

**UNIVERSITAT
JAUME I**

Bachelor Thesis in Economics

**A gravity model analysis of South Korean semiconductor exports to a selected
OECD group of countries**

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This paper estimates semiconductor trade flows between South Korea and a selected group of importing countries, from 2001 to 2020. Semiconductor exports are defined as the sum of HS8541 and HS8542 exports. It employs two specifications of the gravity model, a classic one and an augmented one. For the estimates, I used a panel data regression and I have chosen a fixed effects model after rejecting Hausman's null hypothesis. I find that standard variables of the gravity model, e.g. national income of both countries and distance are statistically significant, with their respective expected signs. In the augmented model, I find a positive effect of the Economic Complexity index of the importing country over the South Korean exports of semiconductors.

Keywords: Semiconductors; Gravity Model; ECI

JEL classification: C23; F10; F14

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1. Introduction

The technological developments of the last century laid the foundation of the modern world where technology and interconnection have become two of the most important aspects of our lives: countries through trade relationships exchange goods and services, while humans interact with each other through communication systems, such as mobile devices, computers, and a whole variety of electronics. Technology, in its most ample definition, including Internet connection, the use of mobile devices and smart tools, is part of our everyday life and its own development. Therefore, there is no aspect of human life that has not been touched or that does not depend on a technological device. At present it is almost impossible to carry out a task, however simple it could be, without using or needing a device connected to the Internet or that isn't intelligent.

In a world that increasingly depends on the Internet connection and that its future development will be marked by the digitalization era, technology has become the cornerstone of conducting activities in offices, colleges, and homes environments. In this context, the link that unites and makes possible for all electronic devices to work are semiconductors.

Contemplated as the brains of modern electronic equipment, semiconductors are present in every electronic device: from military defense to medical equipment, from household appliances to mobile devices, tablets, and computers. Considering the rapid implementation of devices using semiconductors for their operations (storing information or performing the logic operations) and the crisis generated by the latest events causing bottlenecks in the chip production chain, the current and future world is totally dependent on semiconductors and the ability to dispose of them.

The interest in a study of the semiconductor sector based on an empirical analysis arises from the importance of the sector and its importance in the future. Therefore, the aim of this work is the empirical study of the international trade flows of semiconductors with the intention of establishing which variables influence the exchange of these goods, framed in a gravity model approach.

The rest of the paper is organized as follows: Section 2 revises previous empirical literature and the current situation of both the gravity equation model and semiconductor industry is discussed. Section 3 offers a description of the market, paying attention on the historical review, the classification of the semiconductor devices and the global value chain.

Section 4 discusses the description of the data and the specification of the model. Section 5 focuses on the econometric estimates and the methodology, Section 6 summarizes the main findings and Section 7 concludes the work.

2. Literature Review

It is common knowledge within economic development that international trade contributes to the development of a country, a region and even a continent.

Several studies and investigation work support this idea: for example, Frankel & Romer (2017) considered the variation of trade due to geographical factors as a specific data to identify the effects of trade, suggesting that trade, national and international, increases the income of a country by promoting the accumulation of physical and human capitals and by increasing productions at given capital levels. In detail, the relationship between the geographical component of trade and income suggests that a 1% increase in the “trade to GDP ratio” increases per capita income by at least 0.5%. Singh (2010) reviews the literature concerning the relationship between international trade and economic growth and states that the macroeconomic evidence provides substantial support for the positive and significant effects of trade on growth and production, while the microeconomic evidence lends more support to the exogenous effects of productivity on trade.

Trade flows have been studied for decades, with the purpose of analyzing what kind of effects may have on the national economy and what are the determining factors that may influence a bilateral goods (or services) exchange.

Tinbergen (1962) and Pöyhönen (1963) were the first to adapt Newton’s gravity model to analyze international trade flows. The gravity model for international trade is analogous to Newton’s gravitational equation: the bilateral trade flows between any pair of countries or regions are directly proportional to their respective national income (measured sometimes in GDP and others as GNP) and inversely proportional to the distance between them, that is commonly representative of trade costs or frictions, as many studies have verified. Both were the first that, independently and concurrently, discovered that trade flows between two countries are determined by their national incomes, and their distance

Tinbergen’s model included GDP of both exporting and importing countries and the distance between them as explanatory variables and added dummy variables to demonstrate whether the existence of trade agreements could explain the dependent variable. The analysis was carried out considering only commodity trade flows. Among the

findings of Tinbergen's analysis, the exports depend mostly on the exporting country GNP rather than on the importing country GNP. On the other hand, the study of Pöyhönen consider a static model using 1958 data from ten European countries. The model used resembles an input-output model that included the value of the exports from a country to another as explained variable. As explanatory variables, Pöyhönen consider national incomes and distance, as well as some parameters such isolation parameter or national-income elasticities of exports and imports.

Since the early 1960s, the so-called "gravity equation" was used to analyze trade flows, migratory flows, and levels of foreign direct investments, and since it has become popular internationally. For example, Wall (1999) applied a gravity equation model, using the method of ordinary least squares (OLS), to analyze the cost of protectionism on the volume of US exports and estimate the impact on the welfare state. More recently, Botezat & Ramos (2020) applied a gravity approach to analyze the physician's (health worker migration) brain drain, especially the channels through which a sample of developed countries attract foreign medical doctors from developing countries. The PPML estimator was used as the econometric method. To carry out the specification of the model, the key dependent variable is the inflow and outflow of doctors and nurses. The unemployment rate, dummy variables such as common language and colonial-tie, distance, and the ratio of GDP per capita for the county of origin relative to the GDP per capita for the country of destination, were some of the independent variables considered as part of the explanatory variables. The results suggest that a lower unemployment rate at destination increases the migration flows; they also found statistically significant effects of the GDP ratio on migration inflows.

Gupta et al. (2019) analyzed the impact of geopolitical risks on the trade flows using a gravity approach and found that geopolitical risks are negatively related to the trade flows. Likewise, Rodríguez-Crespo & Martínez-Zarzoso in 2019 applied a gravity approach to investigate the effect of internet on aggregate trade flows.

Sanusi et al. (2018) used a vector autoregression (VAR) with a single gravity equation to investigate the determinants of the Indonesian plywood exports, which results show a relationship between GDP, population, exchange rate, price, distance, and Indonesian export volume with lag one and that reciprocal relationship between the variables are statistically significant. Moreover, Kuik et al. (2019) empirically examines the impact of domestic renewable energy policies on the exports performance of renewable energy product, performing a gravitational estimation of international trade and considering bilateral

export flows for wing and solar PV goods as dependent variable and the typical gravity independent variables. They used PPML and the Heckman Sample Selection Estimator as econometric methods.

Despite the prominent use, the gravity approach to explain trade flows was often criticized for lacking a solid theoretical foundation. Anderson (1979) was the first who provided a strong theoretical explanation to the gravity equation. He derived a reduced-form gravity equation from a Cobb-Douglas equation of constant elasticity of substitution (CES) expenditure system, considering national income of two countries and a distance variable, as previous works did. In his analysis, Anderson considered aggregated data and concentrated in commodities goods, considering as differentiated by country-of-origin.

Bergstrand (1985) contributed to provide theoretical foundation to the gravity approach. He also derived a reduced-form gravity equation from a partial equilibrium subsystem of a general equilibrium model, using CES preferences. In his analysis, he treated exporter and importer incomes as exogenous and assumed, like Anderson, perfect substitutability of goods internationally in production and consumption. The gravity model used included, in addition to the variables typically used, price and exchange rate variables, a dummy of preferential trading arrangements and a dummy for adjacency between countries.

The above-mentioned studies only linked bilateral trade flows to the incomes of both countries. Bergstrand (1989) extended the microeconomic foundations for the gravity equation. He incorporated factor-endowment variables as if it were a Heckscher-Ohlin model. In his novel analysis, he added per capita incomes (or population) but kept the Anderson's CES preference. The generalized gravity equation was extended with the purpose of finding out if it was consistent with modern theories of inter-industry and intra-industry trade.

Moreover, Deardorff (1995) demonstrated that gravity model is consistent with several variants of the Ricardian model and proved that a simple gravity equation could be derived from the Heckscher-Ohlin model without assuming product differentiation. In his work, Deardorff concluded that simple forms of the gravity equation can be derived from standard trade theories.

Practitioners of the gravity equation over its early introduction only applied the model using the standard variables, such as national income, distances, and a few dummy variables to explain unobserved factors other than trade flows. It was Bergstrand in his works

done in the 90s that augmented the general gravity equation, considering price volatility and depreciation of the currencies of the countries. Since then, wide variety of variables have been used and empirically tested to find which is explanatory. Some of the most used independent variable includes market size, national income level, country surface area, population, and purchasing power. Geographical distance is another independent variable commonly used in augmented gravity model specifications, which is employed as resistances factor for trade flows. Other variables are common language, common colonial history, preferential trading arrangements or FTA memberships (for example NAFTA, Mercosur, or European Union). The purpose of adding such variables is to control the unobserved country characteristics or other unobserved factor that can either promote or impede trade.

Analysis such as those carried out by Greene (2013) or Martinez-Zarzoso & Lehmann (2003) have implemented augmented gravity equations. In the first, the author derived from the normal gravity equation (with the standard variables) an equation with conditioning variables such the index of trade openness, economic development index or the index of overall competitiveness with the purpose to explain the US trade flows to India, mainly goods from the advanced technological sector (such as electrical machine and parts, aerospace accessories and motor vehicles). The econometric analysis was carried out considering panel data and a fixed effect model (selected over random effects model and OLS), finding that per capita income, trade freedom, importer's physical land area, among others, are significant determinants of US export flows.

In the second article, an augmented gravity approach was implied to assess Mercosur-EU trade. The estimations were carried out using a panel data analysis with fixed effects model and the findings suggested that the standard gravity variables are all significant (importer and exporter income have a positive influence on bilateral trade flows, exporter population has a negative effect on exports while importer population has a positive effect on them). Likewise, the augmented gravity variables happened to be all statistically significant and presented the expected sign, despite the importer infrastructure variable wasn't significant.

Regarding semiconductors, much has been written, especially from a business and economic point of view, despite being an industry that has been in existence for less than approximately 80 years. Nevertheless, this aspect of the industry did not stop the scholars and experts from analyzing its main characteristics. Analysis have been carried out with the

purpose of understanding the structural characteristics, the internal and external factors that could affect its value chain, the relationship between the various agents involved in the production chain, among other aspects.

