GVC and Innovation Co-evolution Trajectories.

The case of the ICT sectors

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Abstract

The relationship between firms' participation in Global Value Chains (GVCs) and the innovative capabilities of firms in Innovation Systems (IS) is receiving increasing scholarly attention. Recent research points to an interdependent relationship between the two, with a resulting range of possible trajectories.

The aim of this paper is to test for the existence of different trajectories in two Information and Communication Technology (ICT) sub-sectors, hardware and software. We use cluster analysis to examine how 45 countries have changed their GVC participation and patenting activity in the period 2005 to 2015. The differences in this evolution across sectors and countries are remarkable. We document a multitude of trajectories in the ICT domain and discuss the sub-sectoral specificities which contribute to explain their differences.

In each sector, only one group of countries is catching up and strengthening its innovative activities in relation to other countries. In the hardware sector, this relative strengthening is associated to a marked decrease in GVC participation, whereas in the software sector it is associated to an increase in GVC participation. Decreases in the relative strengths of sectoral innovation systems are associated with either increases or decreases in GVC integration in both sectors.

Keywords: global value chains, innovation systems, technological capabilities, coevolution, hardware, software, ICT.

JEL: F23, D23, L22, L25, O10, O32, O38.

1. Introduction

The emergence of Global Value Chains (GVC), with firms specializing in specific tasks and breaking up the production process across different countries, has characterized the evolution of the global economy since the early 1990s. Globalization has proceeded hand-in-hand with the expansion of Foreign Direct Investment (FDI), international trade in final goods and managed trade of intermediate goods and services produced and assembled by different actors in different places.

GVC trade grew rapidly until the outbreak of the global financial crisis in 2008, and since then it has stagnated, although half of world trade still seems to be related to GVCs. Recently, GVC trade has been affected by the decline in global economic growth and the increase in protectionism (World Bank, 2020) and, in the most recent months, the abrupt halt caused by the COVID-19 crisis (Baldwin & Evenett, 2020). Manufacturers around the world rely on Chinese inputs and the closure of factories in China (followed by similar measures in other countries) as a result of the onset of the COVID-19 pandemic affected GVC trade profoundly. While it is too early to evaluate the impact of this sanitary crisis, there is a reasonable consensus that even if in the post COVID-19 world GVCs need to be rethought, international supply chains will prove resilient and very much needed (Javorcik, 2020; Miroudot, 2020). For instance, mass production of a COVID-19 vaccine is infeasible for the domestic production capacity of individual countries and will require cooperation within international production networks. Therefore, even in these difficult and uncertain globalization times, GVCs are likely to remain an important component of global trade.

One of the most discussed effects of the rise of GVCs is that it has allowed many countries to enter the global market, based on their specific advantages and on their specialization in tasks rather than final goods. This has been particularly important for emerging and developing countries, whose participation in GVCs has increased their involvement in international trade flows. The World Bank (2020) estimates that a 1 per cent increase in GVC participation boosts per capita income by more than 1 per cent, with the biggest impact on growth occurring when countries move out of export of commodities into export of manufactured parts, components and final goods. However, upgrading is required to sustain high growth rates. In other words, it is only by scaling the value-added ladder and moving, progressively, to more sophisticated forms of participation that a sustainable positive growth impact of GVC integration can be guaranteed.

Given that upgrading requires learning and innovation, it is important to understand how these processes take place in GVCs. Some of the literature emphasizes the role played by the different governance patterns prevailing in GVCs: lead firms are the main actors transferring knowledge (Gereffi et al., 2005), with domestic suppliers a necessary complement with their investments and efforts to strengthen their capabilities (Morrison et al., 2008). An additional element that has a crucial effect on the upgrading prospects of firms in GVCs is the sectoral dimension (Giuliani et al., 2005). In some sectors (e.g., textiles and most traditional manufacturing) vertical relations with suppliers of inputs may be particularly important sources of knowledge, while in others, technology producers may provide the major stimuli for technical change (Pavitt, 1984; Malerba and Nelson, 2011).

The sectoral dimension is central also to defining the characteristics of the Sectoral Innovation System (SIS) in which the firms are embedded, and which shape firms' capabilities to upgrade within GVCs (Lema et al, 2019). What is key, is that the GVC and SIS approaches are complementary; both are needed to understand sustainable growth based on GVC integration.

In this paper, we investigate the co-evolution of GVC participation and SIS strength in a cross-country perspective, focusing on the ICT industry and exploring the potential differences between hardware manufacturing of computing, electronic and optical products and software services such as Information Technology (IT) and other information services. The focus is on ICTs for two main reasons: first, the industry is deeply influenced by GVC trade and, second, it allows us to investigate the dynamics of GVCs and SIS in two very different sub-sectors - one based on manufacturing and the other on services. It has been acknowledged that services play an increasingly central role in GVCs and, therefore, it is interesting to explore whether they show different trends in terms of GVC participation and SIS strength (OECD, 2018).

We study 45 countries at different levels of development in these industries and address the following research questions: Are GVC participation and SIS strength co-evolving positively? Is GVC participation sustaining a process of catching up in innovation capacity? Are we observing diverse co-evolutionary trajectories in different countries and industries?

The paper is organized as follows. Section 2 introduces a theoretical discussion on GVCs and SIS. Section 3 presents the data and the methodology adopted in the empirical analysis. Section 4 presents the evidence based on cluster analysis from a country/sector perspective and illustrates the results with cases and examples. Section 5 discusses the different trajectories followed by the hardware and software industries. Section 6 summarizes the main findings and concludes.

