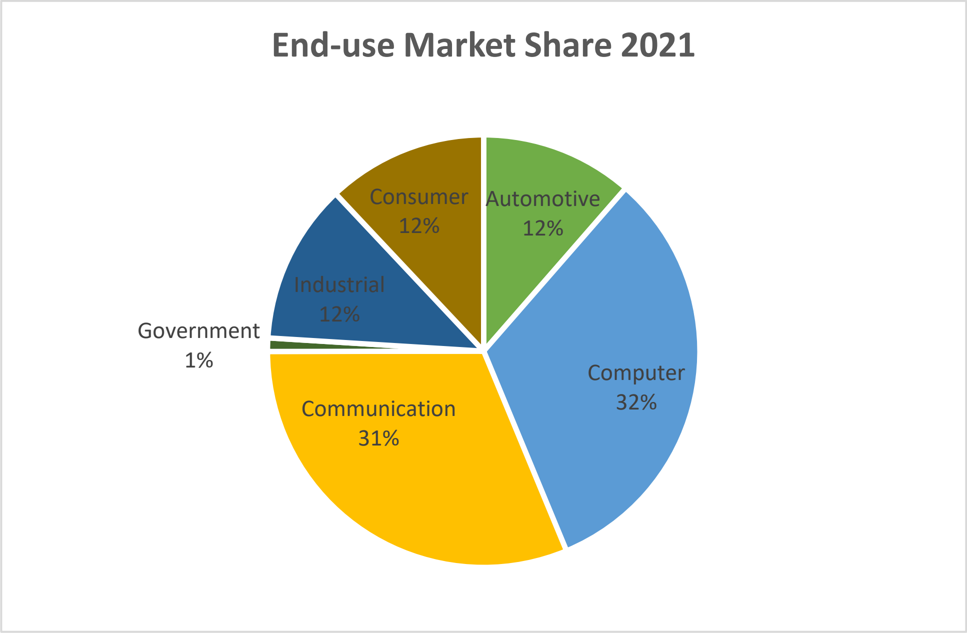


Figure 10 End-use Market Share 2021

Analyzing the data, the semiconductor end applications market is very large with total revenue of $781 billion. Electronic devices take part in all technological industries which strongly depend on chips to develop their products. Besides, the annual growth of all sectors' demand is increasing at 13.3%. The development of smart cities such as 4G and 5G, the internet of things, along with growing demands for wireless audio devices, smart TVs, and other electronic devices can tell that the annual growth could keep this pace or even higher for the following years.

Regarding the market share, computers and communications equally dominate the market with over 30% each. It can easily be explained as almost every person in a developed country has at least one phone and one computer. Besides, both industries are expected to grow at very high rates. The other 40% of the market share is equally split among the automotive, consumer, and industrial sectors. Governments have a very small portion of the chart. However, the automotive chip demand is growing at the highest speed so it will soon overcome other industries. Highlight that the automotive sector today highly depends on electronics as vehicles use today’s latest technology for safety and comfortability purposes.

4 CAUSES OF MICROCHIPS SHORTAGE

As the previous section shows microchips take part in almost every industry and many of them directly depend on IC. Thus, the microchip shortage is critical for the global economy and development. The shortage must be fixed as soon as possible, or global economies will get stacked and suffer ending up in one of the greatest crises in history.

Industries, such as the automotive, are already deeply suffering from the microchip shortage where ICs are arriving with months of delay struggling vehicle mass-production. The problem is only becoming larger as the demand is not getting lower and delays are just becoming longer. The shortage must be fixed soon or eventually, could reach a no-return point collapsing the industry with devastating effects.

Hence, this chapter will deeply analyze all possible causes of the microchip shortage so the following chapter will be able to propose short and long-term solutions.

All previous chapters were necessary to put in context the causes of the microchip shortage. All background, market, production process, and industry elements play an important role in the shortage as there is no one unique cause but multiple that all together have ended up carrying out the current world's greatest and probably worst shortage.

As for every market, the microchip industry simply works following the supply and demand. The problem arises when supply and demand cannot match, and this is exactly what the microchip is facing.

4.1 THE UNFETTERED BOOST IN DEMAND

20 years ago, computers already were crucial for professional purposes. Every office job had computers and many of them start depending on them. The demand was continuously increasing since more computational capacity computers had and hence, more important, and necessary where for carrying out jobs.

Besides, PCs acquired awareness among individuals for personal purposes. By the year 1984, only 8.4% of developed countries' households had a computer. In 1997, 36.6% already have at least one computer but in 2007 almost 70% of developed countries' households had a computer.

The following figure shows how the demand grew from 1984 to 2016:

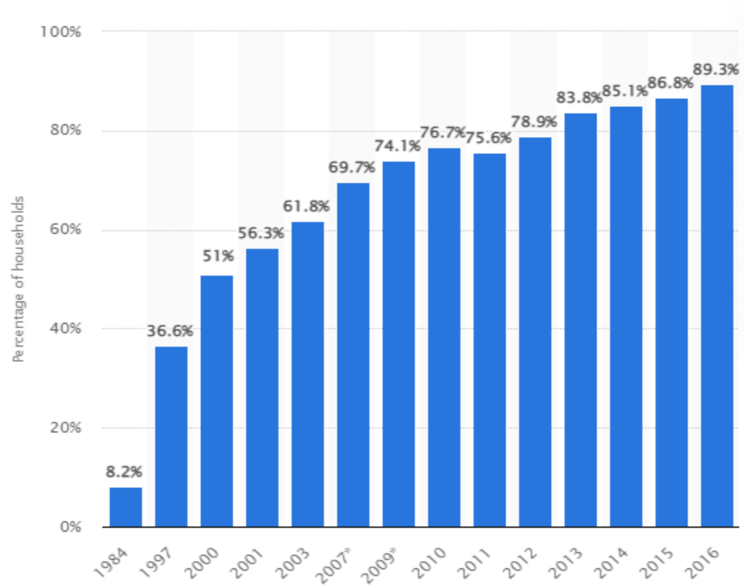


Figure 11 Percentage of Households with a computer by year

It is astonishing how the computer percentage of households increased in the years 2000. There is one reason that explains this growth: the Internet.

The Internet became popular as a telecommunication network The Internet only communicated 1% of the information flowing through two-way telecommunications networks in the year 1993, 51% by 2000, and more than 97% of the telecommunicated information by 2007.

Internet, web, and online services became the cause of the computer boom by the year 2000 but it is still today the cause of continuous growth.

New apps such as Facebook, Twitter, WhatsApp, and Instagram arrived and changed the way we saw the world. Today every person is connected to the Internet and social networks making necessary millions of servers constantly working to hold these networks. The following figure shows all devices connected to the Internet since 1992 [14].

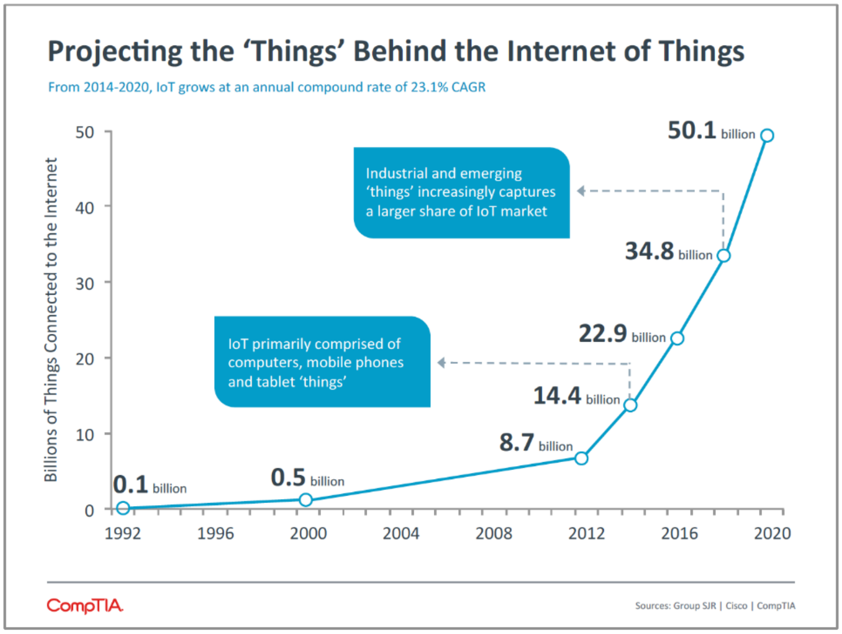


Figure 12 Billions of things connected t the Internet by year

The number of devices connected to the internet is not only still growing these days, but it is increasing at an exponential rate. And it is important to mention that this graph only mentions those that are connected to the Internet but there are millions of consumer electronics that there are not connected to the internet. Not to mention that all these devices need at least 1 but probably several microchips to operate.

Besides, combining the Internet and new technologies, the arrival of the smartphone 15 years ago changed the world. From one computer per household 20 years ago, now each person has at least one phone, a laptop, and probably many other devices such as smart TVs, PCs, tablets, consoles, etc... [15]

The global number of consumer electronics in the last 10 years is the following:

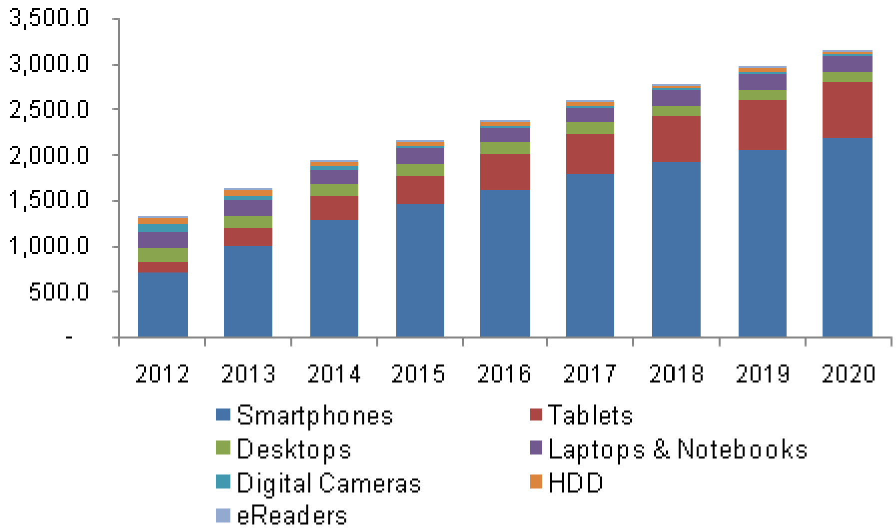


Figure 13 Number of electronic devices by type

The number of consumer electronics has triplicated in the last 10 years, and it is expected to grow at this or even higher in the following years which means that the microchip demand will continue growing at an alarming rate in the future.