It has also been investigated the decision making and firm behavior. Studies such as Hall & Ziedonis (2001) analyzed the patenting behavior of firms in the semiconductor industry, which is characterized by rapid technological change, cumulative innovation and driven by short product life cycles. They found that, throughout the decade of the 1980s, in the US semiconductor industry, the firms patent propensity had increased significantly and, that in contrast, survey evidence had appointed that semiconductor firms didn't count heavily on patents to appropriate returns to R&D. Consequently, a patent paradox arose. To investigate the determinants of patenting in the taken sample of semiconductor firms and find out how they had changed over time, a patent production function previously introduced in the 1980 was used, as empirical analysis. Since the number of successful patent applications made by firms is a count variable with 0 and 1, a Poisson-based model was used and estimated with the maximum likelihood for the Poisson distribution.

Tan & Mathews (2010) focused their study on firms' cyclical behavior in the global semiconductor industry, in order to understand the cyclical industrial dynamics and some of the implications for the structure and performance not only at an industry-level but also at a firm-level. They demonstrated that at the industry level the cyclical dynamics should be differentiated from business cycles and from the industry/technology life cycle. The study reported three stylized facts in relation to the cyclical industrial dynamics: first, the industry is more concentrated during the industry cycle downturns; second, the capital investment of the industry followed a 'pro-cyclical' pattern; and third, firms that pursued a 'counter-cyclical' capital investment strategy during the industry downturn have reaped rewards during the subsequently. Thus, cyclical industrial dynamics play a crucial role in firm rivalry, strategic positioning, and industrial growth, especially in downturns.

With respect of the relationship of the agents involved in the industry and the role that they play, Cohen *et al.* (2003) carried out a study to investigate how could the buyer-supplier relationship affect the attributed costs parameters specifically in the semiconductor equipment supply chain. By taking some assumptions, such as supplier rationality in balancing the three cost elements (cancellation, holding and delay costs), their estimation results suggested that the supplier is very conservative when commencing the order fulfillment, which undermines the effectiveness of the overall forecast sharing mechanism.

They also found that the supplier perceived the cost of an order cancellation to be about two times higher and the holding costs to be about three times higher than the delay cost.

The entire semiconductor industry has faced a rapid decline in price because of the short useful life of the products and how quickly chips become obsolete. Several studies have examined the faster rate of price decline since the mid-1990s and some authors have linked the steeper price falls to structural change of the period of cycle of the industry, from 3-year to 2-year industry cycle. Others have highlighted the fact that technological cycles had come shorter. In addition, some papers have argued that the speed-up in the rate of price decline reflected partially an increased competition between firms, specifically giant firms like Intel or AMD. Aizcorbe *et al.* (2008) analyzed the shifting trends on price over the years, applying an econometric analysis to determine whether swings in price trends are due to a random variation instead due to a structural change within the industry.

The company structure, business models and trends within the industry have also been analyzed in many studies with an empirical analysis using an econometric technique. Hung *et al.* (2017) and Saha (2013) are some of the most cited examples in the current literature. More in detail, there are recent studies that evaluate the performance in the industry, using panel data, between the technical efficiency of the integrated device manufacturer (IDM) business model and the fabless-foundry business model. Estimates indicate that IDMs, which are capital intensive, take advantage of economies of scale and operate more effectively compared to the niche model of fabless companies. Also, a positive relationship and a significant lagged effect of R&D investments in the high technological industry were found (Hung *et al.*, 2017).

Saha in 2013 found that the evolving trends in the semiconductor industry were: foundries transitioning from pure-play manufacturing-only solution to complete integrated circuit new product development (IC NPD) solution providers; the fabless companies were focusing on strategies to design and sale niche products; more IDMs transitioning to fab-lite or fabless; foundries taking complete control of front-end manufacturing and state-of-the-art technology development; and back-end outsourced semiconductor assembly and test (OSAT) companies are in competition to provide scaled packaging solutions to customers. Thus, the competition within any given segment of the semiconductor value chain is continuously increasing.

The works carried out in the economic sphere have had various objectives, among

which we can highlight the one determining the cyclical pattern characterizing the industry and the factors that determine the cycles of the industry. The methodology in these cases contemplates autoregressive analyzes as in the case of Liu (2005) who used an autoregressive vector (VAR) of 12 variables to estimate the determinants of industry cycles; or Liu & Chyi (2006) who used a Markov regime-switching model to carry out the study; or Aubry (2013) who used a VECM model to determine the cyclical of the sector.

Despite all the work and analysis done regarding a gravity approach to trade flows, in the current literature, the application of a gravity equation model as an econometric framework to study determinants or examine trade flows in the field of the semiconductor industry and its subsectors has not been done before yet.

3. Description of the Market

3.1. Historical approach

The semiconductor industry is an interesting case to study due to several reason, among which because it has been one of the fastest growing industries and its innovative characteristic have made it one of the most important industries since WWII.

Most of the authors and experts in the field agree on the fact that the world's semiconductor industry can be separated into three periods, each of them marked by a radical technological innovation: the transistor in 1947, the integrated circuit in 1959 and the microprocessor in 1971 (Malerba, 1985). This division stands because each period had different effects on the development of the technology, the organization of both R&D and production, the competition among firms and the type of governmental support.

The very origins of the semiconductor date from 1947 when the transistor was invented at Bell Laboratories, an US company founded by the famous telecommunication firm AT&T, that gathered the most skilled scientists and technicians of the time, despite that semiconductor devices had been produced long before with the application of the vacuum tubes. Prior to that, between the decades of 1930 and 1940, semiconductor materials such as galena (a natural mineral) or silicon were used for wireless signals and in high frequency detectors; copper oxide and selenium were also used in small current rectifiers. Semiconductor devices were produced with electron tubes (being the triode the most common) and the most common manufactured product was for radio. Triodes were produced on a large scale and companies were characterized by the dominance of vertically integrated scheme of production in US, Japan and Europe. Most of the producers

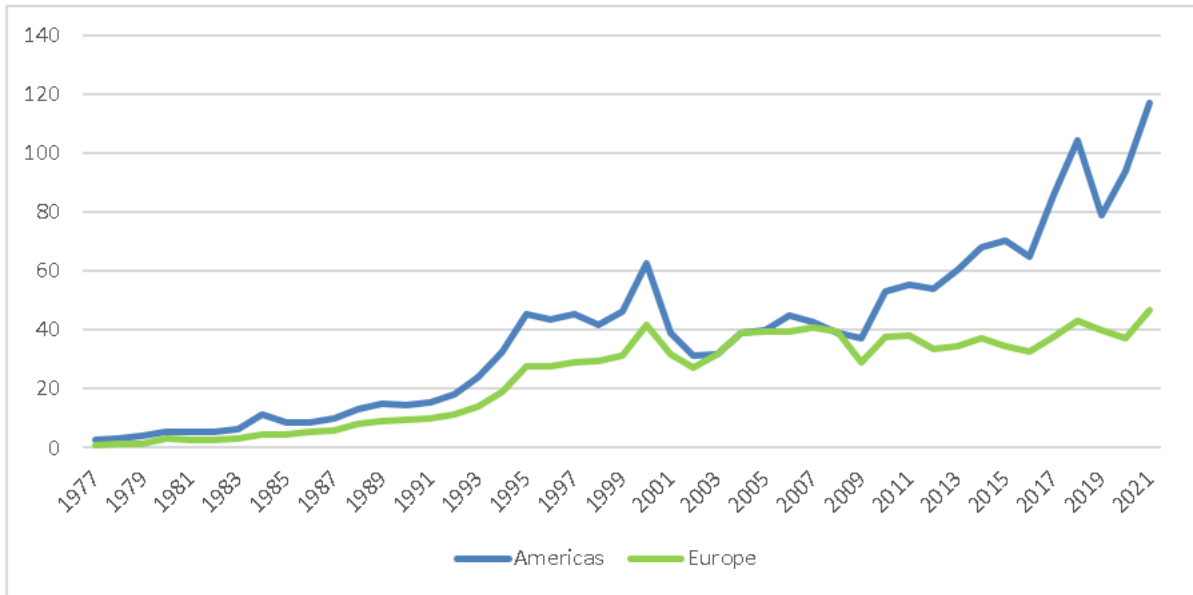
manufactured both electron tubes and semiconductors in-house, forming a stable oligopoly and restricting the entrance of new players by the usage of patent restrictions.

Europe, where firms, mainly electrical firms, possessed advanced technological capabilities in electrical and electronics technologies, turned out to be an important player in the industry, even though that the European industry had been destroyed during WWII and consequently had to rebuilt it. This factor allowed European producers to become pure innovators at the time, remaining among the world's major producers of electron tubes. They even started to manufacture the newly semiconductor devices, with a very active posture in research for new types of electronics components. During the decade 1950s, in the new industry dominated by the transistors, the European firms continued to be internationally competitive because they were on the same level as American firms, and they were even ahead of Japanese producers.

However, as Malerba suggested in his 1985 paper "*Demand structure and technological change: The case of the European semiconductor industry*", the decline of the European industry happened later because of two factors: the absence of governmental incentives and policy support, and the structure of the demand, focused on electronics consumer products rather than public procurement or computer demand. As can be seen in Figure 1, which represents the comparison between the sales of semiconductors worldwide in Europe and America, since the end of the 70's, Europe has not been able to overcome the hegemony of the North American industry. In the 1960s, European producers fell behind American producers in the integrated circuit technology and even though they didn't exit the semiconductor industry. Some reports and surveys indicate that they continued to produce discrete semiconductor devices, and some simple integrated circuit products. Despite the clear disadvantage, the European industry has managed to keep sales of semiconductors around 40 billion of US dollars for more than a decade.

The European demand for digital integrated circuits, one of the most advanced at the time, was satisfied primarily by imports from the US or by newly established US subsidiaries in the continent. The period after the one of transistors, the so-called integrated circuit period, was clearly dominated by US producers. The US semiconductor industry became leader in the innovative, productive, and commercial levels. In the 1960s integrated circuits started to be produced on a large scale and quickly exported their production to Europe and made foreign direct investment in Europe.