2. Global Value Chains and Innovation Systems: The literature

Much of the GVC literature links upgrading to various types of governance (Gereffi et al., 2005) and assumes that lead firms generally have a positive impact on other value chain firms by fostering knowledge transfer, mutual learning and supplier innovation (Farole and Winkler, 2014; Cirera and Maloney, 2017). Pietrobelli and Rabellotti (2011) show that governance patterns have heterogeneous impacts on learning and upgrading mechanisms in value chains. For instance, in modular chains, learning can be the result of pressure to match international standards, and value-chain leaders rarely facilitate upgrading through direct involvement with suppliers, while in relational value chains, where knowledge is less easily codified, learning is based more on intense face-to-face interactions among the actors.

However, as Morrison et al. (2008) point out, knowledge and technology access via GVCs is not influenced only by governance patterns. These authors stress that local suppliers differ in their capacity to absorb, master and adapt the knowledge and capabilities that lead firms might transfer to them. Also, they differ in their openness to complementary sources of knowledge outside the GVC – for example, international trade, FDI, human-capital mobility and international research collaboration (De Marchi et al., 2018).

In addition, Lema et al. (2018) recently stressed the importance of national, local and SIS for shaping firms' capabilities to upgrade within GVCs. Education (especially at the tertiary level) and training systems, policy regimes, the public R&D system, standards and regulatory organizations and the public and private actors offering knowledge intensive business services all contribute to influencing and enhancing firms' upgrading strategies within GVCs. Moreover, SIS are marked by a specific combination of technological opportunities, appropriability conditions, cumulativeness and knowledge base properties which influence firms' involvement in GVCs (Malerba, 2002 and 2005). The experience of countries such as South Korea shows that the formation of strong SIS is crucial to benefit from participation in GVCs and help domestic firms to move up the GVC towards more sophisticated phases of production and higher value added products (Lee, 2013; Fu, 2015).

At the same time, in some cases GVC involvement and increased participation result in improved production capabilities without increasing innovation capabilities. The distinction between production and innovation capabilities proposed by Bell and Pavitt (1993) stresses that the first case means firms acquire the ability and skills to produce, enhance and develop products and, the second case, means they develop the capacity to create new products and new knowledge for a wide range of possible applications and going beyond small adaptations and adjustments. Vietnam is an example here; its large and increasing participation in GVCs in sectors such as electronics, and the import of parts and components which are assembled domestically and then reexported as final goods, has transformed the country into one of Asia's main manufacturing hubs. Vietnam's production capabilities have improved hugely, but without much impact on its innovation capacity (World Bank, 2017).

Lema et al. (2019) suggest an analytical framework which combines the GVC and IS perspectives, to explore possible learning and innovation trajectories for firms in developing countries. They argue that the GVC and IS approaches complement each other in the analysis of the relationships between global and domestic actors that affect the innovation process. The idea of a co-evolution is based on recognition of the existence of forward and backward-feeding flows linking the two phenomena. IS and GVCs contribute to firms' capabilities accumulation (learning), as acknowledged in the literature, alongside important 'feedback flows', which while improving firms' capabilities, strongly influence IS characteristics and value-chain governance.

Based on qualitative secondary evidence, Lema et al. propose four context-specific trajectories as possible routes allowing firms to improve their innovation capabilities as GVCs and IS coevolve. For instance, they show that GVCs and IS gradually and positively interact to facilitate firm upgrading within the GVC. There is evidence, also, of contrasting cases where upgrading follows a different trajectory such as the in-out-in path described by Lee et al. (2018)

in the context of South Korea. This trajectory is characterized by initial participation in GVCs to acquire foreign knowledge and production skills, followed by an intentional separation from foreign-dominated GVCs and investment to strengthen the domestic IS and facilitate functional upgrading. Eventually, latecomer firms and economies reintegrate into the GVC led, this time, by domestic firms who establish their own value chains.

In addition, the effects of the coevolution of GVCs and IS on firms' capabilities depend, also, on a mix of country- and context-specific factors including history, geography and socio-economic context, the macroeconomic and trade policy framework, and on sector specificities such as predominant technological characteristics and knowledge bases, and firm characteristics such as size, openness, technological capabilities and sectoral industrial policies.

The aim of this paper is to test for the existence of these trajectories (Lema et al., 2019) by focusing on a specific industry – ICTs. We study the relationships linking GVC integration and SIS, propose quantitative measures for these two dimensions and use them to derive possible country and sector level trajectories. In the next section we describe our data sources and the methodology used.

3. Empirical Analysis

3.1 Data and indicators

To explore the co-evolution trajectories between GVC participation and the strength of SIS, we build an industry-country level dataset combining information from two sources.

The measure of GVC participation is based on the OECD-TiVA (Trade in Value Added) inter-country input output tables, which provide information on 65 countries over the period 2005-2015. In particular, we rely on the measure of GVC participation produced by Borin and Mancini (2019), introduced in the World Bank Development Report (World Bank, 2020). Their methodology refines that proposed by Koopman et al. (2014) and correctly implements the forward participation index suggested by Hummels et al. (2001). Also, Borin and Mancini (2015) propose a decomposition to deal with bilateral flows and disentangle exports absorbed ultimately by direct importers from those that are re-exported for consumption in a third country.

The indicator of GVC participation measures to what extent a sector s (i.e. Computer, Electronic and Optical Products – hardware, or IT and Other Information Services - software) in country c in year t is globalized, and is computed as follows:

$$\mathrm{GVC_{sct}} = \frac{\mathrm{backward_{sct}} + \mathrm{forward_{sct}}}{\mathrm{export_{sct}}}$$

This encompasses two different types of GVC participation:

- *backward GVC participation* captures the value added imported from abroad which is embodied in domestic sector exports. For example, if the phones exported by China use imported components, then China's GVC participation is considered backward.
- *forward GVC participation* measures the value of exports that is not absorbed in the importing country, but embodied in further exports to third countries.[1] To take the previous example, if Japan exports phone screens to China which then are used in the production of phones, Japan's GVC participation is considered forward.