In recent years one last reason has caused a major increase in the demand for microchips: Cryptocurrencies. Since the arrival of Bitcoin and other cryptocurrencies, a new whole market appeared to offer many opportunities: Crypto mining. Mining currencies is a very complex activity that requires the most powerful computation computers to get a reward in return.

Crypto mining has become very popular in recent years and there are millions of computers dedicated to mining currencies using mainly GPUs to do it. Thus, microchip demand has also been affected by new tendencies such as crypto mining.

In summary, microchip demand exploded 20 years ago with computers, followed by the arrival of the Internet, smartphones, and new technologies the growth became exponential, and finally, the arrival of new digital markets such as cryptocurrencies are increasing microchip demand to such high levels that are almost unreachable for chip manufacturers these days.

4.2 THE INABILITY TO INCREASE THE SUPPLY

Apparently, the demand problem seems very simple to solve. If the demand is higher than the supply, all needed to do is let increase chip production or let new companies enter the market and access the demand unreached by the currently manufactured companies. However, reality differs from theory due to the following causes:

1. Technical Complexity & Limitations
2. Industry dependency on Asia
3. Covid-19

4.2.1 Technical Complexity & Limitations

Focusing first on technical complexity, a current microchip has more than 50 billion transistors. Today transistors are smaller than a virus requiring the most sophisticated machinery to produce them. As mentioned in the supply chapter, very few companies develop machinery for chip manufacturing, and due to its complexity, it takes decades of research to set up a plant for chip manufacturing, and over $10 billion to operate it.

For instance, SMIC the Chinese company that entered the market in the year 2000, although it has government support both financially and politically is still struggling in chip manufacturing and still is not able to produce chips with the same complex technology as TSMC.in fact, it is said that since its lack of success SMIC is now offering TSMC engineers millions to join them. Besides, plant production is 20 years later still under forecast.

Focusing on technical limitations, Moore's law is reaching its edge. R&D boundaries are almost at the very end in terms of computational capacity. Chip customers require more and more computational capacity and smaller sizes becoming a real headache for engineers and chip designers. The traditional way of developing will no longer be useful and new ways must be explored to keep up the pace. The technical limitations of current microchips demand that IDMs invest billions of dollars in R&D.

On the one hand, technical complexity and limitations require billions in investment and decades of development making the industry attractive for very few enterprises and almost impossible to possible new entrants, but even for those very few companies have the power to invest and develop their chips, it is still very hard to produce and increase its supply. Thus, technology complexity and limitation are making a bottleneck in chip foundries which means that supply and demand cannot match with current capacities.

4.2.2 Industry dependency on Asia

The second factor that impedes the supply to match the demand is the industry dependency on Asia. The industry elements analyzed in the previous chapter showed a strong dependency on Asia since the vast majority of silicon mines and silicon foundries are in China and semiconductor foundries are positioned in Asia. In that chapter it was explained how and why the industry was positioned thereby, now is time to see how this Asian dependency can affect the global shortage.

IDMs have been delegating chip production to Asian companies such as TSMC saving millions in the workforce and operating costs. The problem arises when suppliers become stronger than IDMs since the technology used is so complex that there is no supplier competition and therefore IDMs are under suppliers' control.

Thus, any decision, problem, or conflict suppliers make will strongly affect IDMs' production and therefore, they are very fragile and vulnerable. For instance, if TSMC decides to reduce production for internal reasons, AMD won't be able to sell any product as it completely depends on TSMC chip production.

And indeed, three supplier issues helping the global shortage. These are two geopolitical conflicts, the commercial war between China and U.S and between China and Taiwan and the extremely large distribution channels.

Not going very deep into these two conflicts, what one can figure out is that China is putting a lot of effort into developing its chips to monopoly the market. To do so, they are cutting distribution channels and resources such as silicon to both U.S and Taiwan.

Besides, China and Taiwan have been in conflict since Taiwan's independence. Their political conflicts are affecting also commercial activities and above all, the microchip industry. SMIC is stealing engineers and resources from TSMC and other Taiwanese companies, doing everything on their hands to overcome TSMC as the top chip foundry.

These conflicts are logically affecting the whole supply chain, but especially companies such as INTEL, NVIDIA, or AMD since their demand is growing but the supply cannot match it.

In addition to these geopolitical conflicts, the distribution channels are also an important factor in the shortage. Although production is concentrated in Asia, more than 60% is distributed to Europe or America. Apparently, distributing chips worldwide shouldn't be a problem thanks to globalization with very well-designed distribution channels.

The problem arises when all the production concentrated in one single location must be distributed worldwide. Distribution channels are very large and vulnerable, it takes months to ship chips from Taiwan to the U.S. IDMs cannot control the distribution channels or any issue pops up. Besides, distribution channels are also vulnerable to the previous geopolitical conflicts. In fact, due to the commercial war, distribution costs have increased x10 in the last 10 years.

These three factors lie in the lack of capabilities to react. The real problem is the semiconductor foundries positioning and dependency which is so well-defined and complex that IDMs can't react against any of these conflicts. Industry dependency on Asian foundries is so huge that there are no possible solutions to increase the supply or avoid geopolitical and distribution effects with the current elements. These reasons also mean that the bottleneck in chip foundries cannot be easily solved.

4.2.3 COVID-19

Last but not the least, COVID-19 has been the detonator of the global shortage of microchips. All previous factors were driving the microchip industry to a more and more vulnerable and unstable sector which while the industry still worked no one saw them coming.

As with many other crises in history, the problems that really caused the crises were ignored for years becoming greater until a no-return point where all needed is a little trigger that will sink the whole market. In this case, COVID-19 was a big detonator since fabs had to close for several months. The industry was really suffering from previous causes but until the detonator popped up, everyone was ignoring the problems arising. The industry became very vulnerable and fragile to any single event that could sink the whole industry which is exactly what COVID-19 did.

The whole industry struggled, and shortages and long-period delivery delays came. Supply and demand match was under such risk that 2 months of null production is causing at least 4-5 years of shortage and delays. The president of ASML has recently confirmed that "chip supply will be inferior to demand for the following 2-3 years due to the challenges foundries are facing which barely have the margin to increase production and performance".

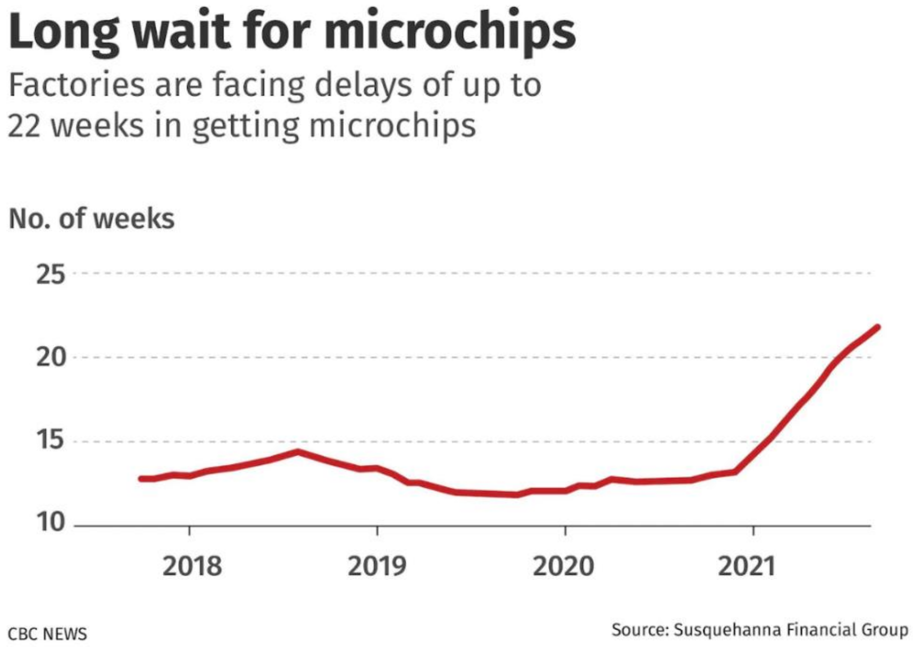


Figure 14 Average number of weeks in getting microchips by year

Currently, chip deliveries are approximately 2-3 months delayed (from 12 weeks to 22), and, in many cases, such as the automotive sector, this delay is sinking the whole industry.

In summary, the global chip shortage comes from a continuously increasing demand that cannot be followed by the fragile supply due to technical complexity and limitations, and geographic dependency on Asia. Since the industry is very vulnerable, the COVID-19 worked as a detonator causing years of shortages and delays.

5 SOLUTIONS TO MICROCHIP SHORTAGE

The main objective of this thesis is to define and implement a solution for the microchip shortage. After analyzing the causes of the shortage, this chapter will propose potential solutions and analyze the effects of every decision proposed. Thus, this chapter will lead to the implementation of one final solution, as the most accurate and potentially better for solving the global industry shortage.

Hence, both supply and demand will again be briefly analyzed to determine if it is possible to confront them and, in that case, propose a solution to match them. The objective is to make changes in one leaving the other intact and see if the shortage can be solved.

5.1 FACING THE INCREASING DEMAND

The continuous growth in demand is the first problem of the global shortage. The goal of this section would be to reduce the demand or at least its increasing rate so the current supply could match it as soon as possible.

