Working Paper Series

#2021-007

Deepening or delinking? Innovative capacity and global value chain participation in the ICT sectors

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Published 26 February 2021

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UNU-MERIT Working Papers
ISSN 1871-9872

Maastricht Economic and social Research Institute on Innovation and Technology
UNU-MERIT

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Deepening or Delinking?

Innovative Capacity and Global Value Chain Participation in the ICT Sectors

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Abstract

Innovation trajectories in global value chains can take highly differentiated pathways. Firms and other organisations operating in a sector in a given country may gain or lose innovative capacity over time compared to their peers in other countries. In this paper we address the question: do stylised trajectories emerge from the analysis of countries' relative innovative capacity and global value chain participation? We draw explorative insights from a cluster analysis of 45 countries on the subsectors of the information and communication technology industry: hardware and software. Our analysis uncovers remarkable differences across sectors and countries. We identify different trajectories and discuss the sub-sectoral specificities which contribute to explaining these differences. The association between the strengthening of innovative capacity and deeper insertion in global value chains applies to only a handful of countries and only in the software subsector. These findings raise questions for future research on innovation in global value chains.

Keywords: Global value chains, Innovation capacity, Innovation trajectories, Hardware, Software, ICT

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

1. Introduction

The emergence of global value chains (GVCs), where firms specialise in specific tasks and the production processes are distributed across different countries, has characterised the evolution of the global economy during the last three decades. Economic globalisation has risen significantly with the expansion of foreign direct investment (FDI), international trade in final goods and managed trade in intermediate goods and services produced and assembled by different actors in different places. GVC trade was growing rapidly until the outbreak of the global financial crisis in 2008, since when it has stagnated although half of world trade is still related to GVCs.[1]

An increasingly discussed question related to the rise of GVCs is whether firms will have more opportunities to access key knowledge and technology, and to increase their innovative capacity by participating in GVCs (Pietrobelli & Rabellotti, 2011; Taglioni & Winkler, 2016; Tajoli & Felice, 2018; World Bank, 2020). Recent research points to an interdependent relationship between GVC integration and innovation, with a resulting range of possible trajectories along which firms may acquire or lose innovative capacity (IC) after insertion in a GVC (Lema et al., 2019). The key argument is that capability building at firm level is interrelated with the many ways in which GVCs and innovation systems may co-evolve.

In this work, we take a sectoral perspective to assess the emergence of stylised trajectories, consistent with theoretical co-evolutionary patterns, by analysing countries' IC and GVC participation. In particular, we look for the existence of different trajectories in the two information and communication technology (ICT) sub-sectors: hardware and software. The focus on the ICT industry is motivated by three reasons: *i)* it is deeply influenced by GVC trade (UNCTAD, 2020); *ii)* it allows us to analyse two very different sub-sectors related to manufacturing and services; and *(iii)* both sectors are highly innovative. It has been acknowledged that the service industry is playing an increasingly central role in GVCs (OECD, 2020), which makes it interesting to compare trends in the manufacturing and service sectors in terms of GVC participation and IC.

We perform a cluster analysis of 45 countries over the 2005-2015 period to address the following research questions: How are changes in the comparative strengths of IC and GVC participation related? Is the strengthening of IC associated to deeper GVC insertion, or conversely to a withdrawal? Which sectoral characteristics might contribute to explaining different joint trajectories?

The paper is organised as follows. Section 2 summarises the literature on innovation in GVCs and introduces the conceptual framework for our empirical analysis. Section 3 presents the data and the methodology used for the empirical analysis. Section 4 presents the evidence from the cluster analysis from a country/sector perspective. Section 5 offers some illustrative cases and

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[1] 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, by the abrupt halt caused by the COVID-19 crisis (Baldwin & Evenett, 2020)

additional secondary evidence to interpret the trajectories followed by the hardware and software sectors. Section 6 summarises the main findings and concludes.

2. Global Value Chains and Innovative Capacity

2.1. The literature

There is a well-established and growing body of literature which combines analysis of GVCs with a focus on innovation in firms, sectors and countries (de Marchi et al., 2018; Reddy et al., 2020; Tajoli & Felice, 2018). A large part of this literature assumes that GVC participation has a positive impact on innovation. Leading firms at the receiving end of GVCs can farm out steps in their manufacturing processes to allow them to concentrate their efforts on the development of and improvements to products and services (Sturgeon, 2002). They also can decompose the innovation process and source problem-solving tasks from specialised suppliers in the value chain (Lema et al., 2015). At the same time, GVC suppliers benefit because participation facilitates knowledge transfer, mutual learning and improvement to routines (Cirera & Maloney, 2017; Farole & Winkler, 2014; Pietrobelli & Rabellotti, 2007). However, supplier learning is far from automatic; in many cases, GVC involvement and increased GVC participation results in improved production capabilities with no accompanying increase in innovation capabilities (Schmitz, 2007). The distinction between production and innovation capabilities proposed by Bell and Pavitt (1993) stresses that the former is related to how firms acquire the ability and skills to produce, enhance and develop existing products, while the latter refers to how they develop the capacity to create new products and new knowledge for a wide range of possible applications, beyond small adaptations and adjustments.[2]

At the macro level, while not examining the role of innovation directly, recent research shows that, controlling for other variables, countries that increase their participation in GVCs do not grow faster (Fagerberg et al., 2018). Some suggest that innovation requires the withdrawal from GVCs and a focus on the development of local value chains (Andreoni, 2019; Lee et al., 2018).[3]

Thus, there is no consensus on the relationship between changes to IC and GVC participation: both deepening participation in and delinking from GVCs may be functional to increasing innovation. Many different trajectories can emerge, depending on the specific circumstances. These involve a wide range of country- and context-specific factors including history,

[2] 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).