Figure 1. Semiconductor sales comparison, 1977-2021 (in billion US dollars): America and Europe



Source: own elaboration with data of the Global Billings Report history (3-month moving average)

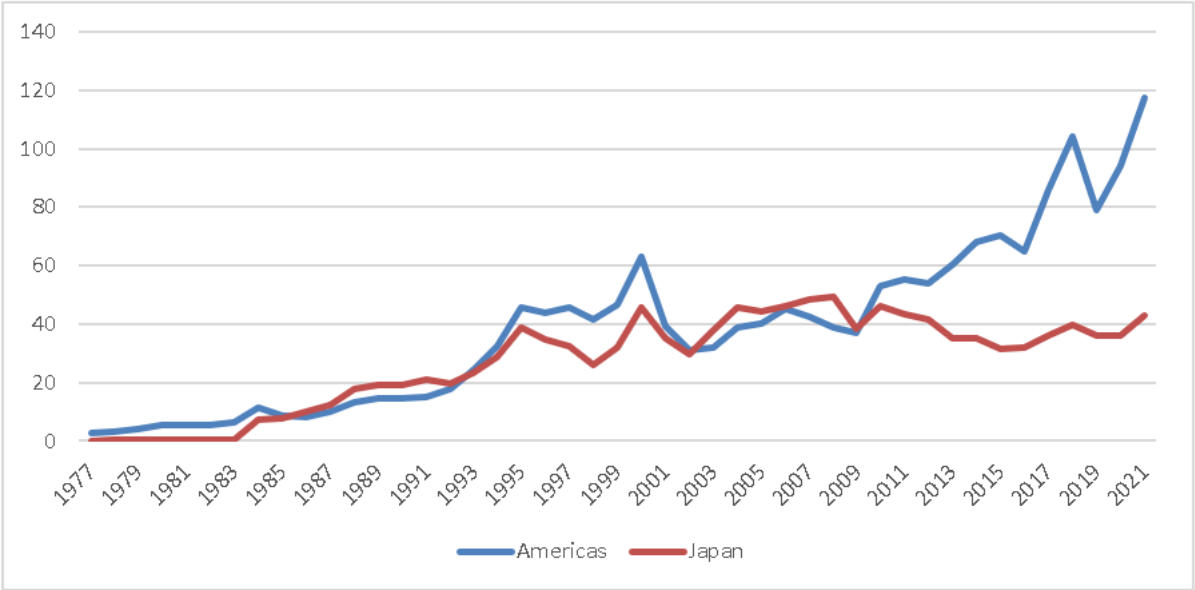
The undoubted American hegemony was because the industry experienced a significant structural change. New specialized companies entered the IC production while several vertically integrated producers were pushed out of the market. At the same time, the successful performance of the American semiconductor industry was the result of the public policy support as tax-related policies and subsidies were among the most common public policies.

The US government's demand to fulfill its military and space programs – within the Cold War and Space Run context- drove the semiconductor industry's growth. In the 1960s the industry grew rapidly due to the sizeable revenues generated from military demand for integrated circuits that afterwards were reinvested into R&D expenditures (Irwin, 1996). Some authors, like Langlois & Steinmueller and Irwin suggested in the decade of 1990s that the military demands for semiconductors generated several spillover effects that affected the shift of the development from military programs to civilian applications of chips, like the manufacture of portable and non-portable radios or electronic calculators.

If we consider the Japanese perspective, its industry stood between the Europeans and the Americans. They were able to protect its market from US penetration by essentially arresting foreign direct investment. During the early years of the industry, Japanese vertically integrated companies couldn't catch up with the innovate pace of its American competitors and could not adequately adapt to the integrated circuit technology. Still Japanese emergence as an important producer of semiconductors began in the late 1970s, with a significant increase of its global share in the semiconductor market, particularly in the memory market segment. In fact, Japanese firms passed from less than 30% of the market share, compared to 60% of US market share by the end of 1970s and by the mid-1980s to a position where Japanese firms were able to close the gap with American producers.

The growth experienced by the Japanese industry was driven by the rapid expansion in demand for transistor from the local consumer electronics industry. The Asian country consumer electronics provided 47% of semiconductor demand, being the comparable figure in the US 8%. This fact also explains that there was a structural difference between the end-use demand for semiconductor in both markets (Irwin, 1996).

Figure 2. Semiconductor sales comparison, 1977-2021 (in billion US dollars): America and Japan



Source: own elaboration with data of the Global Billings Report history (3-month moving average)

Later, in the context of an international trade dispute between Japan and USA, between the late 1970s and throughout the 1980s, Japan overtook the US in semiconductor production thanks to two essential factors; firstly, Japanese firms invested heavily in production capacity, devoting an average of 30% of their sales to capital spending during 1978-1985, and secondly, such investments were supported by large bank ties that granted easier access to capital.

Throughout the 1970s and the 1980s, the global industry also experienced rapid growth, marked by the proliferation of the integrated circuit commercial applications since government expenditures were outstripped by commercial demand, especially in computers, telecommunications, and consumer electronics. It can be seen from Figure 2 that from 1986 to 1993 Japanese world sales exceeded sales of the American industry. In those years, military demand dropped from approximate half of US semiconductor shipments to nearly 10% by early 1980s. Furthermore, to reduce costs, semiconductor firms headquartered in the US started, by the early 1970s, to move labor-intensive assembly operations overseas, particularly to Southeast Asia. Figure 3 shows the significant increase in global sales in these countries thanks to these strategic actions of American companies. Alongside these efforts to compete in costs, Japanese and European firms started to gain more presence in the international market (particularly the Japanese presence in the DRAMs market) and especially in the US market.

On the other hand, European industry lacked of the dynamism of the US industry and the competitive focus of Japan. Most of the European firms did not focus their attention on external sales as Japanese firms did by emphasizing their efforts in high-quality mass production and did not count with the military and computer demand that US enjoyed. Until the 1960s, European semiconductor industry was mainly self-sufficient in transistor, but trailed US innovation and technology that left it uncompetitive in the early digital logic chips, which later on would have defined the international microchip industry.

The adoption of Large-Scale Integration (LSI) technology represented a huge change in the industry, which meant the process of embedding thousands of transistors on a single semiconductor microchip. This represented a trend towards miniaturization and stimulated new fields of applications. Moreover, this regime resulted in the increase in complexity, cumulateness and appropriability of technological changes where complexity was linked to the high number of components and gates, up to 10.000 on a single chip, while

cumulativeness was noticeable in the chain of innovation in products such as memories and microprocessors.

LSI devices were the most advanced types of semiconductors in the last two decades of the last century. The industry at the time was composed of two main types of companies: 1) merchant producers, being Intel the clearest example, which focused their production on specific types of semiconductors or custom devices, and 2) vertically integrated electronics goods producers, such as IBM whose production was linked to the upstream integration of final goods.

Considering the evolution of the industry from a historical perspective, there are various reasons why the evolution of specific industries, mainly the American, European, and Japanese, differs from one another, among them there are country-specific factors – such as scientific and technological infrastructure, the type of financial system and labor market characteristics - and sector-specific factors, such as supply and demand intrinsic characteristics, the role of public policy and the features of technology.

As previously mentioned, considering the demand structure as a crucial factor that influence on the technological evolution of the industry, in Europe and Japan the market was dominated by consumer demand, where semiconductors were used to produce radios and television receivers. Besides consumer and industrial demand, in-house demand continued to be relatively important, due to the vertically integrated firms in both regions. Public procurement, which includes the governmental and state-owned enterprises purchase of goods, was very limited if compared to others.

In the American continent, the US market was explicitly dominated by public procurement, and in particular the military demand and by the 1960s half of the American semiconductor industry's output was purchased by the public sector. In comparison, civilian demand represented only 30% of the demand for semiconductors, driven mainly by computers. Consequently, external demand gained importance compared to in-house market.

The types of demand are fundamental because they mark the needs of the agents: for example, the government demand required smaller, lower power-consuming and higher performance devices and they did not give importance to the price; civilian market on the contrary placed more emphasis on price and within it there was a wide range of segments (such as computer market, consumer market and industrial market, each with its own needs

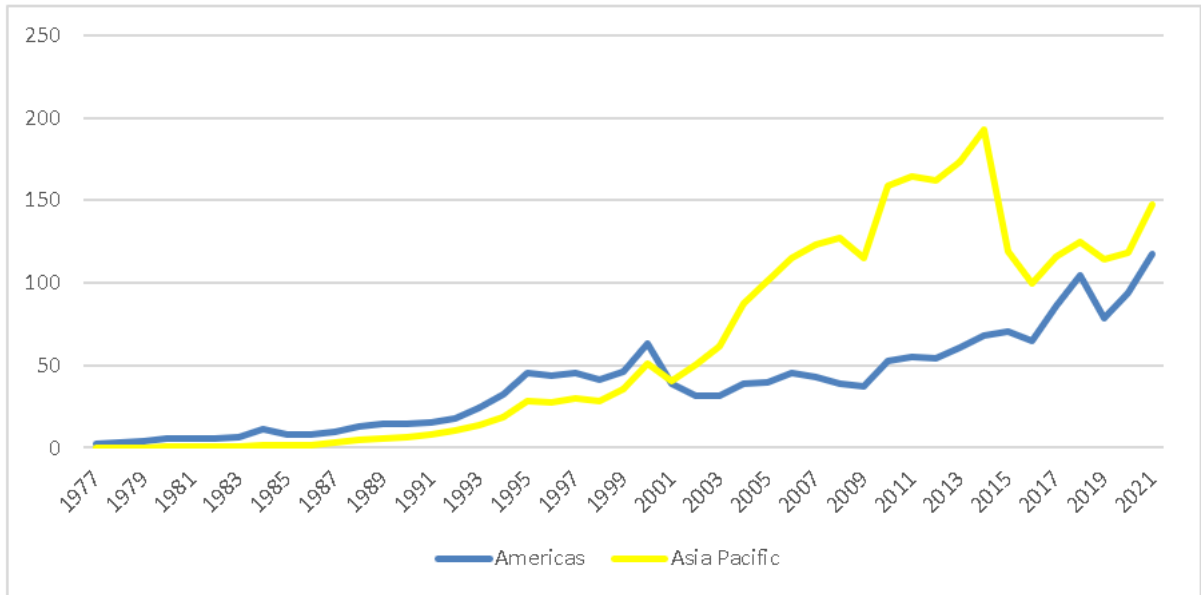
and specifications). In fact, since its invention, the increasing applications of integrated circuits marked the rate of technological change. The computer demand gained importance as a consequence of it because they required semiconductor devices that could execute more complex functions.