Thus, the first alternative is to try to reduce the demand. Is there any possibility to do so?

The demand has been increasing dramatically for the last 20 years. However, as the figures showed, the demand is expected to increase in the following decades at even higher rates.

Electronic consumers' demand is increasing since we are moving to a digital world where ideas such as IoT or metaverse are becoming a reality. Besides, most industries depend today on the microchip industry. Like the automotive, any industry that requires machinery needs microchips to operate. In fact, industry digitalization has become a very powerful competitive advantage. Many industries are investing millions in digitalization and there are even consultancy and advisory companies focused only on helping others to achieve a digital transformation. Data and digital transformation have become critical to succeed in the current market.

The current digital world is surrounded by electronic devices and tons of servers to store data, all of them supported by microchips. But the expectations presume that digitalization and IoT will become even more essential for every industry since these new technologies are just in the first development stages and their potential is unmeasurable. Therefore, reducing the demand is not a real alternative to be considered.

The second alternative is to find a substitute for microchips to match the demand.

Apparently, there are no chances to face the demand increase since reducing the demand is not a real possibility and there are no chip substitutes which leads to the supply that must suffer changes, or the shortage will never be solved.

5.2 FACING THE INABILITY TO INCREASE THE SUPPLY

If the demand will grow for the following decades at high rates, the supply must adapt to the increase and somehow match the demand.

As explained in the previous chapter, traditional ways to increase the supply such as new entrants or increasing current productivity will not succeed due to the three main factors mentioned.

First, the technical requirements and limitations of chips make it impossible for new entrants to arise. Second, technical limitations plus the Asian dependency, and commercial wars do not allow current companies to match the demand. Finally, both Asian dependency and covid-19 caused large unsolvable delays. Thus, we are wondering if any innovative idea will allow us to reverse the current situation.

The supply problem is mainly located in chip foundries. The bottleneck caused by technical requirements needs to be solved, but the Asian dependency makes it today, impossible. Therefore, this innovative solution must first eliminate the Asian dependency so then, production can be increased, and delays can be cut down. Since Asian companies have over 85% chip production, It is required from current non-Asian companies who have the technology, knowledge, and resources to do a huge investment in new foundries away from Asia.

However, developing a new foundry away from Asia is not only a matter of money. It also requires a new supply chain. Foundries suppliers are today also located in Asia since the vast majority of the production is carried out there. Therefore, a new design of the supply chain must be done along with a re-design of stakeholders’ roles. This new supply chain will affect all stakeholders who all together must collaborate to achieve the final goal.

Finally, this new supply chain must be strategically designed to also fix the large distribution and transportation issues. The idea also must reduce the distribution distances between different elements of the supply chain. Achieving it will mitigate risks develop a stronger and less vulnerable supply chain and will avoid new crises such as Covid-19 will cause devastating effects on the industry.

Thus, the solution proposed to the current shortage is the following: Design an innovative supply chain for new chip foundries away from Asia. Define the supply chain strategy and management.

This idea could seem quite simple at first, however, there are so many factors that make this idea very complex to carry out. This unique possible solution requires to re-invent the current industry, changing the way stakeholders take part in the sector so the current factors impeding the supply increase can be avoided. Thus, the following chapter will step by step analyze how and what it takes to develop and execute this idea achieving the final goal, solve the current microchip shortage.

6 DESIGN AN INNOVATIVE SUPPLY CHAIN FOR NEW CHIP FOUNDRIES AWAY FROM ASIA. DEFINE THE SUPPLY CHAIN STRATEGY AND MANAGEMENT

This section will carry out first the development of new chip foundries away from Asia which will help to solve the bottleneck problem of the chip shortage and cut down delays. First, strategic decisions will be made to deploy the most efficient and appropriate supply chain for these new foundries, and then a supply chain action plan & management will be defined to ensure the new supply chain's success.

6.1 SUPPLY CHAIN STRATEGIC DECISIONS

Previous chapters were crucial to understanding and locating the main problem in the chip shortage. New chip foundries must be achieved two goals: First, to meet the current demand, and second, to reduce supply chain distances and hence, delays. But above all, reducing the Asian dependency which will allow the two goals to be feasible.

Thus, the strategic decisions will respond to the four main questions regarding the deployment of this new supply chain: where (location), how (production), when (schedule plan), and who (stakeholders' role).

6.1.1 Location

The first strategic decision is the new foundries' locations. There must be several considerations for choosing the location aside from solving the problems mentioned: potential suppliers and buyers, profitability, and International Risk management.

Looking again into the chip foundries map:

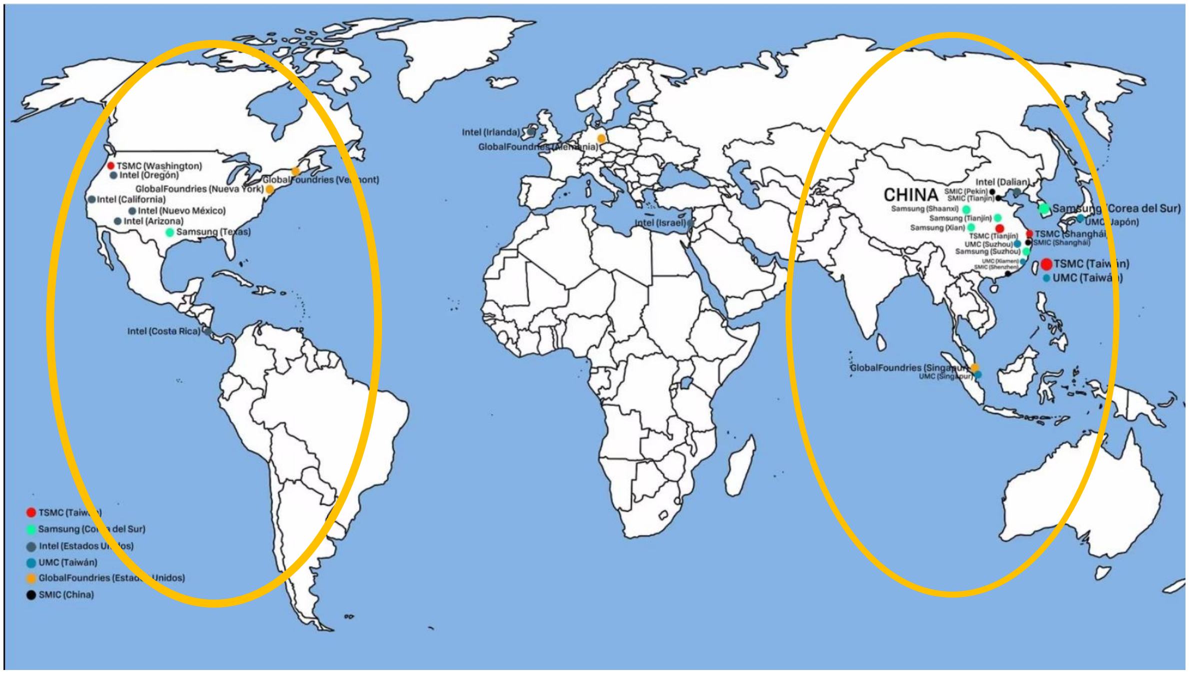


Figure 15Main foundries locations analysis

The map shows that the distribution channels are strongly affected by Oceans. The U.S can supply part of the western part of the world and Asia must supply the eastern part and almost everything else.

In addition, the map clearly shows that aside from Asia and the U.S there is no considerable chip production in the rest of the world. However, chip production cannot be carried out in every corner of the world. It is a must to consider cultural, political, and economic factors in locating a new foundry to minimize risks.

Cultural risk refers to the potential for a company's operations in a country to struggle because of differences in language, customs, norms, and customer preferences. It is required an occidental and global ideology which ensure foreign companies' growth and mutual collaboration to reduce the Asian dependency.

Political risk refers to the potential for government upheaval or interference with business to harm an operation within a country. Regulations for international companies must ensure their safety, independence, and growth.

Economic risk refers to the potential for a country's economic conditions and policies, property rights protections, and currency exchange rates to harm a firm's operations within a country. It is required a developed or emergent countries whose economic situation is positive since foundries' investments are extremely high.

Aside from eastern Asia, which is disregarded since we must reduce its dependency, middle Asia, Africa, and most South American countries, are also disregarded due to these factors.

Therefore, the possible new locations will be Canada, Australia, developed South American countries, and European countries. Analyzing the map some crucial conclusions arise about each of these potential locations:

On the one hand, Canada and South America are very close to the U.S and clearly can be supplied by them. Building a new foundry there will not make a real difference in the supply chain since international distribution channels will still be extremely large. It will only solve the problem locally. On the other hand, building it in Australia will produce the same situation or even worse since Australia is even farther away.

Clearly, Europe has a competitive advantage in distributing the production since it's just in the middle of the two giants' continents. Building foundry in Europe will aside from locally solving the situation, cut both local and global supply chain distances which will make the industry less vulnerable.

Besides, the following chart shows IDMs headquarters, i.e., buyers' location. Unlike Canada, or South American countries, Europe represents currently 10% of the purchases and it is expected to grow up to 20% share by 2030. [16]

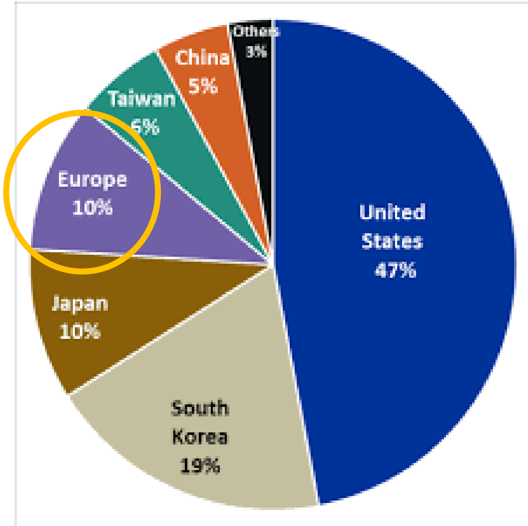


Figure 16 IDM market share by region analysis

This means that building foundries in Europe will help us succeed in reducing supply bottleneck in the most cost-effective way. It will allow matching the local large chip demand erasing the bottleneck but also it will reduce the global distribution distances since it will be an intermediate between Asia and America.