[3] For instance, this is a case of 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 innovation system and facilitate innovation and upgrading. Eventually, latecomer firms and economies reintegrate into GVCs led this time, by domestic firms who establish their own value chains

geography and the socio-economic environment, the macroeconomic and trade policy framework, sector specificities such as predominant technological characteristics, knowledge bases and sectoral industrial policies, openness and the initial level of technological capabilities. While all these factors may play a role, we focus on two factors we deem pivotal.

The first is sectoral specificity, a dimension that clearly plays a central role in much of the GVC literature (Gereffi et al., 2005). Pietrobelli and Rabellotti (2011) show that governance patterns have heterogeneous impacts on the learning and upgrading mechanisms in value chains of different sectors. For instance, in modular chains, learning can result from pressure to match international standards but is rarely facilitated by a direct leader-supplier involvement. Instead, in relational value chains where knowledge is less easily codified, learning is based more on intense face-to-face interactions among the actors. Thus, sector specific governance patterns may have a significant influence on how ICs develop.

The second is related to the initial IC needed to take advantage of GVC participation. In this respect, Morrison et al. (2008) point out that knowledge and technology access via GVCs is influenced not only by governance patterns but also by differences in the capacity to absorb, master and adapt knowledge and capabilities. In this process, a well-developed local innovation system is important for shaping firm capabilities to innovate within GVCs (Pietrobelli & Rabellotti, 2011). Local sectoral innovation systems are marked by a specific combination of technological opportunities, appropriability conditions, cumulativeness and knowledge base properties which may influence firms' involvement in GVCs (Malerba, 2002; Malerba & Mani, 2009). The experience of countries such as South Korea shows that the formation of a strong innovation system is crucial to benefit from GVCs and to help domestic firms move to more sophisticated phases of production and higher value-added products (Lee & Lim, 2001). In other cases, weak innovation systems undermine the development of ICs in GVCs (Kishimoto, 2004).

Based on these insights, Lema et al. (2018, 2019) suggest an analytical framework to explore possible learning and innovation trajectories for firms in developing countries which combine a GVC and innovation system (IS) perspective. They argue that GVC and IS approaches are complementary for an analysis of the relationships between global and domestic actors that affect the innovation process. The idea of co-evolution is based on recognition of the existence of knowledge flows linking the two dimensions: on the one side, IS and GVCs contribute to firms' capabilities accumulation (learning); on the other side, innovative firms via their evolving capabilities, influence local IS characteristics and GVC governance. Hence, they present different context-specific trajectories which envisage increasing, stagnating, or declining innovative capabilities.

The aim of this paper is to empirically test for the existence of different trajectories of IC and GVC participation in the ICT industry. To this end, we propose quantitative measures of these two dimensions, and use them to identify possible country- and sector-level trajectories.

2.2. The conceptual framework

In this section we present a conceptual framework that helps explaining how the *joint movements* between IC and GVC participation may generate different trajectories in different countries and sectors. On this basis we derive expectations and interpret the results of our empirical exercise.

The two foundational elements of the conceptual framework are: IC and GVC participation (for their operationalisation see section 3). The IC considers all national innovators, firms and other organisations, active in a specific (sub)sector and is proxied by patent-related measures.[4] The choice to refer to IC rather than IS, is driven by the recognition that we do not consider the interconnections among actors and the related knowledge externalities characterising sectoral IS. Innovation trajectories refer to relative gains or losses in IC over time.

The second element is *GVC participation*, which measures how much the country is connected to GVCs relative to its trade, and focuses on possible moves further in or out of these chains relative to a starting point.

Table 1 presents a 2 by 2 matrix with the possible combinations of changes in IC and GVC participation. Based on these combinations we identify four hypothetical trajectories:

- *Trajectory 1*: strengthening of IC and deepening of GVC participation,
- *Trajectory 2*: strengthening of IC and delinking (withdrawal) from GVC,
- *Trajectory 3*: weakening of IC accompanied by GVC deepening**,**
- *Trajectory 4*: weakening of IC and delinking (withdrawal) from GVC participation.

Our working hypothesis is that a particular trajectory will prevail depending on the specific techno-economic characteristics of the sector considered. Both the innovation and GVC literatures agree about the importance of sector specificities. In innovation studies, since the seminal contribution of Pavitt (1984), research on sectoral patterns of innovation has flourished and investigates both empirically and theoretically the different characteristics of the innovative process in specific industries, as well as the differences in technological performance and innovation patterns (Breschi, 2000; Malerba, 2002). In this paper, our key dimensions include some of those proposed in Castellacci's (2008) taxonomy which accounts for differences in manufacturing industries and services, assigning the function of sustaining the knowledge base of the ICT paradigm to the software industry, and considering the hardware industry as the carrier of the paradigm. These dimensions are the technological content of the industry (the overall level of IC and the dominant innovation mode), and the function assumed by the industry (its position in the vertical chain), here considered from a global perspective.

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[4] In this paper we refer mostly to IC although we sometimes refer to innovation capability. The former is related to the ability to carry out current processes (and is closer to our patent-based measure); the latter refers to the ability to carry out dynamic processes of improvement and is often used to describe the ability to reproduce innovation success.