In other words, the GVC participation index captures the share of trade crossing borders more than once from a sector perspective, as the flows in value added are normalized by total exports.[2]

Given that we are interested in how GVC participation changes in the two sectors under analysis in different countries, we consider the difference between the last and first year of observation:

$$\mathrm{GVChange}_{sc} = \mathrm{GVC}_{sct=2015} - \mathrm{GVC}_{sct=2005}$$

To measure the strength of the IS we rely on patent applications to the US Patent and Trademark Office (USPTO).[3] The choice to use the USPTO is motivated by the fact that this is the only office which registers software patents.[4] However, using a single patent office could induce a 'home bias', that is, given the same level of inventive activity, domestic subjects may tend to file more patents than foreigners (Dernis and Khan, 2004). For this reason, we ran a robustness check excluding the USA from the analysis.[5] We also exclude countries with only a few patent applications to generate more reliable estimates of changes in the IS. Due to the absence of a general criterion to guide the choice of the threshold, we follow Lee and Lee (2019) and exclude countries with fewer than 10 patents at the USPTO for each of the years covered by TiVA. Our final sample includes 45 countries (see Appendix Table A.1).

[1] A more technical treatment of GVC participation measures is presented in Borin and Mancini (2019).

[2] Whilst we acknowledge that the specific contribution of each form of GVC integration (i.e. forward and backward) clearly plays a role, we decided not to pursue this line of investigation in this paper in order not to confuse the main thrust of the present analysis.

[3] We acknowledge that our exclusive focus on patents means we capture only the technological competence in the IS and ignores organizational and economic competencies, for instance (Dosi and Teece, 1993). However, comparable data at sector level for a large set of countries are lacking. It has been argued, also, that patents capture only a part of technological competence; although this is true, patents are a better measure than most alternatives and relying on USPTO data guarantees homogeneity and accuracy. Finally, patenting entails are closely related to other possible measures of knowledge creation, e.g. scientific publications, to which they are, in any case, strongly correlated.

[4] E.g., the European Patent Convention excludes the patenting of 'schemes, rules and methods for performing mental acts, playing games or doing business, and programs for computers' (art. 52, para. 2). Currently, computer programs can be patented if they provide a technical contribution to the prior art that entails a technical effect going beyond the normal physical interaction between the program and the computer. This is in sharp contrast to methods and software patentable under the US jurisdiction.

[5] The basic composition of clusters does not change. Results are available upon request.

Patents are assigned to countries according to the inventor's country of residence as reported on the patent document.[6] This allows us to account for the country (-ies) where the research leading to the patent was carried out, assuming that the related knowledge will be available in the domestic innovation system.

Given our focus on hardware and software, we include in the empirical analysis only patents related to these two sectors based on the concordance between the International Patent Classification and NACE sectors, as implemented in Patstat (van Looy et al., 2014). Table 1 shows that Computer, electronic and optical products is the NACE sector with the largest number of patent applications. In 2005, about 40 per cent of patents were related to this sector and, since then, patenting activity has grown more than the average in this sector, resulting in an increased share and about 190,000 patents in 2015. In contrast, IT and other information services patents represent only around 2.4 per cent of total applications. Nevertheless, it is interesting that, in this sector, growth in patenting activity was highest during the period considered with almost double the number of applications, from about 5,500 to 10,500 per year.[7]

In the empirical analysis patents are normalized by total national population, as is usual in cross-country comparisons. Moreover, to account for the steady increase in ICT related patents, which was considered the main reason for the recent surge in patent numbers worldwide (Fink et al., 2016), we subtract the sample mean to obtain number of patents per capita. This performs some sort of cleaning and should allow for a better characterization of the relative dynamic performance of the sectors in the different countries.

Based on the above considerations, the relative strength of the SIS in relation to a sector s (i.e., hardware or software) in country c in year t is computed as follows:

$$SIS_{\mathrm{sct}} = \frac{\mathrm{uspto\_patents_{sct}}}{\mathrm{population_{ct}}} - \frac{1}{n}\sum_{c=1}^{N}\frac{\mathrm{uspto\_patents_{sct}}}{\mathrm{population_{ct}}}$$

Like for GVC participation, we are interested in the trajectories of the SIS indicator between the last and first year of the period considered. We calculate the change as:

$$\mathrm{ISchange_{sc}} = \mathrm{IS_{sct=2015}} - \mathrm{IS_{sct=2005}}$$

[6] Patents are counted as fractions, meaning that if the inventors of a patent come from different countries the patent is assigned to the different countries according to the share of inventors (e.g., the present paper would be assigned 0.75 to Italy and 0.25 to Denmark).

[7] Software patenting, the balance between its costs and benefits, and the evident imperfections of the process are a hotly debated issue (Siegel and Suchenek, 2018).

Table 1: Shares of patents by NACE rev.2 sectors at the USPTO

NACE sector	**2005**	**2015**
Computer, electronic and optical products	*39.63*	*43.53*
Chemicals and pharmaceutical products	19.56	18.04
Machinery and equipment	17.92	15.22
Electrical equipment	5.83	6.83
Other manufacturing; repair and installation of machinery & eq.	4.65	3.59
Motor vehicles, trailers and semi-trailers	3.14	3.30
IT and other information services	*1.47*	*2.43*
Fabricated metal products	1.34	1.35
Rubber and plastic products	1.06	1.09
Other non-metallic mineral products	1.53	1.01
Other transport equipment	0.76	0.94
Food products, beverages and tobacco	0.84	0.76
Construction	0.72	0.59
Textiles, wearing apparel, leather and related products	0.54	0.50
Basic metals	0.45	0.46
Paper products and printing	0.35	0.18
Coke and refined petroleum products	0.16	0.17
Wood and products of wood and cork	0.03	0.01
Total patents (#)	***378,544***	***434,521***

Note: authors' calculation on Patstat 2019B

3.2 Methodology

We run a cluster analysis using a k-means algorithm, to identify groups of countries with common GVC participation and SIS strength trajectories, for the hardware and software sectors. Given our set of countries x, each observation is a four-dimensional vector of the following variables:

- $GVC_{sct=2005}$ = level of GVC participation in 2005 and $GVChange_{sct}$ = change in GVC participation between 2005 and 2015;
- $SIS_{sct=2005} =$ level of SIS strength in 2005 and $SISchange_{sct}$ = change in SIS strength between 2005 and 2015.