It has been explained that building a foundry in Europe will solve the two main problems of the shortage but also it will minimize risks. To determine what European Country would be the most suitable to build the foundry we will take into consideration the factors mentioned above: potential buyers and suppliers, profitability, and international risk management.

6.1.1.1 Suppliers' footprints

Locating a chip foundry in Europe requires searching for new suppliers which must as close as possible to the foundry to ensure the new strong supply chain. There are two main suppliers for chip foundry, silicon wafers, and advanced lithographic equipment.

Regarding silicon wafers, the raw material used to produce microchips, the following graph shows the current wafer production. [17] [18]

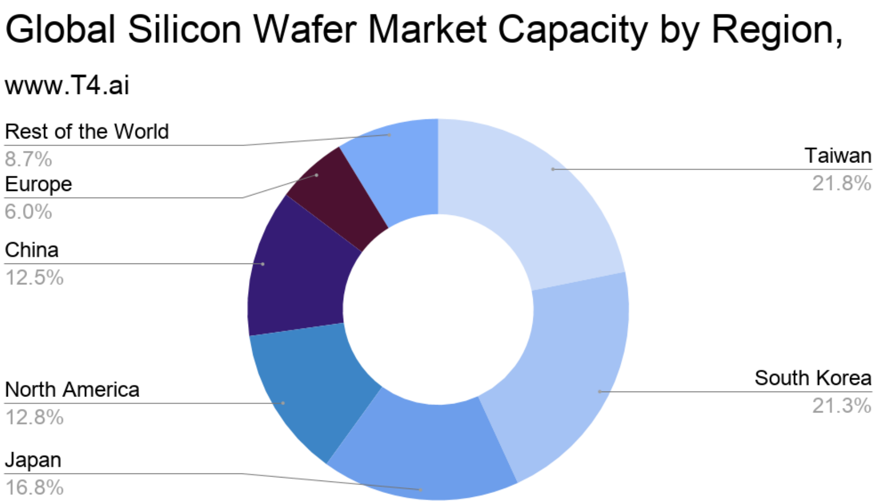


Figure 17 Global Silicon Wafer Capacity by Region

It shows that 6.0% of silicon wafers are produced in Europe. The main silicon wafer manufacturers in Europe are:

Okmetic Oy (Headquarter -Vantaa, Finland): Okmetic is the world's seventh-largest silicon wafer manufacturer and a leading supplier of advanced, high-value-added silicon wafers that are used to manufacture sensors, discrete semiconductors, and analog circuits.

Siltronic AG (Headquarter -Munich, Germany): Siltronic AG is one of the leading producers of hyperpure silicon wafers and has been a partner to many major semiconductor manufacturers for decades.

The new foundries will be supplied by both manufacturers to diversify to mitigate the supply risk. Since the goal is at least to achieve 10% chip production, these suppliers are not large enough to supply the European chip production.

Thus, aside from purchasing silicon wafers from these European suppliers, it will be required to purchase from a third party:

GlobalWafers Singapore Pte. Ltd. (Headquarter - Missouri, United States): GlobalWafers is a global leader in silicon wafers manufacturing. Moreover, the company has recently expanded and now operates in the U.S., Europe, and the Asia Pacific.

GlobalWafers is the most suitable company to supply the rest. Apart from having two wafer plants in Italy (Novara and Medrano), they have recently signed a partnership with Siltronic to invest $3.5 bn in new wafer plants which will allow reaching the 10% chip production. This partnership will be beneficial for the foundry since it will be a healthier competition among suppliers.

Regarding machinery, the well-known ASML is the only supplier located in the Netherlands.

The following map shows suppliers' locations which along with all the previous information will allow determining where to locate the foundry:

Figure 18 Suppliers distribution in Europe

The circle shows which would be the suitable location range for the new foundry to reduce supplier transportation and allow supplier flexibility and reaction. Countries like Germany, Austria, Cech Republic, France, Italy, or Poland would be suitable for locating the foundry.

6.1.1.2 Buyers' footprints

As well to suppliers' locations, another factor that will determine where to locate the chip foundry will be buyers' locations. Regarding buyers' the following graph show chip demand by sector in Europe:

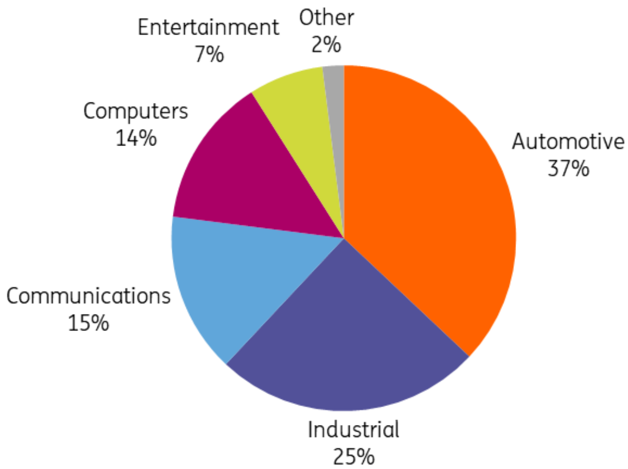


Figure 19 Buyers' demand by industry in Europe

Since automotive and industrial are the leading sectors of chip demand in Europe the foundry should be located where these industries are more powerful in Europe to ensure production flexibility and reaction, lowering supply risks [19].

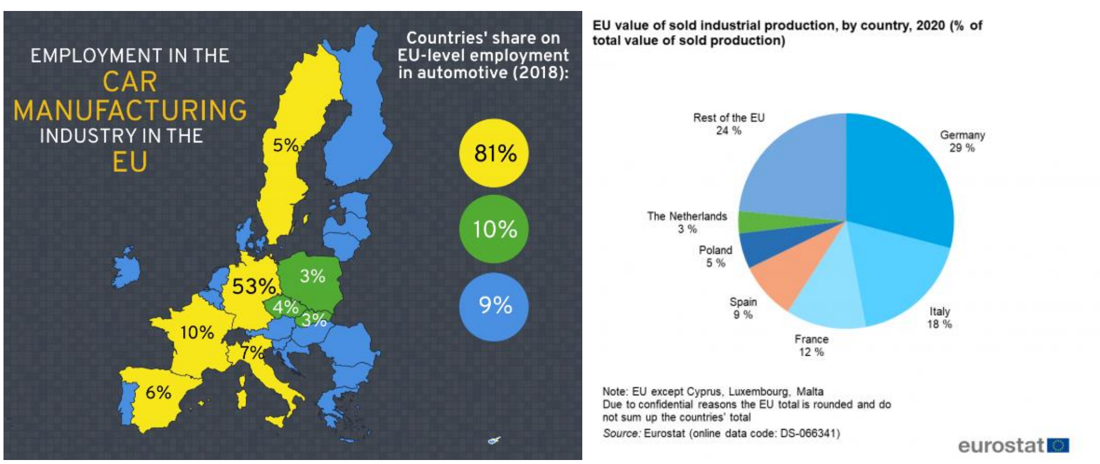


Figure 20 Automotive and Industrial Sectors in Europe

The automotive sector is dominated by Germany, with more than 50% of the European car manufacturing. This means that German car manufacturers will be the largest chip buyers. Regarding the industrial sector, Germany again dominates the market, with a 29% European market share. Both graphs clearly show that Germany will be, by far, the largest chip buyer followed by France, Italy, and Spain.

6.1.1.3 Profitability Analysis

6.1.1.3.1 Cost Analysis

Another critical factor to consider is costs. As mentioned previously, one of the causes of the industry's Asian dependency is cost savings since building and operating a foundry in Europe or the U.S is between 20-40% more costly than in Asian countries like China or Taiwan. Therefore, the cost analysis is crucial so the foundry can compete against these countries.

The cost overview is split into variable and fixed costs required to operate a foundry. These costs are the following:

1. Location
2. Equipment
3. Production & Distribution
4. SG&A

Since there are four candidates where the foundries can be built, a cost analysis comparison will help to decide what country must be chosen.

6.1.1.3.2 Location

The first cost associated with a foundry is the location where it is built. Depending on the country, the price per square meter can vary considerably. Since the foundries are extremely large, the price per square meter is critical to saving investment costs. The following graph gathers the average price (€) per m^2 in each country [19]:

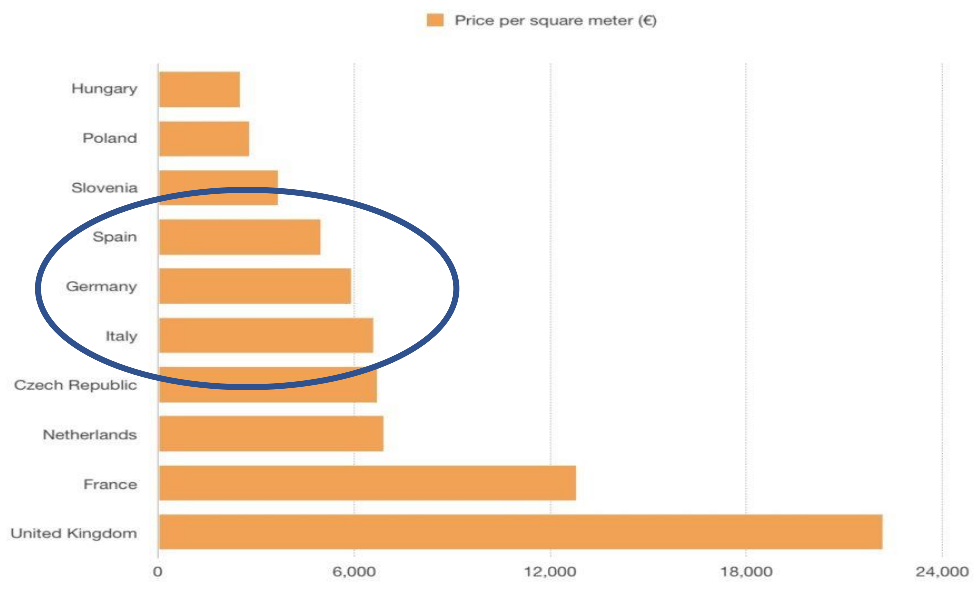


Figure 21 Price per square meter by region

The graph shows that Spain, Germany, and Italy have low similar prices per square meter, however, France has over twice the price of the others which would significantly increase the location cost.