In the IC regime, American merchant producers - Intel, Texas Instruments, Fairchild, among others - dominated the world digital IC market. European and Japanese demand structure were similar with two exceptions: a large demand for digital IC by Japanese calculator firms and the protection of domestic market by the Japanese government.

As previously mentioned, the LSI period was a milestone in the global industry. In parallel with firm's efforts to adopt LSI technology, markets - such as telecommunication equipment and electronics consumer goods - have developed and became rapidly interdependent and interrelated with semiconductor technology. During these years, Japanese firms committed themselves on the LSI technology and were supported by government policy, resulting on in an international competitive position. European firms realized the technological gap and took some time before the new technology influenced the European semiconductor industry, in the meanwhile the world demand for LSI devices was satisfied by American firms.

We have seen how the establishment of the semiconductor industry in the areas mentioned above was a process streamlined by a business network and an industrial development that already existed, given that they are industrialized countries. The expansion of the industry beyond the three regions was a slow process that began with companies' strategies, especially US firms, to take advantage of low labor costs, to overcome tariff barriers, to appropriate their intangible assets and to reduce transaction costs, through foreign direct investment abroad (Yoffie, 1993). In fact, it was not until 2001 that Asia Pacific worldwide semiconductor sales definitively surpassed the sales of the American industry, as can be seen in Figure 3.

Figure 3. Semiconductor sales comparison, 1977-2021 (in billion US dollars): America and Pacific Asia



Source: own elaboration with data of the Global Billings Report history (3-month moving average)

Thanks to the first wave of FDI in the period from 1960 to 1970, as defined by Yoffie in 1993, US firms invested heavily in Southeast countries. As a consequence, a former US company called General Instrument Microelectronics, established a semiconductor packaging business in southern Taiwan, representing the very first semiconductor related company in the island (Chang & Tsai, 2000). Later on, other firms such as Philips, Texas Instruments, Radio Corporation of America (RCA) and Toshiba built their own plants, focusing on labor-intensive downstream assembling and bringing technology for IC packaging, testing, and assembling.

The local government of the island saw the IC industry as strategic and strongly supported its development. In 1974 the Industrial Technology Research Institute (ITRI), an institution that will play an important role of transforming Taiwan’s industries from labor-intensive to innovate-driven, established the Electronics Research and Service Organization (ERSO) with the purpose of acquiring the technological know-how to develop an IC production plant. Four years later the first IC chip was made in the demonstration plant, marking the introduction of the IC manufacturing process that will be of extreme importance for the global value chain and for the world industry in the future.

In 1979, because of the great flow of technology transfer between foreign companies established on the island and local businesses, an industrial park called the Hsinchu Science Park was established to provide high-tech industry with a complete infrastructure and to give administrative support. The first local company to raise was United Microelectronics Corporation (UMC) as a spin-off company of the ITRI demonstration plant. UMC started operations in 1982 as a wafer fabricator. At the same time, the first IC design company was founded in the island, called Syntek. Within 5 years, there were 30 integrated circuit design companies.

A year later, in 1983, Taiwan Semiconductor Manufacturing Company (TSMC), one of the largest and most important companies worldwide, was founded, revolutionizing the local and global industry with a new business model of independent companies cooperating in design and manufacturing. The development of fabless/foundry model was a key inflection point in business model, boosting the innovation, lowering the barriers to entry, and enabling new companies' entrants to specialize in design almost exclusively.

In less than 20 years since the establishment of ITRI, Taiwan had a complete semiconductor industrial system including sub-industries in IC designing, photomask manufacturing, wafer fabrication, IC packaging and testing, with each sub-level specializing in their own area of expertise. Since then, the island plays a crucial role in the global industry and its presence in almost all stages of the global value chain it is indisputable.

Similar to the Taiwanese case, the origins of the South Korean semiconductor industry lie in the expansion of offshore investment in the country, beginning in the early 1960s. At that time, the US manufacturers took advantage of the low wage costs to assemble devices in the Asian country, that were re-imported in the home market. Some authors said that this fact enable a learning effect in terms of realization of the production and entrepreneurial skills associated with semiconductor production. In 1974 a joint venture between Samsung Electronics Group and a group of South Korean expatriates based in US established South Korea Semiconductor. Later the joint venture passed into the sole ownership of the Samsung Group and became Samsung Semiconductor and Telecommunications Company or SSTC; the technology transfer that occurred between the US-based partners and the South Korean technicians was crucial because it provided design and fabrication skills and assembly capabilities.

Furthermore, the industry was able to increase its development thanks to the governmental support. For several years, the South Korean government has continued to play an active role in promoting local technological development through initiatives, granting of subsidies or manpower training programs. Since mid-1960s, the formation of a legal and institutional framework has been promoted: in 1967 the Ministry of Science and Technology (MOST) was established to act as a central agency for policy making, planning and coordination of science and technology; in 1971 a state-financed research center called the South Korean Advanced Institute of Science (KAIS) was created and two years later the Development of Specially Designated Research Institutes Act provided legal, financial, and tax incentives (long-term interest rates for loans or tax exemptions) for both public and private research institutes in specialized fields. The result of such measures was the remarkable expansion of R&D investment, whose GDP proportion went from 0.3% to 1.92% and its expenditure from US 30 billion dollars to more than US 3.900 billion dollars in less than two decades, from 1962 to 1989.

Moreover, other factors such as the increasing openness of the economy, the expansion in the number of small-to-medium sized firms and the low costs obtained by the export-oriented strategy carried out from the 1980s contributed to the expansion of private R&D sector and the accumulation of technological capabilities.

In 1979, following the lead of SSTC, another company called Goldstar Semiconductor was established as the result of a joint venture with the US company AT&T with the purpose of produce linear integrated circuits and discrete devices for local market. Along with the private sector activities, the central government established a national research and development organization called KIET (South Korea Institute of Electronics Technology) with the objective of promote the semiconductor and the computer industries.

The 1980's was the decade of consolidation of the South Korean semiconductor industry due to its rapid development. The expansion of the industry was assisted by two main events. 1) In the government's 5-year plan (starting in 1982) semiconductors were included as one of the principal "target" industries. The interest of both government and private sector in the expansion of the chips industry might be explained because of the research for new markets given the crisis that hit the heavy and chemical industries. Therefore, in 1983 the Semiconductor Industry Fostering Plan was created and because of that the import duty on production equipment for the industry was removed. 2) A significant wave of private sector investment happened, in addition to foreign technology transfer to

South Korea during the same period that played an important role. Under the form of FDI and foreign licensing agreements, technology acquisition increased tremendously in the 1980s thanks to the liberalization and internalization program.

Hyundai set up an electronics company with a massive investment and went directly into very large-scale integration (VLSI) technology, establishing modern manufacturing facilities both in South Korea and the United States of America. Simultaneously, Samsung obtained a special production technology from US firm Micron Technologies that allowed it to produce memory chips in the US and to invest heavily in the expansion of production facilities and new product development.

3.2. Technical aspects

Semiconductors are highly specialized components that provides essential functionality for electronics devices to process, store and transmit data. Today's semiconductors are referred as *chips*, a set of miniaturized electronic circuit composed of active discrete devices, such as transistor and diodes, passive devices, such as capacitors and resistors, and the interconnections between them, layered on a silicon wafer-thin.

As reported by Ezell, S. (2020), modern semiconductors are very different from those invented by the early pioneers; in fact, today's chips contain billions of transistors on a size of a square millimeter and the leading-edge semiconductor manufacturers are producing chips at 5 and 3 nanometer-scale, containing transistors that are ten thousand times thinner than a human hair.

3.2.1. Types and classification

When talking about semiconductors, it is necessary to differentiate between the raw material called semiconductor itself and the product derived from the manipulation and transformation of the raw material that generates integrated circuits and other types of semiconductor devices.

Semiconductor materials are resources found on the planet or made from a chemical compound. There are many different types of semiconductor materials that can be used within electronic devices, and each has its own advantages and disadvantages. The most used materials are: *Germanium (Ge)*, used in early devices from radar detection to the first transistor; *Silicon (Si)*, who is the most widely used type of semiconductor material and the second and the second most abundant element on earth, behind oxygen; *Gallium arsenide*

(*GaAs*), the second most used type of material; *Silicon carbide* (*SiC*) and *Gallium nitride* (*GaN*), among others.

A semiconductor material has a specific electrical property which conducts electricity more than an insulator, such as glass, but less than a pure conductor, such as metallic copper or aluminum. Its conductivity properties can be altered by introducing impurities, a process called “doping”, in order to meet the specific needs of the electronic component, i.e. altering its electrical or structural properties. *Silicon* is the most used semiconductor material due its advantages, being easy to fabricate and providing good general electrical and mechanical properties.

Semiconductor devices are electronic components that have replaced vacuum tubes, also known as valves, in most applications. They can display a wide variety of useful function, such as passing current more easily in one direction, having sensibility to light or heat, amplification, switching and energy conversion. They can be divided into diodes, transistor, and other devices, in which the whole category of integrated circuits falls in.

Diodes are a two-terminal electronic component. It conducts current and has low resistance in one direction but high resistance in the opposite one. Organic Light-emitting Diode (OLED) or Light-emitting Diode (LED) are one of the main diodes with application in most of today’s smartphones, tablets, and personal computers. Other diodes are photodiode, laser diode (LD) and constant-current diode (CLD).

Transistors are used to amplify or switch electrical signals and power. Compared to the diodes, and thanks to its functions, they have a wide application in the electronics sector. They can be divided into bipolar junction transistors or BJTs, field-effect transistor or FET and metal-oxide-semiconductor field-effect transistor or MOSFET. Other types of transistors are: complementary metal-oxide-semiconductor or CMOS, n-type and p-type MOS (NMOS and PMOS), thin-film transistor, phototransistor, insulated-gate bipolar transistor (IGBTs) and Darlington transistor, among many others. In detail, the MOS transistor (MOSFET) is by far the most common transistor, used to build high-density integrated circuits such as digital circuits and analog circuits, allowing to integrate more than 10,000 transistors in a single IC thanks to its high scalability property. In fact, based on an article from the Computer History Museum, approximately 99% of the transistors shipped in the world are MOSFET.