The sample countries are partitioned into K groups C to minimize the within-cluster sums of the squares[8]:

[8] The cluster analysis partitions the sample (clusters) such that the squared error between the cluster empirical mean and the points in the cluster is minimized (Jain, 2010).

$$\sum_{i=1}^{k}\sum_{x\in C_i}\|x-\mu_i\|^2$$

where μ_i is the centroid (the empirical mean) of C_i. The number of clusters K (cardinality) is not known *a priori* and is based on the procedure described in footnote 8. We identify four clusters in the hardware and the software sectors.[9]

To address possible bias related to the selected clustering technique, we ran some robustness checks. First, given that the results of the K-means clustering might be sensitive to the initial randomly picked centroids to initialize the algorithm, we ran the clustering exercise with different starting points and found that the groups do not change substantially. Second, to allow comparison, we ran an agglomerative hierarchical clustering using an average linkage algorithm.[10] In this case, the resulting partition reveals very little and we prefer to base our analysis on the k-mean approach.

4. Cluster Analysis

Section 2 describes how recent research has begun to explore the mutual dependence between GVCs and SIS, emphasizing the many different pathways that these interactive relationships can take. In this section, we build on the empirical results of a cluster analysis of 45 countries to gain deeper insights about the particular role of sectoral specificities in hardware and software.

Figure 1 reports the mean values of the indicators of GVC participation and SIS strength on which the cluster analysis is based. It shows that in terms of GVC participation, the hardware industry is more involved in GVCs than the software sector.[11] We see opposite trends for the two industries, namely a decrease in GVC participation in hardware and an increase in GVC participation for software, confirming the increasing importance of services in GVCs. In terms of SIS strength, as already indicated in Table 1, the hardware industry is more involved in patenting than the software sector and, in the case of both sectors, the IS appears to have grown stronger over time in the period 2005 to 2015.

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[9] The standard strategy consists of running a clustering algorithm for different values of k and comparing the results. In our application, we perform the clustering for values of k between 3 and 10, and then select k according to the Calinski–Harabasz rule, which is the standard metric implemented in Stata for the k-means algorithm. In the case of the software sector, the solutions with 4 and 5 groups are statistically equivalent and we select the solution with 4 clusters, which allows a grouping of the same dimensionality in the two sectors.

[10] This algorithm starts by forming trivial clusters with a single observation to then successively merging clusters in each step until achieving a large cluster containing the whole sample. In this case, the researcher should choose where to cut the tree to harvest the different groups. In our analysis, this algorithm leaves many countries in single groups after grouping the remaining countries. The dendrograms resulting from the hierarchical clusters are presented in Appendix Fig. A.1 and they suggest that the ordering of the countries is quite similar to that discussed in the results section.

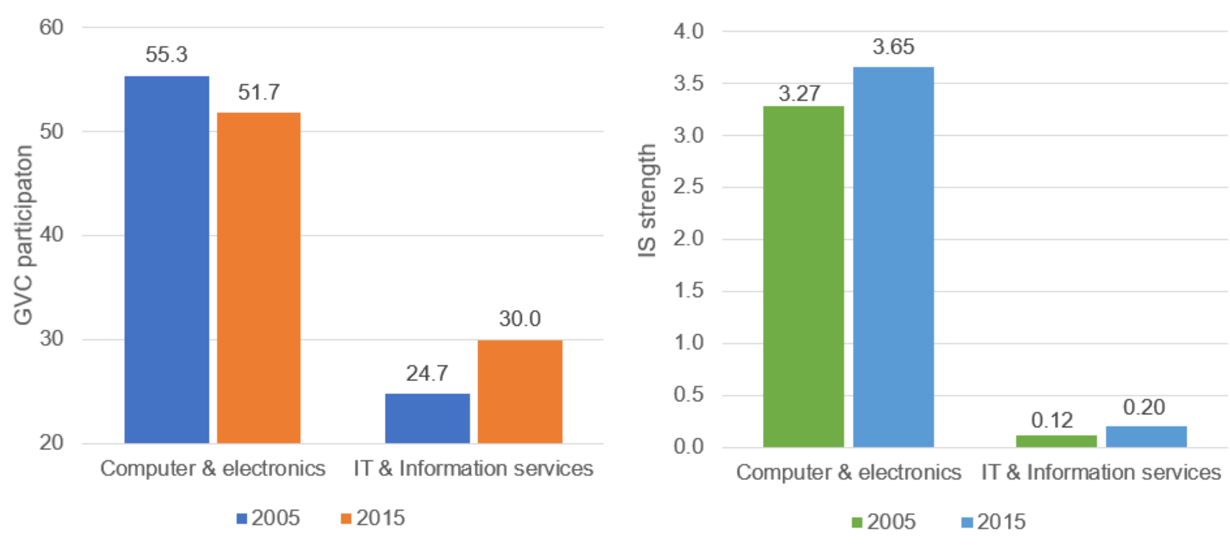
[11] Appendix Table A.2 provides some additional descriptive statistics.

Appendix Table A-3 presents the correlations among the four variables under analysis in the two sectors. For GVC participation and SIS strength, the hardware industry shows that increased IS strength is associated to a decrease in GVC participation. The reverse applies to software: strengthening of the IS is correlated significantly to increased participation in GVCs and, also, to stronger (although not significant) participation at the beginning of the period. Common to both sectors is a positive correlation between SIS strength at the beginning of the period and its subsequent performance, with a much stronger coefficient for software, indicating that countries with initially well-developed SIS experience a greater increase in patenting activity. This signals cumulativeness of the innovation process in the sector and a lack of catch up.