For example, a TSMC foundry is on average a 365.000m^2 plant. Thus, the difference in building this plant among these countries would be [1]:

- Spain: $5100 * 365000 = 1.861 bn€$
- Germany: $5900 * 365000 = 2.153\ bn€$
- Italy: $6500 * 365000 = 2.372\ bn€$
- France: $12800 * 365000 = 4.672\ bn€$

Building the foundry in Spain is around 300M€ cheaper than in Germany and 500M€ than in Italy. The cost differences among these three are considerable but not determinant. However, France will duplicate costs from 2 to 4 billion which is extremely high making France a non-desirable country for building a foundry.

6.1.1.3.3 Equipment

The equipment required to operate the foundry is only supplied by ASML. Each machine costs around $180M and at least 10-15 machines are needed per fab which makes transportation costs insignificant (thousands of dollars). Therefore, there are no competitive advantages regarding equipment costs among the countries [2].

It is assumed that no matter where the foundry is located it will have 10 machines plus 1bn€ of other machinery required.

- Lithographic machinery: $180M€ * 10 = 1.8bn€$
- Other machinery: $1\ bn€$

6.1.1.3.4 Production & Distribution

Production costs are mainly associated with the wafer suppliers. Suppliers will be the same three mentioned for every possible location so raw materials cost (wafers) will be similar. Each raw wafer currently costs around €300 in Europe. However, the suppliers' map showed that Germany and Italy have a small competitive advantage regarding transportation costs associated since they are in a closer range with suppliers.

Every location would have the same production cost with respect to wafers [17]:

- Wafer cost: 200€
- Monthly wafers: 30000
- Production Costs: $200 * 30000 = \frac{6M€}{month} = \frac{72M€}{yr}$

The wafer transportation is carried out by trucks. The average transportation distance for each country Germany is the following:

- Spain: $2500km$
- Germany: $500km$
- Italy: $800km$
- France: $1500km$

The transportation operation cost is calculated as follows:

- The average truck cost per km is $1.09\ €/km$

- A regular foundry has a capacity of approximately 30000 wafers per month.
- Wafer size: $1 * 1 * 1 = 4m3$
- Large 53-ft Truck capacity: $16.15 * 2.43 * 2.7 = 110m3$
- Wafers per truck: $16 * 2 * 2 = 64$
- Trucks per month $\frac{30000}{64} = 469$
- Transportation cost per month:
  - Spain: $469 * 1.09 * 2500 = \frac{1.2M€}{month} = \frac{14.4M€}{yr}$
  - Germany: $469 * 1.09 * 500 = \frac{255K€}{month} = \frac{3.06M€}{yr}$
  - Italy: $469 * 1.09 * 800 = \frac{408K€}{month} = \frac{4.9M€}{yr}$
  - France: $469 * 1.09 * 1500 = \frac{766K€}{month} = \frac{9.2M€}{yr}$

Hence, building a foundry in France will imply an extra 5M€ annual cost while in Spain around 9M€.

6.1.1.3.5 SG&A

The last cost to be considered is Selling, General and Administrative Expenses. This analysis will specifically focus on labor costs that can make a difference in these countries.

The following official chart gathers the hourly labor cost in each European country:

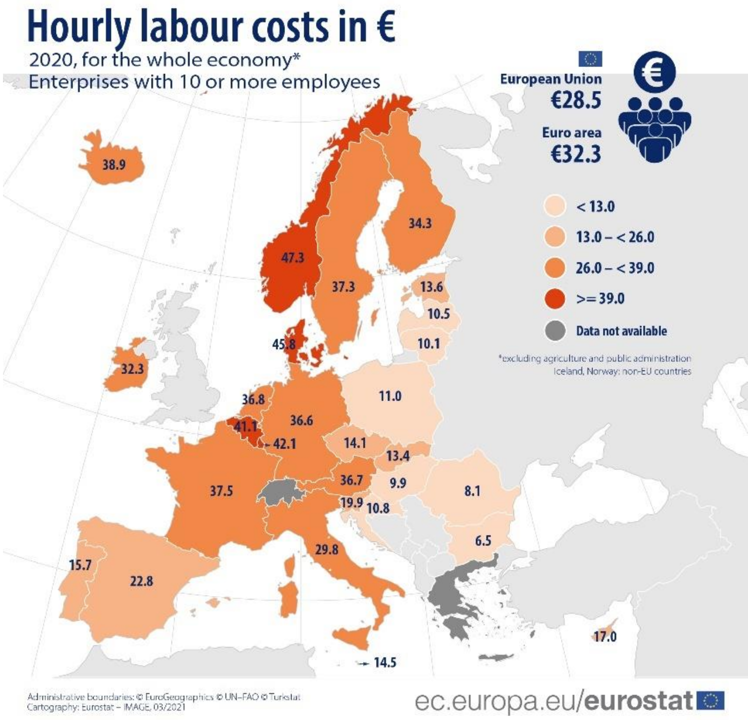


Figure 22 Hourly labor costs in Europe

Spain is by far the cheapest country followed by Italy. France and Germany are both much more expensive.

A chip foundry has around 1500 employees. Assuming an 8h-workday for every employee (40h/week-> 2080h/yr.), the following labor cost will be associated with each country [19]:

- Spain: $1500 * 22.8 * 2080 = 71.136M€/yr$
- Germany: $1500 * 36.6 * 2080 = 114.192M€/yr$
- Italy: $1500 * 29.8 * 2080 = 92.976M€/yr$
- France: $1500 * 37.5 * 2080 = 117.000M€/yr$

Other administrative and general expenses are considered similar for every alternative as $10M€/yr$.

Thus, Spain is by far the cheapest country regarding labor costs. The difference among countries regarding labor costs are higher than regarding production and distribution costs, therefore labor costs will be critical to deciding where to build the foundry.

6.1.1.3.6 Revenues analysis

Revenues are calculated per terminated wafer. TSMC estimates a global sales price of 800€ per wafer. Assuming the same selling prices for every country, foundry revenues would be:

- Revenues: $1200 * 30000 * 12 = 432M€$

6.1.1.3.7 Profitability

Finally, the following table collects all the relevant information for comparing the alternative scenarios in terms of cost and revenues (M€). To better understand what alternative the best is, the payback period is calculated as well:

Table 2 Profitability analysis by region

Country	Location	Equipment	CAPEX	P&D	SG&A	OPEX (yearly)	Revenues	Net Profit	Profit Margin	Payback (yrs)
Spain	1861,00	2800,00	4661,00	86,40	81,14	167,54	432,00	264,46	61%	17,62
Germany	2153,00	2800,00	4953,00	75,06	124,19	199,25	432,00	232,75	54%	21,28
Italy	2372,00	2800,00	5172,00	76,90	102,98	179,88	432,00	252,12	58%	20,51
France	4672,00	2800,00	7472,00	81,20	127,00	208,20	432,00	223,80	52%	33,39

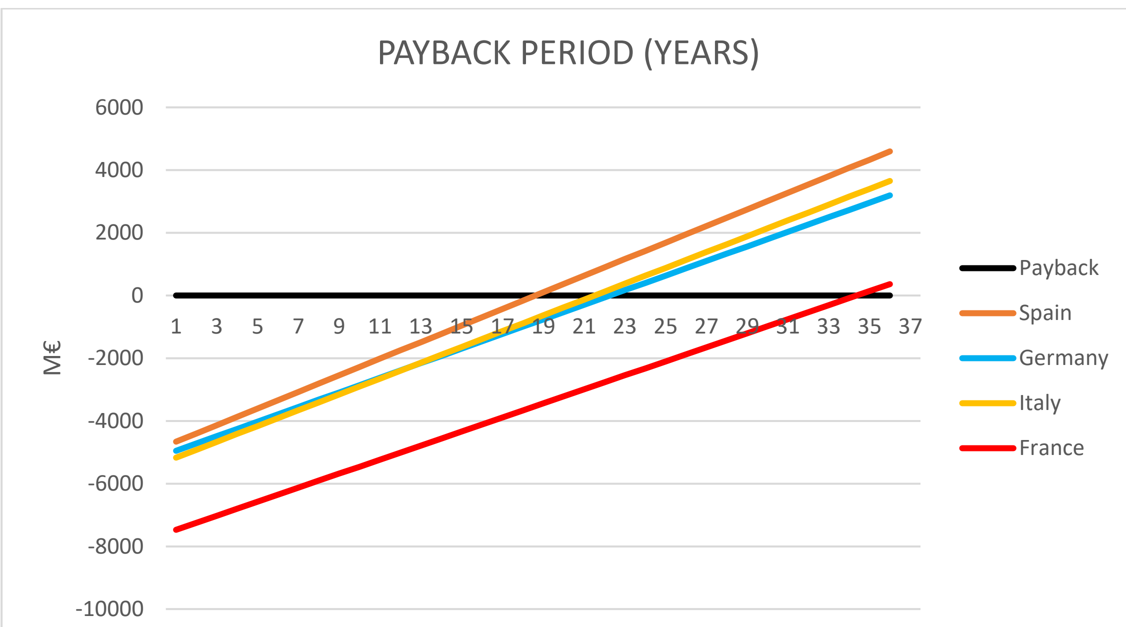


Figure 23 Payback period in years

Spain is obviously the best country regarding profitability with a payback period of 17 years. Considering that the CAPEX is extremely high (~5bn€) the payback period is not very large, so the risk in terms of profitability is quite low. Germany and Italy seem to be quite similar, and France clearly is less attractive.