Table 1: Typology of possible trajectories

	Strengthening relative innovative capacity	**Weakening relative innovative capacity**
Deepening GVCs participation	**Trajectory 1** Deepening and strengthening	**Trajectory 3** Deepening and weakening
Withdrawal from GVC participation (delinking)	**Trajectory 2** Delinking and strengthening	**Trajectory 4** Delinking and weakening

Participation in GVCs is also not homogeneous across industries, and governance patterns shaping how lead firms interact with their suppliers and subsidiaries around the world are sector specific (Gereffi et al., 2005). The different governance patterns across industries influence the role of lead firms in fostering (or hindering) knowledge transfer and learning (Giuliani et al., 2005; Pietrobelli & Rabellotti, 2007 and 2011; Schmitz, 2007). For instance, if the knowledge is mainly tacit and innovation requires intense interaction, lead firms may become involved directly in their providers' learning processes. However, in the case of codified knowledge there is little direct commitment of lead firms, and innovation derives more from pressure to meet the international technical standards required to participate in GVCs. Following UNCTAD (2020), we also consider other dimensions of international production: value chain length and degree of fragmentation, which depends on the modularity of the production process and the economies of specialisation and scale, and other elements that help differentiate between the hardware and software industries based on some recent evidence.

Table 2: Hardware and Software Sectoral Specificities

Dimensions	**Hardware**	**Software**
Innovation		
Type of innovation	Product	Process
Innovation mode	STI	DUI
External sources of innovation	Universities, suppliers	Users
Value Chain		
GVC Governance	Modular	Relational
GVC Length	Long	Short
GVC Fragmentation	High	Low

STI: Scientific and technological-based innovation; DUI: learning-by-doing, by-using, and by-interacting (Jensen et al, 2007)

Source: Authors' elaboration drawing from Castellacci, 2008, and UNCTAD, 2020.

Table 2 highlights the dimensions that identify possible trajectories: type of innovation; innovation mode and external sources of innovation and GVC governance patterns, GVC length and fragmentation. In section 5 we discuss how these sectoral dimensions help to explain the different trajectories of the two sub-sectors.

3. Empirical Analysis

3.1 Data and indicators

To investigate the joint trajectories of GVC participation and IC, we build an industry-country level dataset combining information from two sources: the Trade in Value Added (TiVA) database produced by the OECD[5] and the US Patent and Trademark Office (USPTO) database which provides information on patents.

GVC participation

Several input-output based measures have been developed to capture different aspects of the vertical linkages characterising multi-country production processes (Hummels et al., 2001).[6] In this work we rely on the measures of sectoral GVC participation proposed by Borin and Mancini (2017) and used in the World Bank Development Report (World Bank, 2020). These measures are based on the framework proposed by Koopman et al. (2014) to breakdown gross exports into their domestic and foreign content and to decompose domestic value-added into exports which are: 1) consumed in the importing country, 2) returned to the exporting country (to avoid double counting), 3) re-exported to a third country.[7]

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 involved in:

i. *backward participation* capturing the value of intermediate goods imported from abroad, embodied in domestic sector exports. For example, if smartphones exported by China use imported components, they contribute to China's backward participation;

ii. *forward participation* measures the value of exports which are not consumed in the importing country but are embodied in further exports to third countries. This applies to the case where Japan exports screens to China which then are used to produce smartphones which are exported. The value of the screens contributes to Japan's GVC forward participation.

[5] OECD-TiVA provides information for 65 countries over the period 2005-2015.

[6] An overview of the different approaches used to measure GVC participation can be found in Amador and Cabral (2016).

[7] See Borin and Mancini (2017) for a more detailed and technical description of these GVC measures.

In other words, the GVC participation index captures the share of trade crossing borders more than once from a sector perspective, and in line with the literature, is considered a share of the sector gross exports and is computed as follows:

$$\mathrm{GVC}_{\mathrm{sct}} = \frac{\mathrm{backward}_{\mathrm{sct}} + \mathrm{forward}_{\mathrm{sct}}}{\mathrm{export}_{\mathrm{sct}}}$$

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

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

3.2 Innovative capacity

To measure IC strength at the sectoral level we rely on USPTO patent applications. We acknowledge that our exclusive focus on patents means that we capture only the technological dimension of the IS and ignore organisational and economic competencies (Dosi & Teece, 1998). However, there are no comparable sector level data for a large set of countries. Furthermore, patents guarantee homogeneity and accuracy and are closely related to other possible measures of knowledge creation, e.g. scientific publications.

A further possible bias in our study is related to the fact that the relevance of patenting in software is a hotly debated issue, with an unclear balance between the costs and benefits, and many evident imperfections related to the process (Siegel & Suchenek, 2018). Software sector patents typically are related to subject-matter where method steps can be carried out by instructions contained in a computer programme integrated in the machine, or where some steps are performed external to the machine and require specific technical means (e.g. sensors). This differs from hardware industry patents which are related to the machine or the sensor (and their components). This contributes explaining the very different patenting intensity in these two sub-industries: while typically a machine (e.g. a smartphone) involves hundreds or thousands of patents, a software patent may be related to one clearly identifiable process. Also, software patents are handled differently by different patent offices. To address any possible biases, we chose to use the USPTO which is the only office allowing the registration of computer programmes and methods tied to a machine without requiring a physical effect beyond programme-machine interaction.[8]

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[8] For instance, the European Patent Convention excludes the patenting of 'schemes, rules and methods for performing mental acts, playing games or doing business, and programmes for computers' (art. 52, para. 2). Currently, computer programmes can be patented if they provide a technical contribution to the prior art which entails a technical effect going beyond the normal physical interaction between the programme and the computer. This is in sharp contrast to the methods and software patentable under US jurisdiction. For example, the Amazon Inc. well-known "*one-click*" patent was granted by the USPTO in 1999 but was rejected by the European Patent Office. This illustrates the different attitudes of intellectual property policy toward software patents in the EU and

Table 3 confirms the difference in patenting in the two industries; Computer, Electronic and Optical products is the NACE sector with the largest number of patent applications. In 2005, about 40 percent of patents were related to this sector, and since then, patenting activity has grown more than the average, resulting in an increased share and about 190,000 patents in 2015. In contrast, information technology (IT) and other information services patents represent only around 2.4 percent of total applications. Nevertheless, it is interesting that in this sector, patenting activity growth is the highest during the period considered, with the number of applications almost doubling (from about 5,500 per year to 10,500 per year).