Moving to the cluster analysis, we obtained four hardware and four software clusters (respectively Tables 2 and 3). Both tables present the mean values of the indicators of GVC participation and SIS strength at the beginning of the period, and the rate of change during 2005-2015. Table 4 summarizes the results, with four overall GVC-SIS constellations representing different GVC-SIS trends, which are depicted graphically in Figure 2.

Positive reinforcement is a trajectory combining increased GVC participation with strengthening of the SIS relative to other countries in the same sector, confirming the qualitative analysis proposed in Lema et al (2019). This is observed only for Software Cluster 1 (S1), which includes seven countries, corresponding to 31 per cent of the global market share in 2015, characterized by the strongest level of GVC participation and the strongest IS. Also, these countries show the highest increase in GVC participation and IS strengthening, suggesting a highly cumulative tendency towards self-reinforcing dynamism.

Fig. 1: GVC participation and SIS strength of ICT sectors at the world level



Note: authors’ elaboration from TIVA and Patstat data.

Chain withdrawal with system strengthening characterizes countries with very high although decreasing rates of GVC participation and the strongest hardware SIS, much stronger than in other countries, in line with the in-out-in trajectory described in Lema et al. (2019). This trajectory characterizes Hardware Cluster 1 (H1), which includes six countries, corresponding to 30 per cent of the global market, and major producers such as South Korea, Taiwan and the USA.

Table 2: Hardware Clusters

Cluster	*Countries*	*GVC// GVChange*	*SIS//SISChange*	*Trajectory*
Cluster H1	FIN, ISR, JPN, KOR, TWN, USA	0.504 || -0.03	17.60 || 3.60	• Relatively high GVC participation, but decreasing • Strongest IS, reinforcing
Cluster H2	CAN, CHE, DEU, NLD, SGP, SWE	0.482 || 0.03	5.20 || -0.64	• Increasing GVC participation • Good IS strength, weakening compared to best performers
Cluster H3	AUS, AUT, BEL, DNK, FRA, GBR, IRL, NOR	0.459 || -0.03	-0.64 || -0.21	• Lowest GVC participation, decreasing • Relatively low IS strength, slightly weakening compared to best performers
Cluster H4	ARG, BGR, BRA, CHL, CHN, CZE, ESP, GRC, HKG, HUN, IND, ITA, MEX, MYS, NZL, PHL, POL, PRT, ROU, RUS, SAU, SVK, THA, TUR, ZAF	0.505 || -0.01	-5.27 || -0.64	• Highest GVC participation, moderately decreasing • Lowest IS strength, weakening compared to best performers

Table 3: Software Clusters

Cluster	*Countries*	*GVC//GVChange*	*SIS//SSChange*	*Trajectory*
Cluster S1	CAN, FIN, IRL, ISR, KOR, SGP, USA	0.281 || 0.029	0.352 || 0.533	• Highest GVC participation and strongest increase • Strongest IS, reinforcing
Cluster S2	AUS, CHE, DEU, GBR, JPN, NLD, NZL, SWE, TWN	0.215 || 0.023	0.121 || -0.103	• Relatively low GVC participation, strongly increasing • Good IS strength, weakening compared to best performers
Cluster S3	ARG, BRA, CHL, ESP, FRA, IND, MEX, NOR, RUS, TUR	0.176 || 0.013	-0.126 || -0.099	• Lowest GVC participation, increasing • Relatively weak IS, weakening compared to best performers
Cluster S4	AUT, BEL, BGR, CHN, CZE, DNK, GRC, HKG, HUN, ITA, MYS, PHL, POL, PRT, ROU, SAU, SVK, THA, ZAF	0.298 || -0.001	-0.121 || -0.095	• High GVC participation, slightly decreasing • Relatively weak IS, weakening compared to best performers

Chain deepening with relative system weakening includes three clusters – one hardware and two software – with increasing GVC participation (from different levels) and relatively strong SIS, which, in relative terms, are weakening. Hardware Cluster 2 (H2) includes six countries representing 12 per cent of the global market. In software, S2 includes nine countries, accounting for 22 per cent of the global market and S3 which includes ten countries and a market share of 29 per cent due to the inclusion in this group of India which accounts for 23 per cent of the total.

Negative interaction is the trajectory characterized by a simultaneous decrease in GVC participation and a relative weakening of the SIS, in line with Lema et al. (2019). For hardware, only two clusters follow this trajectory. H3 includes 8 OECD countries and 4 per cent of the global market and H4 includes 25 countries and 52 per cent of the global market because it includes China and other large emerging economy producers such as Mexico, Malaysia and Thailand. For software, there is one large cluster in this trajectory: S4 includes 19 countries, but a total global market share of only 11 per cent.