6.1.1.4 International Risk management

Economic Risk: Analyzing the European economies, the healthiest economies in Europe short by GDP are the following:

TOP 10 Strongest Economies in Europe in 2022 [19]:

- Germany – $3.8 trillion
- United Kingdom – $2.7 trillion (no longer UE member)
- France – $2.6 trillion
- Italy – $1.9 trillion
- Russia – $1.5 trillion
- Spain – $1.3 trillion
- Netherlands – $913.8 billion
- Switzerland- $752.2 billion
- Turkey- $720.1 billion
- Poland- $594.2 billion

Again, Germany is the most suitable economy economically speaking. Although the United Kingdom should be the second, since it has its currency and no longer belongs to the UE, it is economically riskier for building a foundry. Same situation with Russia and Poland which have their currencies more vulnerable than the Euro. In addition, Russia is currently causing the Ukrainian conflict, terrible for businesses so countries next to Ukraine are more exposed to economic and political risks. Therefore, France, Italy, and Spain will be economically interesting in building a foundry.

Political Risks: Members of the European Union share the same regulations for global business. EU countries are very permissive providing a competitive advantage in political risks, which are very low. Besides, the Ukrainian conflict mentioned above is another political factor that should be considered. The foundries must be located far away from the conflict to minimize risks.

Cultural Risks: Most European countries share the same values so the cultural risk should not affect making this decision.

Thus, these four main factors clearly show that Germany must be the most suitable location for building foundries in Europe. Germany is perfectly located for suppliers and buyers and is the healthiest economy in Europe ensuring low risks although is less profitable than Spain. Spain and Italy follow Germany as possible locations both having some pros&cons. France is quite out of interest since is not profitable enough.

6.1.2 Production

The second strategic decision is related to production. Since one of the main goals of this solution is increasing the production to solve the shortage, this section will determine what market share must be achieved by the European suppliers, and therefore, how many new foundries will be needed to face the shortage.

The previous section revealed critical information regarding the production requirements. Currently, there are no European chip producers however, the chip demand in Europe represents 10% of the global demand. This means that Europe is completely outsourcing chips. This means that Europe is clearly more disadvantaged than any other in the world. While the U.S can almost supply America and Asian companies can do the same to Asian demand, they both must allocate a lot of resources to also supply Europe. Therefore, if we refer to the short-term, the ideal European production will be the one that allows Europe to be self-sufficient, which means that the European supply will be the same as the demand, 10%.

To estimate how many foundries will be needed to supply the European demand will be used TSMC information. TSMC has 21 fabs and a current 54% market share. This means that, on average, each foundry can supply approximately 2,57% of current demand. Thus, it can be determined that around 4 (3,88) foundries will be needed to meet the 10%. [20]

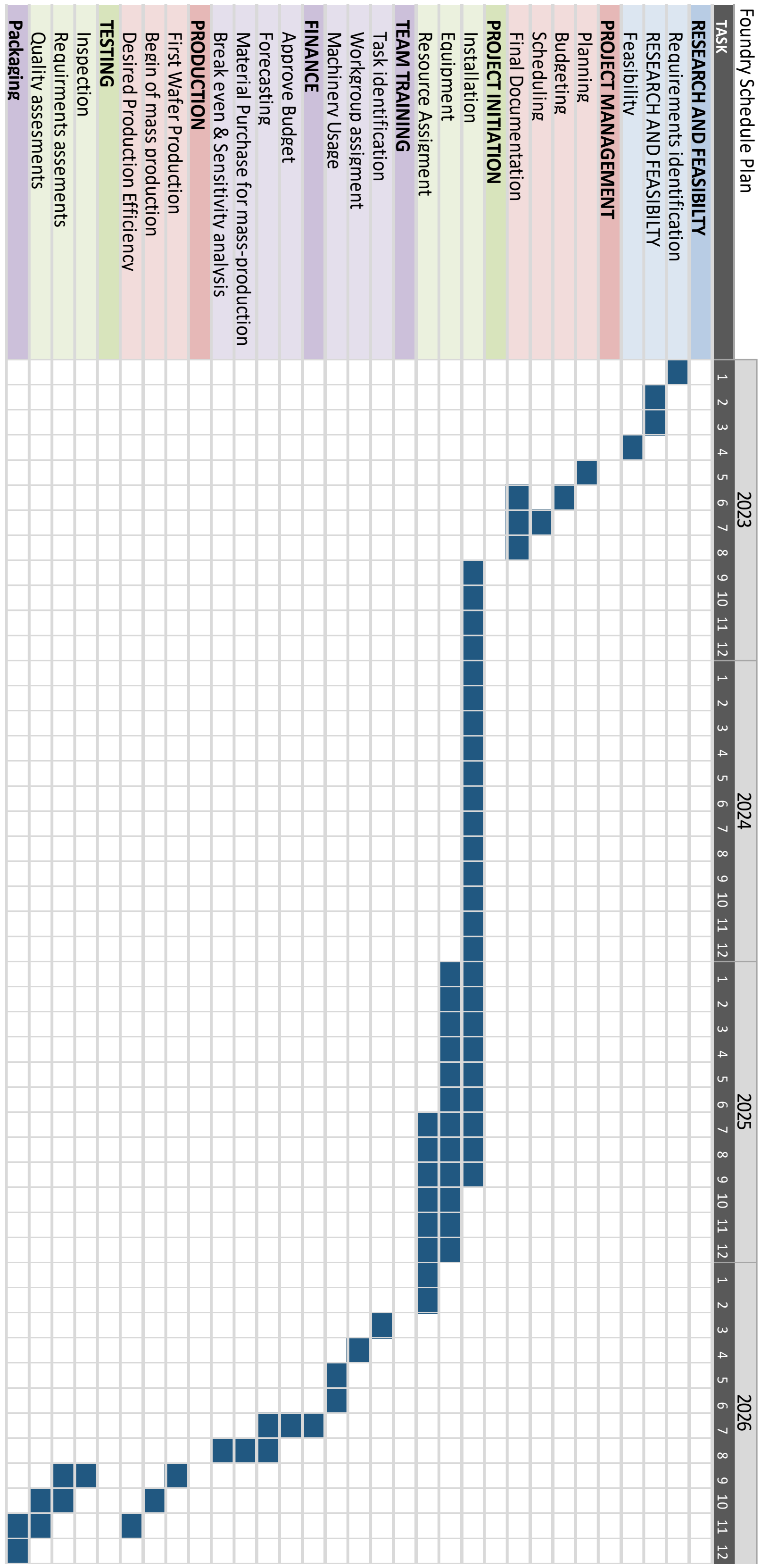
Therefore, this new chip supply chain will require an initial investment of approximately 20bn€ plus yearly operational costs to solve the shortage.

6.1.3 Scheduling Plan

The next strategic decision is a schedule plan. The construction of four foundries will solve the shortage in the short-medium term. Hence, a schedule plan must be developed to define how long will take this new supply chain plan to be carried out and solve the shortage.

The main tasks regarding each foundry project plan are stated in the Gantt diagram with estimated completion dates shown in the following table. The time estimates for each task are written in months:

Table 3 Foundry Project Grantt diagram



Thus, the new chip supply chain will be available and at full performance in a 4-year term. By this time, the shortage will be completely mitigated, and the industry will no longer be fragile and vulnerable.

6.1.4 Stakeholders' role

The last strategic decision is to determine what companies would carry out this plan. Obviously, all the Asian supremacy companies will oppose this plan since they have a competitive advantage with an industry oligopoly. Therefore, it must be occidental companies who must collaborate to develop this plan.

The companies that will carry out must satisfy some requirements but also it must be beneficial for them so they will desire to proceed.

First, these companies must already belong to the foundry industry having the knowledge to build a foundry due to its complexity. New entrants will not succeed. Besides, it must be companies that have the capacity to carry out such enormous investments, both economically and operationally. Each of these foundries requires an investment of around $5bn, a huge amount that not many companies can afford. But also, they must supply a large number of chip buyers, so they must have the experience and capacity to operate the project. The last requirement for these occidental companies is that they must have a global vision and mission pursuing a global benefit from the industry which allows them to collaborate in a foreign continent ensuring the success not only of themselves but the whole industry.

Finally, these companies must be attracted by the new supply chain to develop it so, aside from solving the situation, there must be also benefits for these companies. Thus, these companies must desire to expand their business to Europe so their global presence in several countries or European presence is a must for being attracted to them.

Among occidental companies, there are just two large enough companies that satisfy these requirements: Intel and GlobalFoundries.

To recapitulate, on the one hand, Intel is the world's largest IDM that produces the vast majority of its chips. Intel is one of the few IDMs that play two roles in the supply chain since they have the knowledge and capacity to fabricate their chips as well as manufacture them. Intel manufactures chips in almost every corner of the world including Europe. However, currently, Intel foundries are all located in the U.S. The only problem with Intel is that they will not be willing to destiny a large part of its production to sell to their competitors since Intel also manufactures the chips.

On the other hand, GlobalFoundries is the only occidental chip foundry that already has a presence in several countries. Since GlobalFoundries is a chip foundry that sells directly to IDMs they will have a highly competitive advantage in Europe since they could sell their chips to most of Intel's competitors in Europe.

Thus, both Intel and GlobalFoundries must collaborate to carry out the new supply chain action plan that will be defined in the following section which will finally solve the microchip shortage.

I would like to mention that these and other companies already have small foundries in Europe. It hasn't been mentioned before since these foundries do not represent more than 2% of the total chip capacity and are quite old in terms of technology. In particular, Intel has a foundry in Ireland and GlobalFoundries in Dresden, Germany.

6.2 SUPPLY CHAIN ACTION PLAN & MANAGEMENT

The goal of this section is to deploy an action plan for the new supply chain based on the analysis of the previous section. As mentioned above, this new supply chain must be led by the two large companies who will build the required foundries to solve the shortage and delays. Its company will have its own strategy regarding supply chain action plan and management; hence, they will separately be analyzed but its competency will be taken into account.