Integrated circuits, also referred to as *IC*, *chip* or *microchip*, are a set of electronic circuits placed on a semiconductor-material-made wafer. They consist of a small slide of silicon imprinted with microscopic patterns that contain hundreds of millions of transistors, resulting in the most complex circuits that can compute functions as an amplifier, timer, counter, logic gate, computer memory or microprocessor. Integrated circuits are now used in every life home appliance, smartphones, tablets, medical equipment, military equipment, cars, airplanes, and trains. Depending on the number of components, integrated circuits can be classified as large-scale integration (LSI) and as very large- scale integration (VLSI).

Density and size are two of most important aspects of ICs because, since they confer the ICs advantages of outstanding performance and low power consumption. The size of the state-of-the-art IC chips reaches 3 nanometers and represent an inverse relationship between size and performance power. Today, only few design companies worldwide have the technology to produce chip at that scale, mainly concentrated in South Korea and Taiwan. Furthermore, the density of transistors on a single chip have doubled approximately every two years since the 1960s, a trend known as Moore's Law. This observation projected the rate of growth of the historical trend which is destined to grow as well as their functionality.

Chips can be categorized in two ways: according to the functionality, in which memory chips, microprocessors, system-on-a-chip (SoC) and standard chips are part of, and according to the integrated circuits used, in which digital chips, analog chips and mixed chips are part of.

But, as an OECD trade policy paper suggests in 2019, semiconductors fall into two categories, namely “integrated circuits” proper and the so-called “optoelectronics, sensor, and discrete semiconductors” (OSD). The last represents less than 20% of the total market for semiconductors, much of it used for light-related applications, such as LED lamps.

Instead, according to *BCG & SIA (2021)*, semiconductors can be classified into three broad categories despite the fact that the industry taxonomies describe more than 30 types of product categories: Logic which includes microprocessors (such as CPUs, GPUs and APs), general purpose logic products, microcontrollers (MCUs), and connectivity products; Memory which include semiconductor memories such as Dynamic Random-Access Memory (DRAM) and NAND memory; and Discrete, Analog and Other (DAO) which includes discrete

products such as diodes and transistors, analog products that include voltage regulators and data converters, and other products such as optoelectronics.

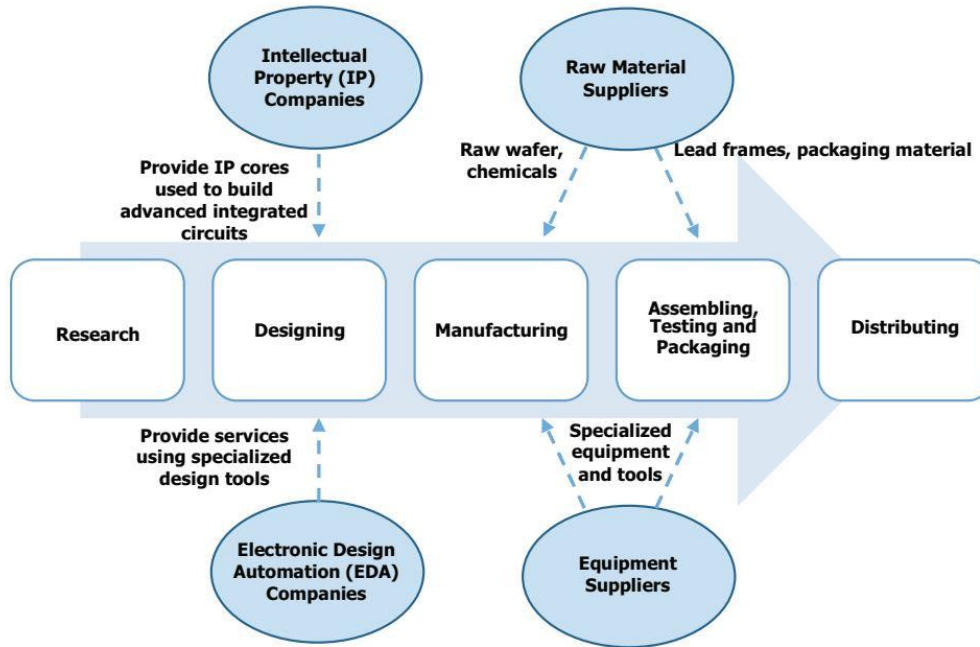
The report also includes a table that describes the multiple applications of these semiconductor categories. For example, in 2019 DAO semiconductor products represented approximately 60% of the global semiconductor sales of the auto application market, while logic and memory represented 28% and 10% respectively; for mobile phones application market, memory and DAO products accounted for 39% and 33% of the global sales, respectively.

3.3. The global value chain

The semiconductor global value chain is complex because the production of chips is one of the most R&D-intensive activities and covers a significant number of specialized tasks performed by different companies around the world. The production of a single chip used to power a computer, or a dishwasher often requires more than 1,000 steps passing through more than 70 international borders before reaching an end consumer. Most of the reports of the most important professional services companies, like *KMPG*, *PwC* or *Accenture*, divide the global semiconductor value chain in three stages: the upstream segment which covers tasks like R&D, the middle segment which covers chip design, manufacturing, and assembly, testing and packaging activities, and the downstream segment which comprises use in electronic equipment.

From a supply perspective, the supply chain is divided between 7 and 10 sectors, depending on the report. *Accenture* (2021) divides the chain into 10 stages, while *BCG & SIA* (2021) and the *CSET Issue Brief* (2021) divides it into 7 sectors. Considering the last division, the 7 sectors of the global value chain are: Research and Development, Design, Electronic Design Automation and Core IP, Fabrication, Semiconductor Manufacturing Equipment (SME), ATP (Assembly, Testing, and Packaging), and Materials.

Figure 4. Semiconductor Ecosystem



Source: SIA (2016). *Beyond Borders: How an Interconnected Industry Promotes Innovation and Growth*, page 6

3.3.1. Research and Development

The R&D stage is the first activity of the chain and includes pre-competitive activities as well as explanatory research on fundamental materials and chemical processes in order to identify leading edge technology in manufacturing and in innovations in design architectures. Data reported by SIA indicates that basic research typically accounted for 15-20% of the overall R&D investment in most leading countries. This type of R&D is performed by scientists from private corporations, universities, government sponsored national laboratories and other independent research institutions.

The United States are by far the leader in semiconductor R&D. For example, total US semiconductor industry investment in R&D reached US 44,000 million dollars, with a compound annual growth rate of approximately 7.2% from 2000 to 2020. The US semiconductor industry is the industry that spends more on R&D as a percentage of sales than any other country's semiconductor industry, with a 18.6% of the sales, followed by

Europe, Japan and China with 17.1%, 12.9% and 6.8% respectively (2020 SIA Factbook, 18-21).

3.3.2. Design

After the research and development activities, the production process itself begins with the design, probably the most important stage of it because it determines the chip's power efficiency and processing speed. The Design phase involves knowledge and skill intensive activities and implies specification, chip size determination, placement of memory and logic. Validation and verification are also needed to ensure that chips will operate as design. It also relies on highly advanced electronic design automation (EDA) software to design electronic systems and on reusable architectural building blocks known as IP cores.

The production process can occur either in a single company, such as integrated device manufacturer (IDMs), or in separate firms, where fabless firms design and sell the chip, foundries fabricate them, and outsourced semiconductor assembly and test (OSAT) firms take care of assembling, testing, and packaging (ATP) activities. Thus, the design and manufacturing activities can be carried out by a single company or can be outsourced.

Nvidia, Broadcom, Qualcomm, Advanced Micro Devices (AMD) are all US-based fabless firms, while Huawei HiSilicon and MediaTek are respectively a Chinese and a Taiwanese fabless company. Among the IDM companies, the most important ones are in South Korea, like Samsung or SK Hynix; in Japan, like Sony and Kioxia; in United States, like Intel or Texas Instruments and in Europe, like Infineon and STMicroelectronics.

3.3.3. Fabrication

Fabrication is the second stage of the production process. In this phase the chip design is printed into silicon wafers, and it requires highly specialized inputs, processes, and equipment to achieve the needed precision at miniature scale. Integrated circuits are produced in cleanrooms that are designed to maintain a sterile environment to prevent contamination, as if it were an operating room. The manufacturing process takes place in semiconductor fabrication facilities called "*fabs*" and starts with a cylinder of silicon (or other semiconducting materials) which is sliced, polished, and then patterned into thin disc-shaped wafers of different diameters. The diameter and the material used can vary depending on the type of device being fabricated.

In detail, once the wafer is cut, is then covered by a photoresist layer, a light-sensitive material. Through a process called lithography, the patterns previously designed are projected by an Ultraviolet (UV) light onto the wafer. Then, areas that were unprotected by photoresist are chemically removed in a process known as “etching”. After etching, “doping” is the next step, which consists in showering the etched areas with ionic gases in order to add impurities to alter the conductivity properties of the wafer. Then, the metal links transistor is added using a similar etching process. The fabrication process described is known as “front-end manufacturing” and depending on the specific product it can have 400 to 1,400 steps taking 12-20 weeks. Most front-end manufacturing take place in East Asia, some cluster in the US and Europe.

Companies like Micron (USA), NXP (Europe), Infineon (Europe), Intel (USA) and Texas Instruments (USA) carry out front-end manufacturing in-house (usually above 50,000 to 100,000 wafer per month, according to *Accenture* report), while fabless companies or foundries like TSMC (Taiwan), Samsung (South Korea), GlobalFoundries (USA), UMC (Taiwan) and SMIC (China) provide front-end manufacturing services.

The complexity of the equipment needed to produce semiconductors makes front-end manufacturing the most capital-intensive sector of the value chain. For example, as reported by SIA x BCG 2021, wafer fabrication accounts for approximately 65% of the total industry capital expenditure and 25% of the value added.

The back-end manufacturing stage of the supply chain includes ATP (assembly, packaging, and testing) activities. This stage involves the transformation of the silicon wafers produced by the front-end activity into finished chips, that is cutting the wafer into separate chips which will later be assembled into electronic devices. Then, chips are packaged into protective frames and enclosed in a protective casing. Packaged chips are rigorously tested and sent to assemblers, who assemble chips into circuit boards.