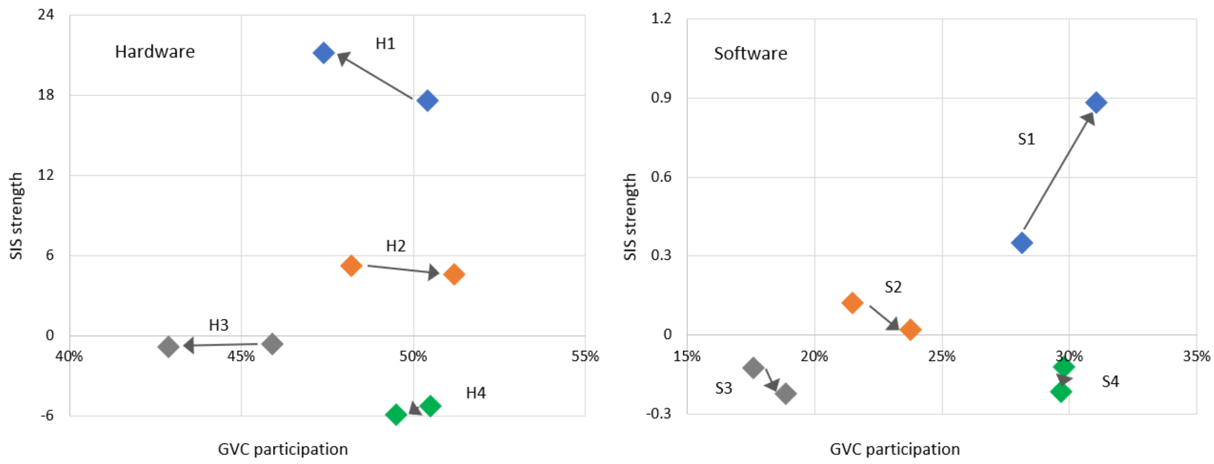
Tab 5: Four GVC-SIS trajectories

Trajectories	**GVC and SIS change**		**Clusters and top 3 countries in terms of global market share (2015)**	
	GVC	*IS*	*Hardware*	*Software*
Positive reinforcement	+	+		**Cluster S1:** IRL, USA, ISR
Chain withdrawal with system strengthening	-	+	**Cluster H1**: KOR, TWN, USA	
Chain deepening with relative IS weakening	+	-	**Cluster H2**: SGP, DEU, CHE	**Cluster S2:** DEU, CHE, GBR **Cluster S3:** IND, ESP, FRA
Negative interaction	-	-	**Cluster H3:** FRA, GBR, IRL (H3) **Cluster H4:** CHN, MEX, MYS (H4)	**Cluster S4:** BEL, ITA, POL

5. The Different Hardware and Software Trajectories

Lema et al. (2019) provide anecdotal evidence of a range of different trajectories of chain-system interactions for a wide variety of different sectors such as textiles, pharmaceuticals and aquaculture in different countries. We provide quantitative evidence of these trajectories in both the ICT sub-sectors analysed and find that there are significant differences between them and, particularly, in those clusters which show increased innovation activity and different GVC patterns for hardware and software. We show also that in terms of SIS strength, there is a high level of cumulativeness: those countries with the strongest innovation capacity at the beginning of the observation period show the greatest capacity improvements over time, while clusters with very low starting levels show large decreases in relative innovating capacity. In other words, this is a signal that they are still failing to catch up in innovation activities.[12]

Figure 2: The GVC-SIS trajectories: 2005-2015



Source: Authors' elaboration.

We found also that the dynamics involved in how the strongest (weakest) clusters gain (lose) further relative strength in the SIS differs for firm participation in the GVCs in these two sectors. This result is depicted in Figure 2, which shows that Cluster H1, the strongest hardware cluster in terms of innovation, presents decreasing GVC participation but stronger innovative capacity. On the contrary, Cluster S1, the strongest software cluster, shows increased GVC participation and improved ability to innovate.

Table 4 Key GVC and SIS dimensions of sectoral specificities of the two sectors

		Hardware	**Software**
SIS	**Type of innovation**	Product	Process
	Ability to codify	High	Low
	Mode of learning	STI	DUI
	External sources of innovation	Universities, suppliers	Users
GVC	**GVC Length**	Long	Short
	Fragmentation	High	Low
	Governance	Modular	Relational

Source: Authors' elaboration drawing on UNCTAD (2020), Pavitt (1984) and Castellacci (2008)

[12] This is not surprising and confirms a basic tenet of evolutionary economics regarding the cumulative nature of technological development (Dosi 1988; Winter 1998).

We argue that the reasons for these differences lie in the specificities of the techno-economic characteristics of these sectors, including their knowledge bases and the tradability of their products and services. The salient features of these characteristics are presented in Table 4, which identifies sectoral specificities related to the GVC and SIS dimensions.[13] In what follows we discuss the results for the hardware and software sectors referring to their sectoral specificities.

5.1 Hardware

Computer, electronic and optical products, or electronics (hardware) deals with mass produced goods based on science-based manufacturing (Pavitt 1984; Castellacci 2008) According to Castellacci (2008), it is the carrier industry of the ICT paradigm (Perez 2004). End products such as computers, smartphones and tablets typically have modular product architectures and integrate components drawing on wide variety of science bases. According to Sturgeon (2002), beginning in the 1990s, this sector experienced a 'delinking' of production and innovation, with innovation activities increasingly concentrated in a small number of high-tech clusters with different types of specialization and production globally dispersed along GVCs. Today, following a global economy-wide trend starting after the financial crisis in 2008, this sector is becoming less GVC-intensive as shown in Figure 1.

Cluster H1 includes Finland, Israel, Japan, Korea, Taiwan and USA, countries known for their high-tech industrial districts and, in most cases, for their household brand, global lead firms. These brand name firms benefit from the 'local buzz' in their home-lead markets (Morrison et al. 2013) and are the leaders in the global GVC reversal trend, with more parts and components manufacturing localized and, in particular, office machinery and computers where GVC trade has declined, as opposed to telecommunications equipment where it has remained strong (Gaulier et al. 2020). This cluster has followed a chain withdrawal with system strengthening trajectory.

Thus, in electronics, SIS strengthening seems to be less dependent on integration into GVCs, and the countries in Cluster H1 have built critical mass and strong knowledge systems which are able to recreate their dynamics independently of GVC trade relationships. One example is South Korea, which has the highest overall turnover in the global hardware industry and is home to computer and smartphone own brand manufacturers such as Samsung and LG. Over time, South Korea has changed its growth strategy from economies of scale to innovation-driven growth, supported by one of the world's most ambitious R&D support schemes (Kim 2020). South Korea has been integrating *both* backward through outsourcing of manufacturing

[13] UNCTAD (2020) shows how the configuration of international production and GVCs varies remarkably across sectors. To classify these configurations, they consider the following three dimensions: value chain length, geographical spread of value added and value chain governance (UNCTAD, 2020, figure IV.5). We use these factors for the GVC dimensions and draw on Castellacci's (2008) modification of Pavitt's (1984) taxonomy for the hardware SIS dimension.

and assembly to lower cost location such as China and Vietnam, *and* forward as a supplier of specialized electronics components to advanced economies. However, its stronger SIS has allowed Korean electronics firms to withdraw from GVCs, as Korean global suppliers of high-tech parts and components have increased the strength of their own brand products and localised the related supply chains (Lee et al. 2018).