6.2.1 Intel's supply chain

Action plan

Intel plays a crucial role in the European supply chain. The IDM giant already has a fab in Ireland that satisfy a portion of its European demand. Considering that Intel is one of the unique enterprises that both fabricate and manufacture their chips, currently, Intel foundries destinate their total chip production to Intel's chips, which means, they are both supplier and buyer at this stage of the supply chain and they don't export chips to competitors. Thus, Intel's plan must first, satisfy its whole European demand and second, help ensure satisfying the global Intel demand, especially in middle east Asia thanks to its strategic position in Europe.

Hence, although one more foundry will be enough to intel for satisfying the vast majority of their European demand, it will be totally worth building a second foundry ensuring supply chain resilience in both Europe and middle east Asia and a flexible strategy. It will also satisfy the expected demand growth.

Using the previous analysis, the location selected for Intel's new fabs will be Germany and Italy. Germany is the best potential location for building a new foundry based on the analysis and is the closest potential location to middle east Asia. Italy has been selected as the second location instead of Spain since Intel has already an office in Milano, but they don't have it in Spain which is very beneficial in terms of mitigating risks and also saving costs. This plan will have an initial investment of approx. $10bn dollars and a payback of almost 22 years.

Supply chain management

Supply chain management refers to the management of the flow of goods and services and includes all processes that transform raw materials into final products. It involves the active streamlining of a business's supply-side activities to maximize customer value and gain a competitive advantage in the marketplace. For this case, SCM consists of selecting what suppliers and what demand will satisfy each foundry.

Suppliers' management

First, ASML will supply all foundries with their machinery since is the only equipment supplier.

Second, the Ireland fab, that already exists will be supplied by Okmetic Oy and Siltronic since they are closer than GlobalWafers. Two different suppliers have been selected to ensure resilience and reduce supply risks. Under a supply problem from any of these two suppliers, GlobalWafers production is large enough to help satisfy this foundry.

Third, the new German foundry will be located next to the Siltronic AG fab reducing supply distance and risk to the minimum. It will also be partially supplied by Okmetic Oy for the same reasons. Under a supply problem from any of these two suppliers, GlobalWafers production is large enough to help satisfy this foundry.

Finally, the Italian foundry will be supplied by the two GlobalWafer fabs located also in Italy. Although there are from the same supplier, since they have two fabs, it is considered that the supply is diversified as it would be different suppliers. Under a supply problem from any of these two suppliers, Okmetic's production is large enough to help satisfy this foundry.

The following map below will show exactly how the foundries will be supplied. The current foundry is colored in blue while the new ones are colored in red:

Figure 24 Intel suppliers' management

Buyers' management

As explained above, the Intel case has the particularity that Intel is its own buyer. Therefore, these three foundries must supply Intel's main offices and distribute chips to every country Intel has a presence in. Since intel's products are worldwide, they must distribute to every single country in Europe. Then, Intel will store its chips until its sold to end consumers. The buyers' management in reality consists in distributing their products from these foundries to every single corner of Europe. The supply strategy follows the logical distribution of resources, the smaller distances the better.

Thus, the current Intel foundry located in Ireland since is older and smaller than the others will only supply Intel warehouses and clients in Great Britain, and Nordic countries, and will help the French and Spanish demand.

The Italian foundry will supply Italy, a portion of France and Spain, Switzerland, and North Africa. This foundry plays a crucial role in Intel's strategy. It will also be in charge of exporting Intel products to other continents in case it is necessary to ensure resilience. As mentioned above, these three foundries will produce more chips than the European demand, hence, the redundancy in production will be destinate to help Intel's global demand under any risky situation.

The German foundry will play another important role in the supply chain. This foundry will supply the vast majority of the European continent and also neighbor countries such as Russia or Arabian countries.

Finally, the relationship among these foundries is quite simple. Under any critical circumstances that impede Ireland or German production, the Italian foundry will destinate its excess production to supply the others' demand. In case it is the Italian foundry the one that is not available, then the German foundry will reduce its production to neighbor European countries to satisfy the European demand. The European neighbor countries' demands will be satisfied by the Israeli and Chinese foundries. Besides, the Ireland foundry will still satisfy part of the Italian foundry demand such as Spain or France. In case it will not be enough, Intel also could outsource chips to the other European foundry, GlobalFoundries.

The following map better shows the intel distribution in Europe:

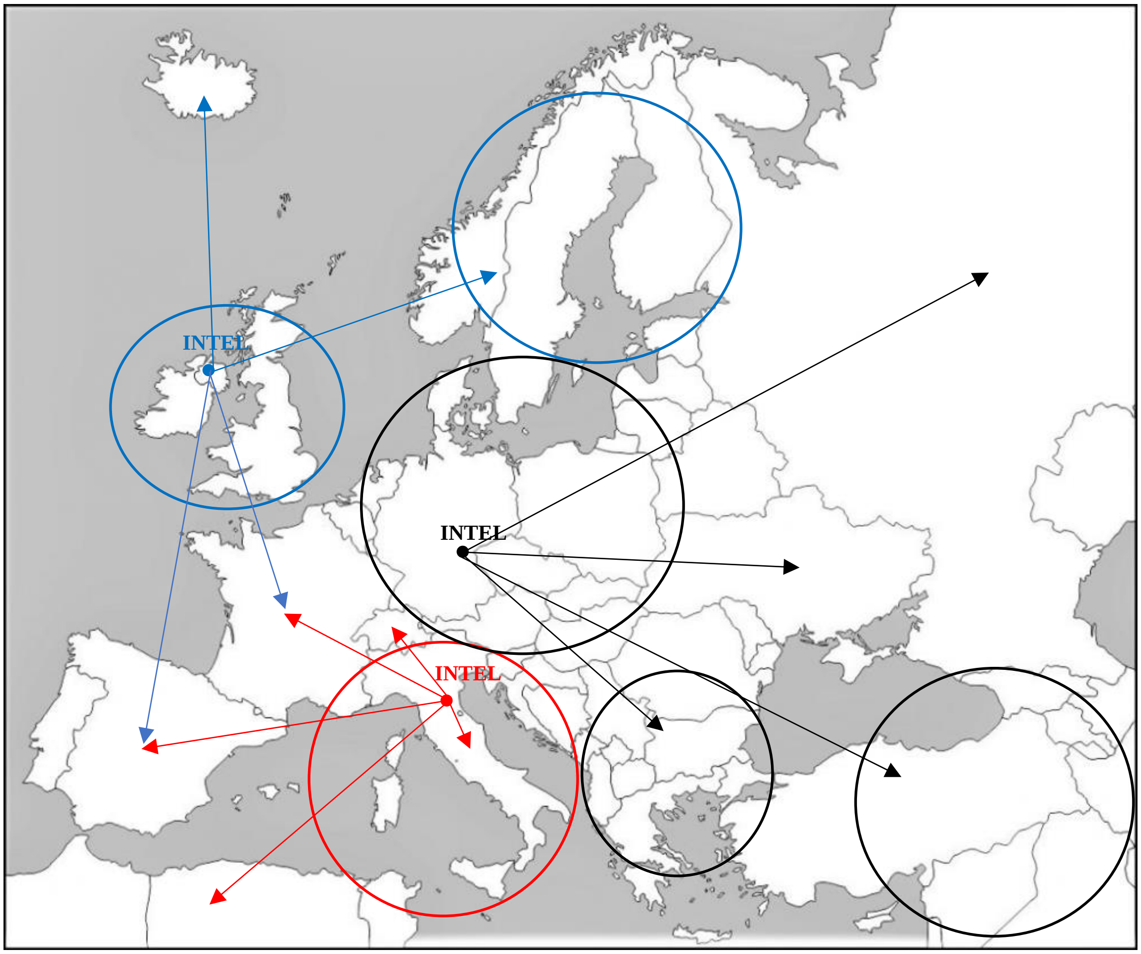


Figure 25 Intel buyers' management

6.2.2 GLOBALFOUNDRIES' supply chain

Action plan

The GlobalFoundries case is quite different from Intel's, especially regarding the buyers' management since they only fabricate microchips that are directly sold to chip manufacturers. Although GlobalFoundries is a divesture from AMD, the currently mainly fabricates chips for the automotive and industrial sector with customers such as Qualcomm. But they must take the advantage of acquiring new clients by building these foundries in Europe. These new potential clients could be the main Intel competitors that are reacting to Intel's move to Europe and have also decided to build manufacturing fabs in Europe. For example, Apple decided to invest $1 bn in a new manufacturing plant in Germany. Therefore, these three foundries must supply companies with a potential European presence such as Apple, NVIDIA, obviously AMD, and many others from different industries. Since they have no real competency, their competitive advantage is a plus to redundant the production by building more foundries than needed to satisfy the European demand since the risk of not selling their production is extremely low. Therefore, aside from the current German foundry, the GlobalFoundries strategy would be to build two more foundries to satisfy the demand.

GlobalFoundries already has a fab in Dresden, Germany, therefore, to diversify production reducing risks, their two new foundries will not be situated in Germany although is the best potential location. The other potential locations for building a foundry are Spain and Italy. Thus, GlobalFoundries will build a foundry in each country. The Italian foundry will be situated in the north of Italy, next to GlobalWafers fabs. The Spanish foundry will be located on the northeastern side where land and labor costs are cheaper and distribution distance to both suppliers and buyers are smaller.

With these two new foundries, the whole European demand can be satisfied and there will be also some extra production ensuring supply chain resilience in both Europe and middle east Asia and a flexible strategy. It will also satisfy the expected demand growth and help ensure satisfying the global chip demand, especially in middle east Asia thanks to its strategic position in Europe. This plan will have an initial investment of approx. $9bn dollars and a payback of almost 20 years.

Supply chain management

The GlobalFoundries SCM will follow Intel's structure defining what suppliers and what demand will satisfy each foundry.

Suppliers' management

First, ASML will supply all foundries with their machinery since is the only equipment supplier.

Second, the current German fab will be supplied by Okmetic Oy and Siltronic since they are closer than GlobalWafers. Two different suppliers have been selected to ensure resilience and reduce supply risks. Under a supply problem from any of these two suppliers, GlobalWafers production is large enough to help satisfy this foundry.