Despite their limitations, to measure IC in this study we use patents, based on concordance between their International Patent Classification and NACE sectors (Looy et al., 2015), retrieved from the USPTO. This choice could introduce a home bias due to information from a single patent office; given the same level of inventive activity, US applicants may tend to file more patents at the USPTO than foreigners (Dernis & Khan, 2004). For this reason, we ran a robustness check excluding the USA from the analysis.[9] Also, following Lee and Lee (2020) and an established tradition in patent studies, we exclude countries with less than 10 patents at the USPTO for each of the years covered by TiVA which produced a final sample of 45 countries (see appendix Table A.1). Patents are assigned to countries according to the inventor's country of residence as reported on the patent document.[10] This allows us to consider where the research leading to the patent was carried out, assuming that the related knowledge is available in the domestic innovation system.

In the empirical analysis patents are normalised by total national population, a frequent practice in cross-country comparisons. Moreover, to account for the steady increase in ICT related patents, which is considered the main reason for the recent surge in patent numbers worldwide (Fink et al., 2016), we subtract the sample mean from the per capita number of patents. This allows for better characterisation of the relative dynamic patent performance of the two sectors in different countries.

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

$$\mathrm{IC}_{\mathrm{sct}} = \frac{\mathrm{uspto\_patents}_{\mathrm{sct}}}{\mathrm{population}_{\mathrm{ct}}} - \frac{1}{n}\sum_{c=1}^{N}\frac{\mathrm{uspto\_patents}_{\mathrm{sct}}}{\mathrm{population}_{\mathrm{ct}}}$$

As in the case of GVC participation, we are interested in the trajectories of the IC indicator between the last and first years of the period considered, therefore we calculate the change as:

the USA which are due partly to the tendency of software patents to make more general claims. More information on the "one-click" patent can be found in USPTO (1997).

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

[10] 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).

$$\text{ICchange}_{sc} = \text{IC}_{sct=2015} - \text{IC}_{sct=2005}$$

Table 3: 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***

Source: 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 IC 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;
- $GVChange_{sct}$ = change in GVC participation between 2005 and 2015;
- $IC_{sct=2005}$= level of sectoral IC strength in 2005;
- $ICchange_{sc}$ = change in IC strength between 2005 and 2015.

The sample countries are partitioned into K groups C to minimise the within-cluster sums of the squares:[11]

[11] The cluster analysis partitions the sample in clusters so that the squared error between the cluster empirical mean and the points in the cluster is minimized (Jain, 2008).

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

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.[12]

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 centroids randomly picked to initialise 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 agglomerative hierarchical clustering using an average linkage algorithm.[13] In this case, the resulting partition reveals very little and we prefer to base our analysis on the k-mean approach.

4. Cluster Analysis

In this section, we build on the empirical results of the cluster analysis of 45 countries to obtain insights into the role of sectoral specificities in the hardware and software sectors. Figure 1 reports the mean values of the indicators of GVC participation and IC strength on which the cluster analysis is based. It shows that in 2005 GVC participation was much higher in the hardware industry than in software, but also that there are opposite trends at play.[14] GVC participation is decreasing in hardware and increasing in software, confirming the growing importance of service GVCs. In terms of IC strength, as indicated in Table 1, the hardware industry is much more involved than the software sector in patenting, and although IC has strengthened over time in both sectors, the software industry growth rate is much higher than the rate in the hardware industry.

Appendix Table A-3 presents the correlations among the four variables under analysis for the two sectors. For GVC participation and IC strength, the hardware industry shows that increased IC strength is associated to a decrease in GVC participation. The reverse applies to software:

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[12] 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.

[13] This algorithm starts by forming trivial clusters with a single observation, then successively merging clusters in each step until a large cluster containing the whole sample is achieved. In this case, the researcher must choose where to "cut the tree" to harvest the different groups. In our analysis, this algorithm leaves many countries in singleton 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 countries is quite similar to that discussed in the results section.

[14] Appendix table A.2 provides some additional descriptive statistics.

the strengthening of the IC is significantly correlated to increased participation in GVCs, and also to stronger (although not significant) participation at the beginning of the period. Common to both sectors is the positive correlation between IC strength at the beginning of the period and its subsequent performance, with a much larger coefficient of software, indicating that countries with initially well-developed IC experience a greater increase in patenting activity. This points to the cumulativeness of the innovation process in the sector and a general lack of catch-up.

Fig. 1: GVC participation and IC strength of ICT sectors

	Level in 2005	Growth rate (2005-2015)
	GVC participation	
Computer & electronics	55.3	-6%
IT & Information services	24.7	21%
	IC strength	
Computer & electronics	3.27	12%
IT & Information services	0.12	70%

Note: Authors' elaboration from TIVA and Patstat data.

The cluster analysis identifies four hardware and four software clusters which, based on the direction of change during the period 2005-2015, are assigned to the four trajectories identified in Table 1. The clusters are presented in Tables 4 and 5 which show the mean values of the indicators of GVC participation and IC strength at the beginning of the period, the rate of change during 2005-2015, and the list of the countries in each cluster. The four trajectories in the two industries are depicted also in Figure 2.