Cluster H2 has experienced chain deepening with relative system weakening. Despite the overall contraction in the GVCs in this sector, H2 is the only cluster whose countries have increased their GVC trade significantly – this includes Singapore which has the highest turnover in hardware. For many years, Singapore has been home to numerous multinationals which used Singapore as an assembly and semiconductor testing platform. It is also an electronics trading hub where many own equipment manufacturers have established international procurement offices (Goh and Lau 1998). SIS strengthening was essential in the early stages when Singapore was entering GVCs (Hobday 1995). Later, integration was based more on trade in and manufacturing of some increasingly commodified and, eventually, obsolete specialized components such as hard disk drives. Although Singapore is increasing its innovation capabilities relative to the other ASEAN [14]countries (Chew et al. 2020), it does not have own brand manufacturers and has been unable to match the pace of innovation in the countries in Cluster H1.

Clusters H3 and H4 both followed patterns of negative interactions, but different ones. H3 includes advanced economies such as France (telecoms) and the UK (the Silicon Fen Cambridge industrial district). Ireland is part of this cluster and has experienced a surge in software but decreasing levels of innovativeness and GVC integration in hardware (see below). The major H4 exporters are emerging economies, which are known for their global supply platform roles in the electronics sector and include China, Mexico and Malaysia. GVC participation has declined in these countries and, in the case of China, this has been followed by growth of local value chains. Global flagship firms, such Huawei and Lenovo, have focused on growth in the global market for both their products and services, and world-class knowledge assets (Rashidin et al. 2020; Luo and Lemański, 2016). At the mid and low end of the mobile phone industry, Chinese firms have invested in innovation and extended backward linkages to suppliers of bundled technologies to extend their forward linkages and satisfy a growing base of low-cost Chinese consumers (Humphrey et al. 2018). However, as its relative decreasing innovation capacity indicates, China's electronics innovation system experiences some problems (Lewin et al. 2016; Fu et al. 2013; Altenburg et al. 2008). The main bottleneck in China is in the area of semiconductors. Although the semiconductor industry has grown rapidly, China remains dependent on imports for a large share of its global consumption of chips. Although China's government has increased its investment in innovation, the results are

[14] The Association of Southeast Asian Nations (ASEAN) is a regional grouping with ten members: Brunei, Cambodia, Indonesia, Laos, Malaysia, Myanmar, the Philippines, Singapore, Thailand, and Vietnam.

not (yet) being demonstrated in firm-level responses and Chinese chip firms are unable to keep pace with the rapid technological changes (Lee et al. 2016). Moreover, although in absolute terms there was a patent 'explosion' starting in the 2000s, most patents were filed with SIPO – the State Intellectual Property Office of China (SIPO) now the China National Intellectual Property Administration - CNIPA, and only a small share was also filed with USPTO, mainly by a few large, export-oriented hardware firms (Eberhardt et al. 2017).[15]

5.2 Software

IT and other information services, that is, software, include knowledge intensive business services firms. Driven by these advanced knowledge providers, this industry is the supporting the knowledge base of the ICT paradigm (Castellacci 2008). From a value chain perspective, this sector trades in high-value added IT business services as distinct from lower value-added services such as logistics (UNCTAD 2020). Software value chains are integrated rather than being standalone configuration in electronics, and transactions are difficult to codify (Lema 2015). Compared to hardware, software is traded in GVCs only to a limited extent, but unlike in hardware the trend is increasing.

Cluster S1 presents evidence of a positive reinforcement between GVCs and the IS, and includes Ireland, Israel and USA as major international traders. This cluster shows that the strongest innovators are also those characterized by GVC deepening. In this cluster, Ireland is the most important player in the global software industry. It has been described as a Celtic Tiger, based on its period of fast growth spurred by an influx of FDI by international IT firms between the mid-1990s and the late-2000s when it matched the growth rates of the Asian Tigers (Donnelly 2012). An important component of this success story and its resurgence after the economic crisis at the turn of the millennium were the investments made in the national IS. These took the form of subsidies for high-tech investments, support for IT start-ups and establishment of institutions to support the strengthening of the knowledge economy (Coe 1997; Arora et al. 2004; Annan-Diab and Filippaios 2017; White 2004). Ireland can be considered an example of strong and increasing integration into GVCs accompanied by high domestic investments in human capital and innovation.

Clusters S2 and S3 have both followed the trajectory of chain deepening with relative IS weakening. S2 includes mainly OECD countries, where Germany has the highest turnover. S2 countries are characterized by initial relatively low GVC participation which increased slightly over the observation period. The countries in this cluster have relatively strong software SIS but are not improving as fast as the leaders (e.g., Ireland). Cluster S3 includes some emerging economies, notably India. In these countries initially GVC participation was the lowest but has increased slightly over time. Their software SIS are fragile and becoming weaker compared to other countries. India's software SIS has for long faced problems related to changing from the

[15] Note that it is important to take account of China's size in order not to skew the analysis: the level of USPTO patents is low when normalized to the population size.

delivery of standard services to innovation and R&D (Altenburg et al. 2008). Although there are some major software suppliers in India which are delivering innovative solutions for customers across the world, these are concentrated in select leaders in a small number of clusters (Mittal et al. 2020). Also, their innovations do not result in patents (Lema, 2015).