Third, the new Spanish foundry will be supplied by Siltronic AG fab and GlobalWafers although the two GlobalWafers foundries are closer than Siltronic, it is better to diversify the Spanish suppliers since the distances are quite large and reaction capabilities are smaller for this foundry. Under a supply problem from any of these two suppliers, the other GlobalWafers foundry is large enough to help satisfy this foundry.

Finally, the Italian foundry will be supplied by the two GlobalWafer fabs located also in Italy. Although there are from the same supplier, since they have two fabs, it is considered that the supply is diversified as it would be different suppliers. Under a supply problem from any of these two suppliers, Okmetic's production is large enough to help satisfy this foundry.

The following map below will show exactly how the foundries will be supplied. The current foundry is colored in blue while the new ones are colored in red:

Figure 26 GLOBALFOUNDRIES suppliers' management

Buyers' management

As mentioned, the GlobalFoundries case is different regarding buyers to Intel since. As mentioned GlobalFoundries' customers are in the automotive and industrial sector but there is a lot of potential since many potential clients are investing in European fabs to help solve the shortage. Hence, GlobalFoundries distributes its chips to these companies' main locations where their products are manufactured. Then, these companies will be in charge of manufacturing, storing, and distributing their final products to final customers. The buyers' management consists in selling and distributing their products from these foundries to the largest manufacturers in Europe. Therefore, the first thing to do is set where GlobalFoundry's potential clients are located. The following map gathers relevant information about main manufacturing fabs from relevant customers:

Figure 27 GLOBALFOUNDRIES potential buyers

Thus, the current foundry located in Dresden, Germany, will focus on the German supply since most of the largest current and potential clients are in German. These buyers will be the largest IDMs so their demand will be extremely large. Nordic countries and the Czech Apple plant will also be supplied by this foundry.

The Italian foundry will supply Italy, a portion of France, Belgium, the Netherlands, and Greece. Since these countries require chips for the automotive, industrial, and other sectors which are smaller than the large IDMs demand, the Italian foundry can supply more countries than the German.

The Spanish foundry will play another important role in the supply. This foundry will Spanish, French, Irish, and Britain clients from the automotive, industrial, and other sectors. It will also oversee exporting its products to other continents in case it is necessary to ensure resilience. As mentioned above, these three foundries will produce more chips than the European demand, hence, the redundancy in production will be destinate to help GlobalFoundries's global demand under any risky situation.

Finally, the relationship among these foundries Under any critical circumstances is the following. In case something impedes Italian or German production, the Spanish foundry will destinate its excess production to supply the others' demand. In case it is the Spanish foundry the one that is not available, then the German foundry will reduce its production from IMDs to satisfy the European demand. The IDMs' demands will be satisfied either by the U.S. foundries or by outsourcing from Intel.

The following map better shows the GlobalFoundries distribution in Europe:

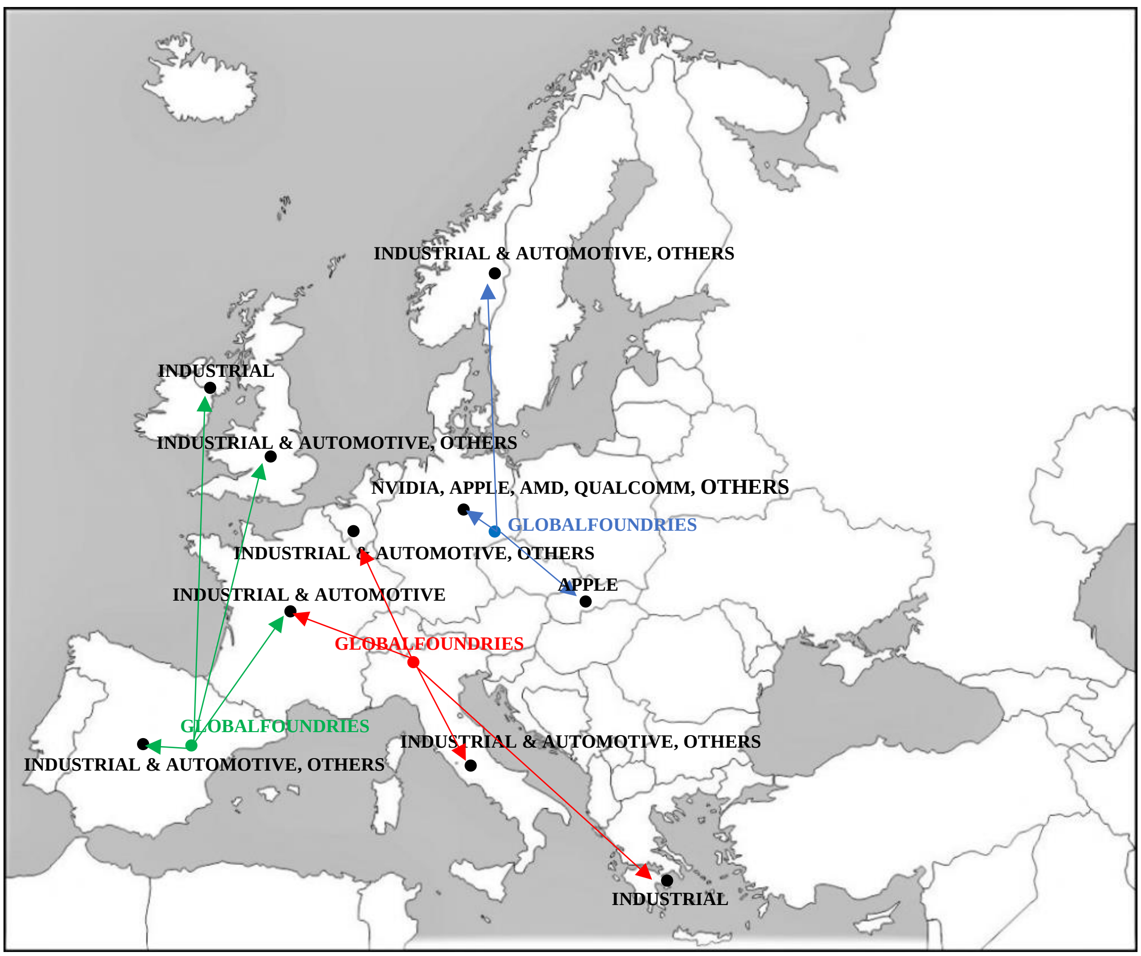


Figure 28 GLOBALFOUNDRIES buyers' management

7 CONCLUSIONS

This research project presents the microchip industry, the causes of its shortage crisis, and the only feasible solution under the title “Confronting technology's greatest crisis: Global chip shortage. Design of an innovative new supply chain.”

The microchip industry appeared just 70 years ago with the invention of the transistor. Since then, technology provided by electronic devices has become essential in every day’s life. The industry is growing at an alarming rate achieving such a demand that the supply is unable to follow.

In addition, the demand also is expecting more sophisticated chips duplicating their power every two years which is also very challenging for chip manufacturers suffering from technical and physical limitations. Very few companies have the power and knowledge to operate in the microchip industry. Thus, the microchip supply chain is currently extremely fragile and vulnerable and has a strong dependency on Asian foundries that have over 85% market share.

Finally, Covid-19 hit the world causing devastating humanitarian and economic effects. It especially affects vulnerable industries since fabs had to shut down for at least 3 months. The microchip industry was undoubtedly the industry that suffer the most from Covid-19. However, the main causes of the chip shortage are the ones mentioned above while the Covid-19 was the detonator.

Today, mankind must deal with one of the greatest technology crises of its existence. With continuously growing demand and the extremely complex and sophisticated industry, traditional solutions such as new entrants or simply increasing the current supply are not feasible. There is only one possible solution to solve the shortage: Design an innovative supply chain for new chip foundries away from Asia. Define the supply chain strategy and management.

The analysis made resulted in the design of a new supply chain in Europe based on four new foundries that will reduce the Asian dependency, supply the European demand, and also will help to ensure the chip global demand making the industry robust. The stakeholders that will carry out this plan will be Intel and GlobalFoundries since they are occidental companies that already have a European presence and it will be beneficial for their own business.

The construction of four new foundries from Intel and GlobalFoundries will solve the shortage by ensuring the supply of European microchip demand. The analysis showed that Germany and Italy would be suitable locations for Intel's foundries while Italy and Spain would be the right choice for GlobalFoundries. Besides, the redundant production from the two existing foundries will help to have a strong supply chain resilience that can quickly adapt to changes through strong communication among foundries and supported by a positive relationship between Intel and GlobalFoundries since they are not real competitors in the market.

The plan requires an investment of approximately $19 bn that will solve the shortage in four years when mass production will be unlocked in every single foundry. This plan requires a huge investment from these two companies that won't see results in a very short therm. However, in the medium-large term it not only solves the problem but also will be profitable for them since the payback period is approximately of 20 years. Delays will also be reduced to the minimum since transportation distances will be smaller than ever.

The European chip foundry map with the 6 foundries is the following, where the current foundries are colored in black and the new ones in red:

Figure 29 Expected foundries locations in Europe

This flexible supply chain strategy must and will be supported by other companies' investments that already announced their expansion to Europe to solve the current shortage (APPLE, NVIDIA, QUALCOMM, among others). The European expansion of potential buyers will encourage other chip foundries to expand their business from Asia to Europe and compete in this new market. Thus, the new European supply chain not only will solve the current shortage in approximately four years but also will help to react against the expected microchip demand growth in the upcoming years.

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9 SUSTAINABLE DEVELOPMENT GOALS

This thesis is also committed with Sustainable Development Goals. The new supply chain will heavily cut down distribution distances. Billions of chips must be distributed worldwide every year by ships and trucks which currently are one of the main causes of pollution. Therefore, reducing distribution distances will have a huge impact on C02 and other emissions reduction which is one of the main SDG.

Besides, the world is evolving towards digitalization where increasingly, instead of using tons of paper, documents, contracts, and all data are digitally stored in servers or clouds. The microchip industry plays the most important role in world’s digitalization. These changes make an enormous impact on the environment and, therefore, play an important role in the SDG.