Trajectory 1 is observed in the *Software Cluster 1 (S1)* and includes seven countries corresponding to 31 percent of the global market share in 2015. It combines increased GVC participation with strengthening of the IS relative to other countries in the same sector. This cluster had the strongest IC in 2005, and this increased during the period of analysis. By 2015, the cluster had reached the highest degree of GVC participation and the strongest IS in the sub-industry, suggesting a highly cumulative tendency with self-reinforcing dynamics.

Trajectory 2 is found in the *Hardware Cluster 1 (H1)* and includes six countries, corresponding to 30 percent of the global market, and including major producers such as South Korea, Taiwan and the USA. The trajectory is characterised by withdrawal from GVCs and IC strengthening. Innovation capacity is strongest in 2005 and continues to strengthen up to 2015. At the same time, in 2005 GVC participation is high and in line with other hardware clusters but decreases later, indicating a delinking process from the international production system.

Trajectory 3 includes three clusters – one hardware and two software – which show increased participation in GVCs (starting from different levels) and (relatively) weaker innovation capacity. *Hardware Cluster 2 (H2)* includes six countries representing 12 percent of the global market. *Software Cluster 2 (S2)* includes nine countries, accounting for 22 percent of the global market, and *Software Cluster 3 (S3)* consists of ten countries and a market share of 29 percent. India, which accounts for 23 percent of the global market is part of this last cluster.

Trajectory 4 consists of delinking (falling GVC participation) and relative weakening of IC. In hardware, two clusters follow this trajectory: *H3* includes 8 OECD countries and 4 percent of the global market, and *H4* includes 25 countries and 52 percent of the global market including China, Mexico, Malaysia and Thailand. In software, only *S4* conforms to this trajectory and includes 19 countries but a total global market share of only 11 percent.

In Section 5 we provide a detailed analysis of this evidence to explain the emergence and evolution of these clusters of countries.

5. The Different Hardware and Software Trajectories

The cluster analysis offers quantitative evidence related to the four trajectories identified in Table 1 and highlights the significant differences among them within the ICT sub-sectors. In Figure 2 we observe that only two clusters - *H1* and *S1* - show an increase in the relative strength of innovation capacity. In both cases, a high level of cumulativeness is confirmed since they already had the highest IC at the beginning of the period (Dosi, 1988; Winter, 1998). In contrast, clusters with very low starting levels show large decreases in relative IC, revealing that they are failing to catch up in innovation.

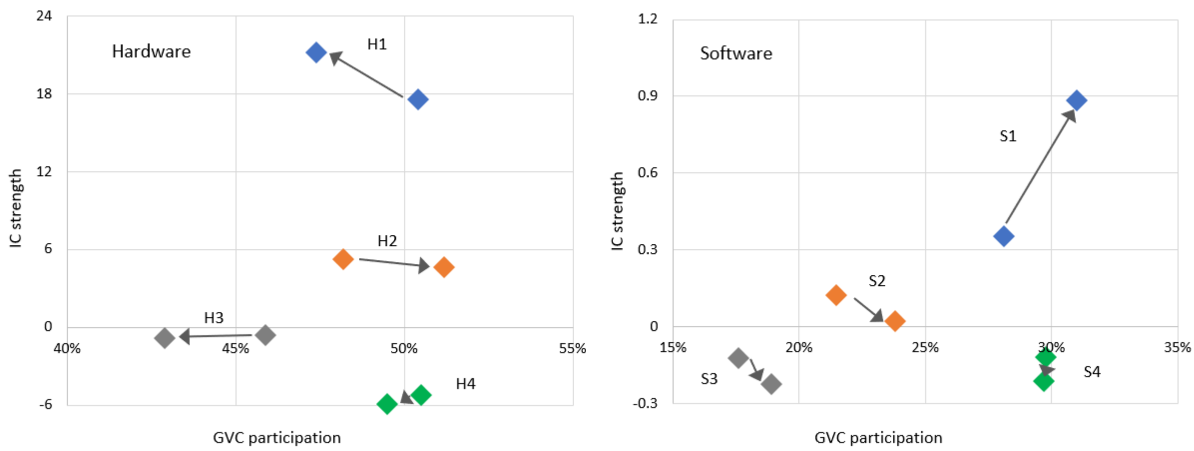
Table 4: Hardware Clusters

Cluster	*Countries*	*GVC || Change (%)*	*IC || Change (%)*	*Trajectory*
Cluster H1	FIN, ISR, JPN, KOR, TWN, USA	0.504 || -6.0%	17.60 || +20.0%	T2: Delinking and strengthening
Cluster H2	CAN, CHE, DEU, NLD, SGP, SWE	0.482 || +6.2%	5.20 || -12.3%	T3: Deepening and weakening
Cluster H3	AUS, AUT, BEL, DNK, FRA, GBR, IRL, NOR	0.459 || -6.5%	-0.64 || -32.8%	T4: Delinking and weakening
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 || -2.0%	-5-27 || -12.1%	T4: Delinking and weakening

Table 5: Software Clusters

Cluster	*Countries*	*GVC || Change (%)*	*IC || Change (%)*	*Trajectory*
Cluster S1	CAN, FIN, IRL, ISR, KOR, SGP, USA	0.281 || +10.3%	0.352 || +66.0%	T1: Deepening and strengthening
Cluster S2	AUS, CHE, DEU, GBR, JPN, NLD, NZL, SWE, TWN	0.215 || +10.7%	0.121 || -85.1%	T3: Deepening and weakening
Cluster S3	ARG, BRA, CHL, ESP, FRA, IND, MEX, NOR, RUS, TUR	0.176 || +7.4%	-0.126 || -78.6%	T3: Deepening and weakening
Cluster S4	AUT, BEL, BGR, CHN, CZE, DNK, GRC, HKG, HUN, ITA, MYS, PHL, POL, PRT, ROU, SAU, SVK, THA, ZAF	0.298 || -0.3%	-0.121 || -78.5%	T4: Delinking and weakening

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



Source: Authors' elaboration.