In comparison, back-end manufacturing is relatively less capital-intensive and employs more labor than the front-end manufacturing, although it still requires significant investment in specialized facilities. Most of the assembly, test and packaging houses are in lower-cost locations, including Southeast Asian countries like Malaysia, Vietnam, China, and Taiwan.

3.3.4. Support ecosystem

Companies engaged in design and manufacturing, regardless of whether they outsource some of the services, are supported by a highly specialized supplier ecosystem. This supplier companies provide several inputs like materials, electronic design automation (EDA) software and services, core intellectual property (IP) and semiconductor manufacturing equipment (SME).

3.3.4.1. Electronic Design Automation (EDA)

EDA consist in sophisticated software to design chips, as they have become extremely complex webs of thousands of millions of transistors interconnected. It also consists in services to support designing semiconductors. So, EDA tools are indispensable to achieve state-of-the-art designs and to keep companies competitive.

The most important companies specialized in design activities are almost all concentrated in USA, controlling 70% of the global market for EDA tools *Accenture* (2021, p. 21). Some of those companies are Cadence Design Systems, Synopsys, and Mentor Graphics.

3.3.4.2. Intellectual Property (IP)

Semiconductor IP cores are reusable design components that are used to build integrated circuits. As is in most of the cases cost prohibitive to create new circuit design from the beginning, IP houses that own IP blocks license to other companies. They are heavily protected by patents, trade secrets, and control of standards to maintain competitive advantages. Development costs have increased drastically as chips become more complex. The costs associated with designing for state-of-the-art 3 nanometer chip, for example, range from 500 million to over 1,500 million dollars *Accenture* (2021, p. 22).

Among the companies dedicated to IP Core, almost all of them concentrated in the USA, there are two firms, ARM, and Imagination Technologies, that are British-based companies.

3.3.4.3. Semiconductor Manufacturing Equipment

Semiconductor manufacturing requires dozens of different types of advanced wafer fabrication and processing equipment, test equipment, and assembly or packaging equipment provided by specialized vendors. SME tools are used for wafer manufacturing, wafer handling, wafer marking, process control, lithography, deposition, etch and clean

chemical mechanical planarization, among others. “Services” include support services provided by SME firms to help with setup and repair equipment.

Most of the SME companies are in United States, like Applied Materials, LAM Research and KLA; Japan, like Tokyo Electron; and the Netherlands, like ASML.

3.3.4.4. Materials

Chip manufacturing companies also rely on specialized materials suppliers. Some of the materials needed in the front-end manufacturing are photoresist, photomask, silicon wafers, polysilicon, wet processing chemicals (used in etching and cleaning process) and gases (used to protect the silicon wafer from atmosphere exposure). Some of the back-end materials include organic substrates, ceramic packages, bonding wires, and die-attach materials.

Companies that supply semiconductor materials also supply other industries (for example pharmaceutical), making this stage of the global value chain less vulnerable to external or industry-specific shocks, especially if compared to other phases of the chain. Semiconductor materials suppliers are located worldwide though the most important ones are concentrated in South Korea, Europa, and Japan.

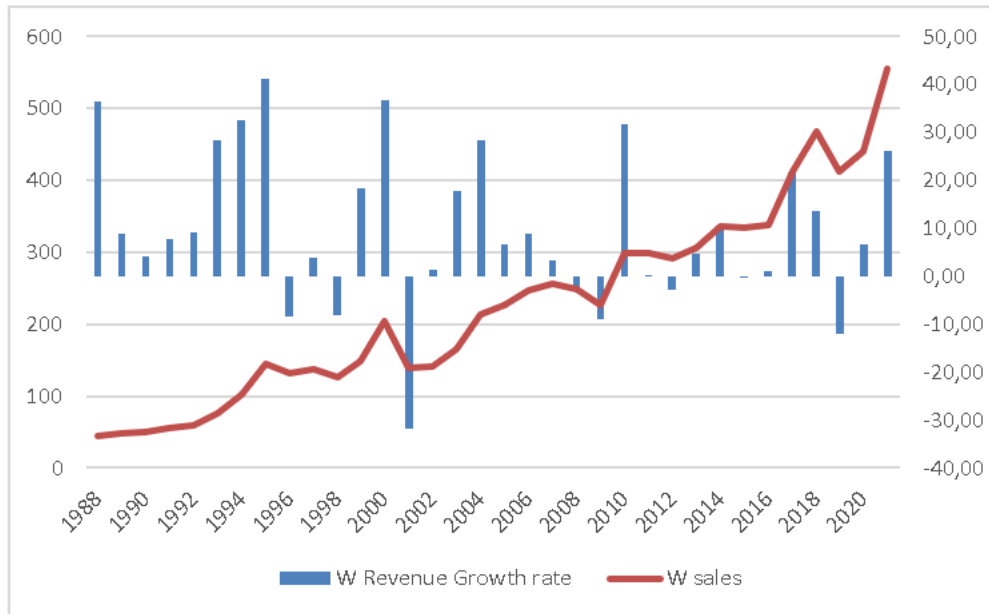
3.4. Recent situation

There are certainly larger industries than semiconductors, e.g. gas and oil industries, but none of them have the peculiar characteristic that more than 80% of the production comes from a very small group of countries. The importance of this industry lies in the fact that, in many other end markets, the absence of a chip, often costing less than one US dollar, can prevent the sale of a device worth a hundred or even a thousand times more.

According to some analysis done by the consulting firm Deloitte, the recent chip shortage has caused losses more than US 500 billion dollars worldwide and of US 210 billion dollars for the automotive industry in 2021.

Semiconductor sales have typically followed an upward trend, marked by a strong cyclical pattern of booms and busts, as shown in figure 5:

Figure 5: W Revenue Growth Rate (right axis, in %) vs W Sales (left axis, in billion US dollars)



Source: own elaboration with data of Statista’s “Global semiconductor industry revenue growth rate from 1988 to 2022” and “Semiconductor industry sales worldwide from 1987 to 2022”.

But problems related to chip shortages may persist as late as 2023 and global production will take time to keep up with demand. The imbalance between supply and demand was the main problem in the industry in recent years and affected the entire value chain.

However, experts believe that consequences of this scenario will not be so persistent and that they will begin to ease in the coming year, in part due to the increase in the output capacity in manufacturing plants and improvements in the supply chain. The strategy of adding more capacity had started before the bottleneck problems: the capacity of 300mm and 200mm wafers, mainly demanded by manufacturers that sell chips to the car industry, is expected to increase by 10% and 15% respectively.

On the other hand, the most advanced chips, between 65nm and 10nm, are expected to increase wafer capacity by approximately 25% to 10% during 2022, highlighting the characteristic technological progress of the industry. Other supply chain improvements

can reduce lead times, supported by a new, more connected, and integrated model based on digital capabilities.

The shortage of qualified workers in the industry is another problem that is added to the troubles of the bottlenecks in the supply chain. According to Deloitte's report, in 2021 more than 4 million skilled workers left their jobs in the US, among which almost 300 thousand belonged to the chip sector. In addition, there was already a talent shortage in Taiwan and South Korea a couple of years ago. In China, more than 200,000 design and manufacturing professionals have left their jobs within the industry in 2021 and that number is expected to fall again throughout 2022.

Considering the digital transformation, if semiconductor companies want to stay competitive, they must develop new products, implement rapid scale-up productions, and focus on innovation and efficiency. For example, the Deloitte Semiconductor Transformation Study (STS) found that three out of 5 chip companies have already begun a digitalization process by mid-2021, even though half of the companies surveyed have yet to adapt their transformation strategy to the dynamic events that affected the market. It also suggests that companies should also strengthen collaboration with extended supply chain partners, to better integrate new technologies, such as AI, edge computing, 5G communications, Internet of Things. Leveraging these technologies internally would mean better data visibility between the corporate and utility networks and automate key processes.

4. Descriptive statistics

4.1. The model

This paper attempts to analyze semiconductor trade flows from South Korea, the second major semiconductor exporter in the world, to a selected number of importing countries. The well-known gravitational approach is used in order to know what variables affect the bilateral trade between the countries. Two models are presented. Firstly, the standard gravity model with both importer and exporter GDP and the distance between them as explanatory variables and the exports from South Korea to the selected group of importing countries as the variable to explain. Secondly, the previous model is augmented by adding several conditioning variables with the purpose of controlling for unobserved country characteristics that can explain the independent variable (promote or impede South Korean exports).

As mentioned in the literature review section, the gravity model has been widely used due its simplicity and because it usually produces a good fit. The pioneers were Tinbergen (1962) and Pöynönen (1963) who employed the gravity equation to analyze international trade. The economic intuition of the gravity equation is based on Newton's law of gravitation, that states that any object attracts another with a force that is directly proportional to the product of their masses and inversely proportional to the square of the distance between them:

$$F = G \frac{m_1 m_2}{r^2},$$

where F is the gravitational force attracting the two bodies, m_1 and m_2 are the masses of the bodies, r is the distance between the centers of their masses, and G is a constant known as gravitational constant.

Anderson (1979), Bergstrand (1985) and Deardorff (1998) were the first works that established theoretical foundation to the gravity equation, showing how it derived from trade models with product differentiation and increasing returns to scale or its consistency with several variant of the Ricardian and Heckscher-Ohlin models.

The above-mentioned papers applied the general gravity model to international trade, replacing the gravitational force for the volume of exports between a pair of countries, which is a function of their incomes and their geographical distances:

$$(1) \quad X_{ij} = \frac{\alpha Y_i Y_j}{D_{ij}}$$

$$i \neq j$$

where X_{ij} represents the flow of goods (or services, or both if the aggregated variable is considered) from country i to country j , Y_i and Y_j are the national incomes, D_{ij} denotes the distance between them and α is a constant.

Traditionally, the economic size of a country was measured by its GDP, as in Tinbergen's work. But it can also be represented by the per capita GDP, as Bergstrand (1989) suggested. Moreover, some authors consider the population as a variable that represents the economic size of a country, although it can give rise to the absorption effect (a country exports less when it's big) or that of economies of scale (a big country more than a small country). The distance variable is considered as a proxy of the transport costs of the bilateral trade. More recently, many authors also use infrastructure variables, such as stock

of public capital or railroads network, as variables to model transportation cost. Martinez-Zarzoso & Nowak-Lehmann (2003) used an infrastructure index as an explanatory variable in an augmented gravity equation, to demonstrate that transport costs are not only explained by distance.