Cluster S4 followed a pattern of negative interaction and includes a range of countries, the most significant of which, such as Belgium, Italy and Poland, are located in Europe. This cluster has high levels of GVC participation overall similar to Cluster S1 (Figure 2) but is the only group in software with slightly decreasing GVC participation and SIS weakening, starting from a relatively weak base.

6. Discussion and final remarks

The role of GVCs in development has been discussed from several different perspectives. Many authors claim that GVC integration and international specialization in tasks offer remarkable potential for firm and country-level upgrading, but that this potential is necessarily conditional on a process of learning and innovation by local firms. In turn, this process is related, also, to the context, which can foster or hinder innovation, and its systemic features.

In this paper, we addressed these issues and tested for the existence of interdependence and possibly coevolution trajectories between GVC participation and SIS strength. We adopted a cross-country perspective and focused in the ICT industry and the hardware and software sectors. The sample of 45 countries at different levels of development in these two industries was used to investigate our research questions, examine the catching up processes at play and the diverse trajectories followed by different countries.

Our analysis shows that the differences in the evolution across sectors and across countries are remarkable. We identified several trajectories in the ICT domain and discussed the sub-sectoral specificities explaining their differences.

There are three aspect to bear in mind when explaining and interpreting our findings. First, the variations are dependent on sectoral specificities. In hardware, none of the clusters combines a positive reinforcement between increasing GVC integration and strengthening of the innovation system. Stronger SIS was not accompanied by greater GVC integration. The combination of product innovation and fragmented modular value chains means that countries that were strong innovators at the beginning of the observation period have been able to withdraw from GVCs and increase their relative innovation capacity. Arguably, this is because the delinking of innovation domains into separate specific areas means that firms can innovate independently of their position in the GVC and rely more on domestic suppliers and local universities in the national SIS. In modular GVCs, such as hardware, there are few instances and opportunities for innovation interdependence, and this increases as the sector evolves. Conversely, innovation interdependencies are high in software, where process innovation depends on overseas users in short value chains. In relational chains characterized by dense exchanges of the knowledge required to innovate, such as in software, increasing innovation strength is associated to greater GVC participation.

Second, there are some big differences regarding whether national innovation systems manage to create synergies between the hardware and software sectoral systems. For example, Finland and Israel are strong innovators in both subsectors, whereas Japan has increased it software strengths, but lost strength in hardware. In this respect, it is important to note that a finer-grained analysis is needed to determine these synergies or their absence. Supposedly, in Israel, where the focus is on high-tech hardware components and systems, there is complementarity with the software sector focused on 'embedded software' used directly in hardware products, as opposed to stand alone business software services.

Third, our findings raise questions about the relationship between production and innovation in IT. While it is often assumed that above average innovation activity is required to remain competitive in knowledge-intensive sectors, many countries in clusters that move along (relatively) declining innovation paths are simultaneously increasing their production output. Here, GVCs seem to compensate for lack of local markets, for example, Singapore in hardware and India in software. These countries may be thriving based on increasing commodification of certain hardware and software domains.

The study has some limitations since we focus only on patents to capture SIS 'strength'. Whilst we would agree that patents often capture only a part of technological competence, they are a better measure than most of the alternatives, allow detailed sector-level analyses and are strongly correlated to other measures of knowledge creation such as scientific publications. It would also have been preferable to have a longer time series to analyse GVC integration, but the data were not immediately available delay.

We realize that we scratch only the surface of a complex multidimensional phenomenon, but we believe we have advanced the work in this area More research is needed, perhaps using the forward and backward dimensions of GVCs and including in the analysis additional measures of SIS strength. Future studies could target the time dimension and sequencing in the processes analysed more explicitly.

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Appendix

Table A.1: List of countries included in the analysis

Argentina (ARG)	Greece (GRC)	Republic of Korea (KOR)
Australia (AUS)	Hungary (HUN)	Romania (ROU)
Austria (AUT)	India (IND)	Russian Federation (RUS)
Belgium (BEL)	Ireland (IRL)	Saudi Arabia (SAU)
Brazil (BRA)	Israel (ISR)	Singapore (SGP)
Bulgaria (BGR)	Italy (ITA)	Slovakia (SVK)
Canada (CAN)	Japan (JPN)	South Africa (ZAF)
Chile (CHL)	Malaysia (MYS)	Spain (ESP)
China (CHN)	Mexico (MEX)	Sweden (SWE)
China, Hong Kong SAR (HKG)	Netherlands (NLD)	Switzerland (CHE)
Czech Republic (CZE)	New Zealand (NZL)	Taiwan (TWN)
Denmark (DNK)	Norway (NOR)	Thailand (THA)
Finland (FIN)	Philippines (PHL)	Turkey (TUR)
France (FRA)	Poland (POL)	United Kingdom (GBR)
Germany (DEU)	Portugal (PRT)	United States of America (USA)

Table A.2 Descriptive statistics

	Average	Median	Std. dev	Min	Max
			Hardware		
GVC	0.494	0.470	0.135	0.210	0.760
GVChange	-0.011	-0.031	0.069	-0.119	0.208
SIS	0.000	-4.232	7.993	-5.644	24.137
SISchange	0.000	-0.792	3.386	-7.143	13.298
			Software		
GVC	0.252	0.257	0.086	0.105	0.575
GVChange	0.012	0.016	0.040	-0.078	0.137
SIS	0.000	-0.111	0.235	-0.145	1.110
SISchange	0.000	-0.105	0.264	-0.182	1.053

Tab A.3: Correlations: hardware and software

	Hardware				Software			
	GVC	GVChange	SIS	SISchange	GVC	GVChange	SIS	SISchange
GVC	1				1			
GVChange	-0.46*	1			0.22	1		
SIS	0.02	-0.05	1		-0.19	0.16	1	
SISchange	0.12	-0.33*	0.34*	1	0.24	0.27*	0.70*	1

Source: Authors' calculations. Note: * significant at 5% level

Figure A.1: Dendograms from hierarchical clustering