Moreover, the two clusters with the relatively strongest ICs show very different GVC participation trends. *Cluster H1*, the strongest hardware cluster for innovation shows decreased GVC participation, while *Cluster S1* shows an increasing trend in GVC participation (Figure 2).

We can derive three main findings from the cluster analysis:

i. The starting point matters – in both sectors only the (*ex ante*) strongest clusters show (*ex post*) stronger relative IC growth, which means that a cumulativeness effect is at play in both sectors;

ii. Relative increases in innovativeness are associated with GVC participation differently in the two sub-sectors: in the hardware sector a relative innovation increase is associated to a decrease in GVC participation, while in the software sector the opposite applies.

iii. While the above trend is strong and clear, when IC decreases the picture is less clear and is inconclusive. Decreases in innovation are associated to both increases and decreases in GVC participation (in both sectors).

To explain the observed patterns, we next discuss the findings in sequence.

5.1 Explaining the overall cumulative diverging trends

Our results suggest that already strong innovators become even stronger over time, while less strong innovators show relatively worse innovation performance over time. To explain these findings our main argument is that the observed patterns reflect the specificities of the sectors but there are also some dynamics at play which influence both sectors simultaneously.

Positive cumulativeness suggests that both sectors benefit from increasing knowledge returns to innovation. Some countries appear in the most dynamic clusters in both sectors (e.g. USA, South Korea, Finland and Israel that belong both to *H1* and *S1*). This suggests that there is increasing dynamism not only within but also between the hardware and software sectors, and some countries are able to leverage these synergies. This may be explained by the disruption and recombination between hardware and software made possible by the 4th industrial revolution which has provided unexpected windows of opportunity.

However, these opportunities are not exploited equally by all countries – as reflected by the fact that most of the clusters in the sample lose their relative IC. We return to these issues later.

5.2 Explaining the GVC delinking and innovation strengthening trajectory in hardware

This trajectory is observed in *Cluster H1* which includes Finland, Israel, Japan, Korea, Taiwan and USA, countries known for their high-tech industrial agglomerations, and in most cases for their brands as global lead firms. These firms benefit from the ‘local buzz’ in their home markets (Morrison et al., 2013) and are leading the global GVC reversal trend by manufacturing more parts and components domestically. This applies especially to office machinery and computers where GVC trade has declined compared to telecommunications equipment where GVC trade remains strong (Gaulier et al., 2020). The countries in *Cluster H1* have built critical mass and strong knowledge systems which allow to reinforce their performance independently of GVC trade relationships. One example here is South Korea which has the highest overall turnover in the global hardware industry and hosts computer and smartphone own brand manufacturers such as Samsung and LG. Over time, South Korea has changed strategy from growth based on economies of scale to growth driven by innovation, supported by one of the world’s most ambitious R&D sponsorship schemes (Kim, 2020). South Korea has been integrating *both* backward by outsourcing manufacturing and assembly to lower cost location such as China and Vietnam, *and forward* by supplying specialised electronics components to advanced economies. However, its strong local IS has allowed

Korean electronics firms to withdraw from GVCs, and Korean global suppliers of high-tech parts and components have increased the strength of their own brand products and set up local domestic supply chains (Lee et al., 2018).

What are the key sectoral characteristics that explain the GVC delinking trend in those countries that are innovating faster? The salient features of the hardware sector are a predominance of product innovation, structured knowledge generation (R&D) to support those innovations, and large innovation networks with a preponderance of knowledge inputs from universities and specialised suppliers. In the past, there has been a delinking of innovation from production (Pisano and Shih, 2009) and a continued tendency to outsource manufacturing activities along highly fragmented value chains with multiple links (Table 2).

This sector includes a large range of consumer electronics, telecommunications and office equipment. These different types of hardware have distinctive features and uses but their knowledge bases overlap. During the observation period, a large part of the drive for innovation was related to increasingly 'smart' equipment, 'servicification' and digital networking exemplified by the Internet of Things (IoT). These developments have produced disruptions in several domains and increased numbers of global platforms and ecosystems of new flagship firms.

The increasing internet-aided networks and standards facilitating interoperability between both final products and components assembled into open architectures during the production process, have created major changes in firms' capability requirements. In general, the complexity of innovation has increased, with no firm able to master all the knowledge domains involved. Hence, there is a division of labour among firms with different specialisations, so that flagship firms work with other actors in distinct domains such as high-precision engineering, chip-design, compression of media data, optics and software for user-interfaces, several of which are new entrants.

These actors tend to concentrate in localities hosting a range of technology domains, e.g. technology 'valleys' that integrate both hardware and software. Knowledge-intensive activities increasingly involve 'open innovation' in highly innovative ecosystems (and if necessary global innovation networks) which are taking an increasing share of overall sector value added, and tend to co-locate in proximity to major centers of final demand.

As innovation has become more complex, manufacturing complexity has decreased. New advanced digital and computer-aided manufacturing technologies are reducing the need for routine tasks and altering the organisation and content of work (Sturgeon, 2019). Global manufacturing service firms are transforming many hardware domains and replacing labour with automation processes. In some cases, these domains have moved closer to customers and are engaging in parts of the innovation process involving engineering tasks (Raj-Reichert, 2018).