The equation (1) can be expressed also in a log-linear form, applying natural logarithms on both sides of the equality:

$$(2) \quad \ln X_{ij} = \beta_0 + \beta_1 \ln Y_i + \beta_2 \ln Y_j - \beta_3 \ln D_{ij},$$

where the parameters $\beta_0, \beta_1, \beta_2, \beta_3$ are the parameters to estimate. The log-linear form is usually applied for estimation purposes because it allows to measure the elasticity of the dependent variable to changes in the independent/s variable/s.

The first model presented in this paper is a *classic model* that has as the variable to explain the South Korean exports of semiconductors and as explanatory variables the exporter and importer GDP's as well as the distance between them. Considering these variables, the specification of the classic model would be:

$$(3) \quad \ln Exports_{ijt} = \beta_0 + \beta_1 \ln GNIpcKOR_{it} + \beta_2 \ln GNIpc_{jt} + \beta_3 \ln Dist_{ij} + \mu_{ijt}$$

$$i \neq j \quad t = 2001, 2002, \dots, 2020$$

Equation (3) refers to the South Korean exports of semiconductors to twenty-seven importing countries, from 2001 up to 2020. $GNIpcKOR_{it}$ and $GNIpc_{jt}$ are the per capita national income for the exporter country and for the importer respectively in the year t . The coefficients of the per capita GNI variables are expected to be positive. On the one hand, a higher per capita national income in the exporting country, $GNIpcKOR_{it}$, indicates a higher level of production, which increases the volume of exports. On the other hand, a higher per capita national income of the importing country, $GNIpc_{jt}$, indicates higher demand and therefore a greater volume of imports (exports from country i). The coefficient of the distance variable D_{ij} is expected to be negative since it represents the cost of transporting the merchandise. It should be noted that μ_{ijt} is the term error that accounts all variables that are not specified in the model. The equation (3) can be also expressed with normal GNI. In Section 5 both models will be estimate separately.

The second model represents an augmented gravity model. To the equation (3) other variables are added to the equation, with the aim of finding the determinants of the dependent variable. Therefore, the *augmented model* would be the following:

$$(4) \quad \ln Exports_{ijt} = \gamma_0 + \gamma_1 \ln GNIpcKOR_{it} + \gamma_2 \ln GNIpc_{jt} + \gamma_3 \ln Dist_{ij} + \gamma_4 \ln ECI_{jt} + \gamma_5 MVA_{jt} + \gamma_6 MVAkor_{jt} + \varepsilon_{ijt}$$

$$i \neq j \quad t = 2001, 2002, \dots, 2020$$

where, apart from the variables of the (3) equation, γ_0 represents individual effects, $\ln ECI_{jt}$ represents the natural logarithm of the “Economic Complexity Index” of the importing country j in the period t . In the data description section, it will be explained in more detail what this index consists of. As an index that describes the complexity of a country’s economy, is expected to have a positive impact on the volume of exports of semiconductors, since as the economy develops more, it will produce more complex and developed products that probably need semiconductors for their assembly.

$MVAkor$ and MVA refers to the manufacturing value added of both exporter and importer countries respectively. These variables are not presented in log since they are already calculated in percentage. The value added of the South Korean manufacturing industry is expected to have a positive sign since a higher weight of the industry over the GDP increases the volume of semiconductor exports. However, the expected sign of the importing country's value-added manufacturing industry is ambiguous. A higher added value can mean that the importing country’s manufacturing sector has developed enough not to depend on South Korean exports or that it has grown significantly and the productive capacity as well, so it would need more imports of semiconductors to produce.

4.2. Data description

This paper analyzes the South Korean exports for semiconductors with 27 countries, that were selected based on the data availability and general characteristics. The group of destination-countries were selected from the OECD members: Canada, Mexico, United States, Japan, Israel, New Zealand, Austria, Belgium, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Netherlands, Norway, Poland, Portugal, Slovak Republic, Slovenia, Spain, Sweden, Switzerland and United Kingdom. This study uses panel data for analysis over 20 years, from 2001 to 2020. Annual trade data of semiconductor flows were obtained from the International Trade Center (ITC) trade map

webpage (www.trademap.org), at the Harmonized System 6-digit level. The following table summarizes the sources used to collect the data:

Table1: Data sources

Variables	Sources
- Manufacturing, value added	World Bank's <i>World Development Indicators</i> (WDI)
- Population	
- GNI at constant prices	
- Distance	CEPII
- ECI	<i>Observatory of Economic Complexity</i> (OEC)
- Semiconductor Exports	International Trade Center (ITC)

Source: own elaboration

To build the dependent variable, exports of HS8541 product (Diodes, transistors, and similar semi-conductor devices; Photosensitive semiconductor devices, ...) and exports of HS8542 product (Electronic Integrated circuits and microassemblies; parts thereof) were added to obtain the volume of South Korean semiconductor exports to each *j* country, as Brown (2020) did. It is measured in thousands of US dollars and has an annual frequency from 2001 to 2020. Data were available for all countries and for all years, except for New Zealand in 2002 which no HS8541 and HS8542 exports was reported.

Data of distance was extracted from the Centre d'Études Prospectives et d'Informations Internationales (CEPII) which is a French institute for research into international economics. The distance variable ($Dist_{jt}$), measured in kilometers, corresponds to the "*dist*" data of the CEPII's database on distance (*GeoDist*), which is calculated following the great circle formula and considers the coordinates (latitude and longitude) of the most important cities in terms of population.

For the *Economic Complexity Index*, the data was obtained from the Observatory of Economic Complexity (OEC), which is an online data visualization platform focused on geography and dynamics of economic activities. The OEC integrates and distributes international data regarding trade to empower the analysis at a public, private and academia level. The index was developed by Hidalgo and Hausmann (2009), who demonstrated that countries with higher economic complexity experienced a higher rate of economic growth and showed that the complexity level of a country's economy can predict the types of products that it will be able to develop in the future, suggesting that the development of new products depend on the capabilities available in that country. Thus, the ECI is a measure of

the productive structure and the relative knowledge intensity of an economy. It represents the knowledge accumulated in a population and that is expressed in the economic activities present in a country.

A high ECI indicates that the economy is diverse, sophisticated and its development should be high in terms of the accumulation of knowledge. The higher the index, the greater the complexity. It is calculated using the revealed comparative advantages (RCA) matrix (Hidalgo and Hausmann, 2009; Mao and An, 2021). The index sets a positive number to countries with more complex economies, and a negative number to countries whose economies are less diversified. Thus, Germany, Japan, Switzerland, and South Korea are among the countries with the highest, while Nigeria or Venezuela are some of the countries with lower rates. In our sample of importing countries, Greece, Portugal, and New Zealand are among the countries with less economic complexity.

Population and national income data was obtained from the World bank database. On the one hand, the population is measured considering the de facto definition of population, which counts all residents regardless of legal status or citizenship. On the other hand, it is proposed as a variable that represents the national income the Gross National Income (formerly GNP). The reason why relies on the fact that semiconductor firms have several factories around the world and that the supply chain is deeply fragmented, so an indicator such as GDP does not consider the value produced offshore. GNI is measured in 2015 US dollars and has an annual frequency from 2001 to 2020. Per capita GNI was also considered, since the paper's purpose is to analyze trade flows at a disaggregated level. Data for Greece from 2001 up to 2004 is missing.

The data for the value added of Manufacturing (MVA) for each country was also obtained from the World Bank database. MVA represents the total estimate of net-output of all resident manufacturing activity units obtained by adding up outputs and detracting intermediate consumption. It is presented as proportion of the GDP with an annual frequency. Data for Canada in 2019 and 2020 was not reported, as well as for New Zealand in 2020.

Now that we have described where the data was extracted and how the variables were obtained, the next section illustrates the estimation's part and the econometric methods used.

5. Econometric Estimates

The data collected includes 20 years, from 2001 to 2020 and 27 countries, which give us a panel data of 540 observations. But as explained in the data section, some data in certain countries are missing therefore we have an unbalanced panel. Given the fact that panel data, also known as longitudinal or cross-sectional time series data, is a dataset in which the behavior of individuals is observed across time, it contains information on both intertemporal dynamics and individuality, the effects of unobserved variables can be controlled or the effects of variables that change over time but not across entities (Hsiao, 2007). This is important because the semiconductor industry entities do not provide free accessible data due to the strategic importance in the policy.

The statistical software package used to conduct the estimations is STATA. For each model, three econometric methods are applied. For each model, a normal GNI and a per capita GNI form of the models were considered.

The most widely used methods for estimating a gravity model and in general panel data models are Pooled Ordinary Least Squares (OLS), the Fixed Effects Model (FEM) and the Random Effects Model (REM). Considering the individual effects, it is necessary to determine if they are fixed or random. The literature suggests that the process of model choice for panel data begins with considering whether the observations are a random sample of a given population, which is a subset of individuals (or entities or countries) randomly selected to represent an entire group. In this paper, the sample of countries was not randomly selected because they are all OECD members and most of them are developed countries with high-income economies. Consequently, a fixed effect model should be more appropriate.

Nevertheless, a Hausman specification test is applied to determine if random effects are preferred over fixed effects, under the null hypotheses of no correlation between the individual effects and the regressors in the model. The individual effects are treated as fixed. Consequently, a FEM is more appropriate than a random model if the null hypotheses of no correlation between the country-specific effects and the regressor is rejected.

A Breusch Pagan test was applied to determine if random effects are preferred over a linear regression (pooled OLS). If the null hypothesis is rejected, then a REM is more suitable. We can select with confidence a Fixed Effects Model if both Breusch Pagan and Hausman null hypotheses are rejected.

6. Results

Tables (2) and (3) show the regressions results. Table () presents the estimated coefficients of the gravity model, the standard model that incorporates both GNI of the importer and exporter country and the distance. For each econometric method, gross national income and per capita gross national income were considered.