Many of the processes which previously required human workers can be transferred digitally from buyers to suppliers and can be performed faster using robotised processes, for example to manufacture semiconductors. Features such as force sensing, vision, and proximity sensors as well as automation software allow robots to perform repetitive, delicate and sensitive tasks which require precise handling of fragile devices (Kingatua, 2019).

Arguably, these developments have increased the barriers to entry (and survival), in particular for low-cost locations which caused the earlier offshoring boom in this sector. Reshoring tendencies are being increased by the higher requirements related to the organisation of sophisticated production processes, customisation to meet consumer demand, and essential market knowledge (Raj-Reichert, 2018).

These developments help to explain the apparent synergy of GVC retraction and relative increased innovativeness in the new digital economy. These changes call for open innovation centered around platforms and standards, with more integration of competences in the innovation process. Many manufacturing activities, apart from the most routinised ones, have moved closer to the end-customer and are increasingly robotised, resulting in reshoring. There seems to have been a resurgence in national production and innovation systems in this sector. In addition, changing discourses around offshoring in highly globalised sectors, and increasing protectionism and trade wars, are contributing to these ongoing tendencies in GVCs.

5.3 Explaining the GVC deepening and innovation strengthening trajectory in software

This trajectory applies only to the software sector. *Cluster S1* shows that the strongest innovators are those characterised by GVC deepening, and include Ireland, Israel and USA as major international traders. In this cluster, Ireland is the most important player in the global software industry and has been described as a Celtic Tiger, based on its fast growth spurred by 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 Ireland's success 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 (Annan-Diab & Filippaios, 2017; Coe, 1997). Ireland can be considered an example of strong and increasing integration into GVCs accompanied by high domestic investments in human capital and innovation.

Which sectoral specificities might explain why deeper GVC participation and accumulation of innovation capability are being mutually reinforcing in the software sector? Table 2 distinguishes between sectoral characteristics related to innovation, and dimensions related to GVCs. In the former case, the distinctive *type* of innovation is process innovation, the typical *mode* is doing-using-interacting or DUI and the *main external sources* are users. In the latter case, the *governance pattern* is typically relational, GVCs are *short* with *few links,* and there is a low level of *fragmentation*.

The software sector covers a wide variety of digital processes and serves many different sectors and domains. Software sector economic activities are mostly customised services. Patented software innovations are in the areas mostly of packaged software (e.g. ERP – enterprise resource planning and CRM – customer relations management systems or different types of operational systems) or so-called 'system on chip' software which is embedded in a wide variety of electronic goods and makes them increasingly software intensive. These different areas require distinctly different types of knowledge and learning processes (Malerba, 2002) .

A large part of the creative process is focused on software system design, and the innovative process is centered on understanding the application setting and the different potential users. This makes externalisation (Nonaka, 1994) in the form of codifying application routines into system commands, a key process. This process relies on the definition of software requirements which is facilitated by immersion in the client domain, and close interaction with users to run trials and fix bugs. The innovative process relies on the capacity of enterprises to interact with users through learning by doing, by using and by interacting (Parrilli & Alcalde Heras, 2016). In this setting, user-driven innovation (von Hippel, 1986) and user-producer interaction (Lundvall, 1985) are the norm and sometimes occur in networks of users.

These processes have implications for how GVCs are organised. The issues related to codifying knowledge and the complexity of the user-producer interactions, mean that innovation in the software sector is characterised by intensive exchanges and frequent face-to-face contacts both forward in the chain with users and backward with suppliers. It is imperative to understand needs and specifications before the labour-intensive process of writing code begins. Also, although final solutions ('products') may be sold worldwide, the supply chain typically involves only a few actors.

It is worth recalling that the scope of our analysis is confined to the segment of the global software sector that is patent active and engages in global trade in intermediates. In this segment, intellectual property rights are important for generating returns to innovation, although a large part of innovation might not be patented.

The deepening of GVCs over the period of observation reflects the increased need of being present in the main markets in proximity to lead users. Over the years, software has become an increasingly important driver of the emerging flexible ICT techno-economic paradigm which relies on platforms. Dominant original equipment manufacturers are reliant on external specialised suppliers, and major businesses purchase packaged software and cloud-based 'software as a service' solutions. Process innovation involving strong interdependencies relies on lead-market users in value chains. In other words, there are strong synergies between GVC deepening and the increase of patented innovations.

5.4 Explaining the loss of relative innovation capacity

The association between the loss of relative IC and GVCs is complex and may take different patterns. In what follows, we provide some country examples to illustrate the multifaceted dynamics occurring in Trajectories *T3 – Deepening and Weakening* - and *T4 – Delinking and Weakening*.

First, a loss of IC implies decreased ability or inclination to compete in GVCs, and vice versa. The recent rise of protectionism, together with the growth of domestic markets with preferences for established (and cheap) rather than cutting edge (and expensive) technologies, may play a role.

Many countries following the *T3* trajectory are emerging economies known for their global supply platform activities in the electronics sector, but which are recently experiencing increased domestic demand for electronics. China is an important case. For example, 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 in order to extend their forward linkages and satisfy a growing base of low-cost Chinese consumers (Humphrey et al., 2018). In this market segment China is delinking from GVCs because it is producing more domestically and it is increasingly focusing on its home market.