Table 2: Estimate results for the *classic model*

Dependent variable: lnExports	Pooled OLS		Fixed Effects		Random Effects	
	Normal GNIs	Per capita GNIs	Normal GNIs	Per capita GNIs	Normal GNIs	Per capita GNIs
lnGNI	1.3203*** (0.541)		1.7664 (2.605)		1.355*** (0.18689)	
lnGNIkOR	1.3118*** (0.4099)		1.2571 (0.907)		1.444* (0.818)	
lnDist	-1.099*** (0.0936)	-1.8457*** (0.2105)	(omitted)	(omitted)	-1.088*** (0.218)	-1.6861* (0.9598)
lnGNlpc		0.1885 (0.204)		3.3099 (2.796)		1.5621 (1.348)
lnGNlpcKOR		2.092*** (0.684)		1.2275 (0.883)		1.8707** (0.831)
constant	-52.898*** (11.502)	2.8765 (7.478)	-73.324 (54.483)	-37.289 (25.619)	-57.661** (25.175)	-10.561 (19.592)
N	534	534	534	534	534	534
R-squared	0.5361	0.1011	0.1041	0.12103	0.1037	0.114
Prob > F	0.0000	0.0000	0.028	0.0514	0.0000	0.0079

Robust standard errors in parentheses. *** p-value < 0.01; ** p-value < 0.05; * p-value < 0.1

Source: own elaboration

As expected, in all three methods, both importing countries' and exporting country's national incomes has a positive impact on the semiconductor exports, either taking into account the per capita variable or the normal. The positive sign indicates that national income is directly related to trade, although not all methods have a statistically significant effect. The distance's coefficient has the expected negative sign and is significant for POLS and RE methods, at least at 10% significance level. Distance is omitted in FEM because is a variable that does not change over time.

When least squares estimator is considered, a 1% increase in importing country national income translates into approximately 1.32% increase in the volume of semiconductor exports, at a 1% level of significance, ceteris paribus. Similarly, a 1% increase in the gross national income of South Korea will increase its semiconductors

exports 1.31%, significant at a 1%. In per capita terms, a 1% increase of South Korean gross national income will increase its semiconductor exports approximately 2%, at a 1% of significance. A 1% decrease of the distance between South Korea and the importing country, in both normal and per capita terms, will increase the semiconductor exports approximately 1.1% and 1.9%, respectively.

When random effects estimator is considered, the magnitude of the effects does not have an important change and their level of significance does not change much. For example, a 1% increase in per capita gross national income of South Korea increases its exports approximately 1.87%, significant at a 5%. A 1% decrease in the distance increases the semiconductor exports volume 1.68% approximately, at a 10% level of significance.

The R-squared is presented in the table. It shows that, in the pooled OLS, the independent variables explain the 53.61% of the dependent variable movements, in the normal GNI terms. In the per capita terms, only 10.11% of the variability observed in the dependent variable is explained by the regression model.

P-values of the F-test are also reported in the table. This test indicates whether all the regression coefficients in the model are different than zero. As almost all p-value are smaller than 0.05 alpha level, null hypothesis is rejected. Therefore, the models have predictive capabilities since all regression coefficients are statistically different than zero, at a 5% of significance.

As both Hausman and Breusch-Pagan results shown that fixed effects can be chosen with confidence, it is necessary to extend the classical model, adding other explanatory variables.

Table 3: Estimate results for the *augmented model*

Dependent variable: lnExports	Pooled OLS		Fixed Effects		Random Effects	
	Normal GNIs	Per capita GNIs	Normal GNIs	Per capita GNIs	Normal GNIs	Per capita GNIs
lnGNI	0.0287 (0.161)		4.511** (1.96)		0.1693 (0.529)	
lnGNIkör	1.046** (0.414)		-0.5746 (0.981)		0.6739 (0.622)	
lnDist	-0.6555*** (0.117)	-1.2837*** (0.239)	(omitted)	(omitted)	-0.5118 (0.409)	-0.7787 (1.168)
lnGNIpc		-1.1541*** (0.175)		4.478** (1.972)		1.2664 (1.106)
lnGNIpcKOR		1.2321* (0.633)		-0.9853 (0.981)		0.4158 (0.776)
lnECI	1.5231*** (0.261)	3.541*** (0.317)	3.8295** (1.642)	4.0266** (1.569)	3.1681** (1.236)	3.7738** (1.494)
lnPop	1.3429*** (0.146)		-6.145 (5.096)		0.9677* (0.565)	
MVA	0.001 (0.026)	-0.2067*** (0.027)	-0.2232*** (0.049)	-0.2219*** (0.0497)	-0.1342*** (0.045)	-0.1736*** (0.042)
MVAkor	0.2451*** (0.067)	0.1396 (0.089)	0.1643* (0.081)	0.1612* (0.0827)	0.1753* (0.0895)	0.1612* (0.088)
constant	-43.641*** (11.204)	19.381*** (6.655)	4.4746 (58.184)	-28.396* (25.619)	-28.4648 (21.478)	-3.028 (15.379)
N	531	531	531	531	531	531
R-squared	0.6488	0.3332	0.3071	0.3062		
Prob > F	0.0000	0.0000	0.0004	0.0003		

Robust standard errors in parentheses. *** p-value < 0.01; ** p-value < 0.05; * p-value < 0.1

Source: own elaboration

Comparing the results from table (2) with those of (3), the R-squared of the second model has increased significantly in the fixed effects. In detail, 30.71% of the variance for the dependent variable is explained by the independent variables, meaning that the augmented model fits the data better than the classic model. The null hypothesis of the F-test is rejected with 95% of confidence, hence regression coefficients are statistically different than zero.

As previously mentioned, a fixed effects model is more suitable than random effects and we will focus on the results of the models of normal GNI and per capita GNI.

When considering normal GNI model form, the coefficient of the importing country gross national income has the expected positive sign which indicates that a 1% increase in the importing GNI increases South Korean semiconductor exports approximately 4.5%, at a 5% level of significance. This result is greater than the one obtained in the classic model.

The sign of distance's coefficient is negative as expected but does not show statistical significance. The elasticity of the per capita GNI of the importing country was a similar magnitude to the one of the normal GNI model. A 1% increase leads to a 4.478% increase in the volume of exports. However, if the GNI of South Korea is considered, the estimated coefficients have an unexpected sign. The reason why the estimated coefficient has a negative sign is beyond the purpose of this paper. Further research should focus on address these results.

The ECI variable has the expected positive sign and is significant at 5% level. This indicates that South Korean semiconductor exports increase approximately 3.83% when the ECI index of the importing country increases 1%. As the importing economy develops, becomes more complex and its productive capabilities increase, it needs to import more semiconductors to produce more complex products. In per capita terms, the sign is also positive and significant at 5%. It shows a similar magnitude of the ECI coefficient's effect. A rise of 1% of the ECI index of the importing country increases South Korean semiconductor exports approximately 4%.

South Korea's manufacturing value added presents the expected positive sign and statistically significant at a 5% level, meaning that the higher the overall net-output of the South Korean manufacturing sector the greater the semiconductor exports. An increase in one additional unit of the exporting country MVA causes an increase of the semiconductor exports of 16.43% at a 10% level. If GNI per capita is considered, the magnitude of one additional unit of South Korean MVA is analogous to the magnitude of the model with normal GNI (16.12%, 16.43%). On the other hand, the estimate coefficient of the importing MVA shown an unexpected negative and significant sign at a 1%. This would require further research, but we think that it could be caused by out limited sample.

Finally, the population also has the expected negative sign, but no significant.

7. Conclusions

Throughout this paper, a review of the literature on the gravity model has been made to investigate its current explanatory scope and on the empirical works related to the semiconductor industry. A detailed description of the characteristics of semiconductor materials, of the electronic devices most used today and of the supply chain was also made, with special emphasis on the main agents involved. The current panorama of the industry and the challenges that it may face in the future were also briefly described.

The objective of this study is to apply the Gravity Equation Model (Simple and Augmented) to model the trade flows of semiconductors. The Augmented Gravity Equation included the typical gravity variables, an index, and other variables to capture the influence of South Korea's semiconductor exports. The results are based on a study of 27 developed OECD countries over 20 years (2001-2020). Regression analysis was done based on a panel data sample using three methods: Pooled OLS, RE, and FE. The FEM model was selected based on the results obtained by the Breusch-Pagan and Hausman tests, in addition to being a method that offers more efficient results and better fit to the data.

In general, the results of the estimates have coincided with the expected signs. National income and distance were found to determine the trade flow of semiconductors, as most of the literature suggests regarding international flows. There were also some unexpected results: the negative sign of the national income variable of the exporting country, in this case South Korea, and the negative sign of the population variable in the fixed effects model. Future research would have to investigate these aspects to check if these relationships are indeed negative. One possible reason is the limited panel sample.

The most relevant result is that the economic complexity of a country determines the commercial flow of semiconductors. This implies that as a country develops, its economy becomes more complex, its productive capacity improves and as a consequence it can produce more complex goods than it could before. This result has an important implication since in a world in which semiconductors become more and more important, complex economies producing complex products, will need more complex intermediate inputs such as semiconductors.

As this is the first attempt to explain semiconductor trade flows under a "gravity approach", other variables have been left out. However, the highly strategic nature of the semiconductor industry for the international political scene means that many databases are not easily accessible. The private nature of surveys, reports and other sources of information make empirical analysis of flows difficult.

To finish, future studies should extend the gravity model to see if other variables can also explain bilateral trade in semiconductors. Further analysis may also include data regarding firm's production capacity, firm's patent behavior, government subsidies and tax variables, or consider the effect of the exchange rate on bilateral trade flows. A study could also be done to analyze trade flows considering the USA or China as the main exporters.

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Appendix

Appendix A: Hausman test results

Table 4: Hausman test results

Normal GNI	Per capita GNI
H0: Random Effects Model is preferred H1: Fixed Effects Model is more appropriate	
Chi2 (6) = 49.30 P-value = 0.0000	Chi2 (5) = 28.57 P-value = 0.0000

Source: own elaboration using 'hausman, sigmamore' command in Stata

Appendix B: Breusch-Pagan test results

Table 5: Breusch-Pagan test results

Normal GNI	Per capita GNI
H0: Random Effects Model is preferred H1: Pooled OLS is more appropriate	
Chibar2 (01) = 674.31 P-value = 0.0000	Chibar2 (01) = 2377.63 P-value = 0.0000

Source: own elaboration using 'xttest0' command in Stata

Appendix C: Heteroskedasticity test results

Table 6: Heteroskedasticity test results

Normal GNI	Per capita GNI
H0: Homoskedasticity H1: Heteroskedasticity	
Chi2 (27) = 2587.09 P-value = 0.0000	Chi2 (27) = 2490.71 P-value = 0.0000

Source: own elaboration using 'xttest3' command in Stata