Moreover, the reduction of relative IC indicates that China's electronics innovation system is experiencing some problems (Lewin et al., 2016). For example, despite its increased semiconductor activities, China remains dependent on imports of chips. The Chinese government has increased its investment in innovation, but Chinese chip firms are currently unable to keep pace with the rapid technological changes (Lee et al., 2016). Moreover, although starting in the 2000s patent numbers have exploded in absolute terms, most patents were filed within the former Chinese State Intellectual Property Office (SIPO) - now the China National Intellectual Property Administration (CNIPA) and only a small share was also filed at other offices (e.g. USPTO), mainly by a few large and export-oriented hardware firms (Eberhardt et al., 2017).[15]

Second, in the hardware industry there are some countries following the *T4* trajectory characterised by relative loss of IC and deepening of GVC activity. For example, Singapore (in *Cluster H2*) has the highest turnover for hardware but has lost relative IC. For many years, Singapore hosted numerous multinationals using the country as an assembly and semiconductor testing platform. It was also an electronics trading hub and home of various equipment manufacturers international procurement offices (Goh & Lau, 1998). Strengthening the local system of production and innovation was essential in the early stages of Singapore's GVC activity (Hobday, 1995). Later, integration was based more on trade and manufacturing of some increasingly commodified, and now obsolete specialised components such as hard disk

[15] Note that to avoid the analysis being skewed it is important to consider China's population size: the number of USPTO patents is small when normalized to the population size.

drives. Although Singapore is increasing its innovation capabilities relative to the other ASEAN countries[16] (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 *H1*. Singapore has deepened its GVC integration over time but in activities at the lower end of the GVC (Chang and Nguyen, 2020). It became known as a location for trade in components and light assembly which required relatively little IC; some innovators have specialised in (obsolete) commodified technologies and are leveraging economies of scale. All-in-all, there seems to be a threshold to trigger a positive interaction between IC and GVC integration in the era of digitisation. Self-sustained cumulativeness is not granted and requires active investment at the national and sectoral level.

Third, in the case of software, and considering countries in *T3 – Deepening and Weakening*, it would seem that the intensity of some GVC links has increased, but their dynamics has decreased allowing fewer global learning opportunities. This has led to a weaker innovation capacity in some countries compared to the leading ones. For example, India struggled in moving from delivering standard services to more cutting-edge innovation and increased R&D, whilst still participating in GVCs (Altenburg et al., 2008). Although there are some major software firms in India which provide innovative solutions to customers across the world, these are concentrated in a few leaders of a small number of clusters (Mittal et al., 2020). Also, again, most of these innovations do not result in patents (Lema et al., 2015).

All-in-all, with our analysis we only scratch the surface of a rather complex phenomenon involving both country and sector specificities. A more fine-grained analysis accounting for the large heterogeneity in countries' experiences would be helpful to understand the common factors underlying specific country trajectories.

6. Conclusions

The role played by GVCs in economic growth has been discussed from several different perspectives. Many authors claim that GVC integration and international specialisation in specific tasks offer remarkable potential for innovation in firms and countries, but point out that this potential is necessarily conditional on learning and IC building by local firms. This process is related also to the context which can foster or hinder innovation, and its systemic features.

In this paper, we have addressed some of these issues and investigated the interdependence between the possible trajectories involved in GVC participation and IC. We adopted a cross-country perspective and focused on two ICT industry subsectors: hardware and software,

[16] The Association of South East Asian Nations (ASEAN) is a regional grouping of 10 countries: Brunei, Cambodia, Indonesia, Laos, Malaysia, Myanmar, the Philippines, Singapore, Thailand and Vietnam.

investigating whether stronger IC is associated to a deeper insertion or a withdrawal from global value chains in a sample of 45 countries.

Our analysis shows remarkable country differences in the evolution of these subsectors. Four theoretical trajectories and their related clusters of countries are identified, finding evidence of strong cumulativeness in IC in both the hardware and software sectors: only the strongest clusters (*ex-ante*) increase (*ex-post*) their relative innovation capacity. We found also that increases in IC in the hardware sector are associated with a decreased GVC participation, while the reverse applies to software. In both subsectors, clusters of countries experiencing a reduction of their relative IC are associated sometimes to increased GVC integration and sometimes to decreased GVC integration.

When interpreting our findings, there are two main aspects which should be considered. First, the variations identified are related to sectoral specificities. In hardware, the combination of product innovation and fragmented modular value chains suggests that countries that initially were strong innovators have been able to withdraw from these GVCs and increase their relative IC. Thus, we do not observe an association between increasing GVC integration and stronger IC. Arguably, the codification of knowledge into specific innovation domains could promote firm innovation regardless of their GVC position. Firms need to rely more on domestic suppliers and local universities, that is on a proximate innovation system. In the case of software, innovation relies strongly on the interdependence among global actors, and process innovation is fostered by overseas users in short value chains. In software, relational chains and dense exchanges of the knowledge required to innovate seem to prevail, and increasing IC is associated to greater GVC participation.

Second, we identified some possible complementarities between the hardware and software sectors. Countries such as Finland and Israel, have been able to exploit these dynamics and are leaders in both subsectors. The recombination of hardware and software triggered by Industry 4.0 technologies might explain this success. Different national systems of innovation have different ability to foster and exploit these synergies. A finer-grained analysis is needed to understand the synergies (or lack of them) among different subsystems.

This study has some limitations. We proxy sectoral innovation capacity using patents, which we acknowledge capture only a part of technological competence. However, they allow detailed sector-level analysis, and are strongly correlated to other measures of knowledge creation, such as scientific publications. Overall, they still are a better measure than most of the alternatives. Also, a longer time series would have allowed analysis of the different phases of GVC integration; however, the focus on ICT sectors (software in particular) reduced this possibility.

We studied a complex multidimensional and dynamic phenomenon which certainly needs further research. For example, future work could use the forward and backward dimensions of GVCs and include in the analysis additional measures to proxy for sectoral systems of innovation. Future research could also introduce the dimensions of time and sequencing in the analysis and account more explicitly for country differences.

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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

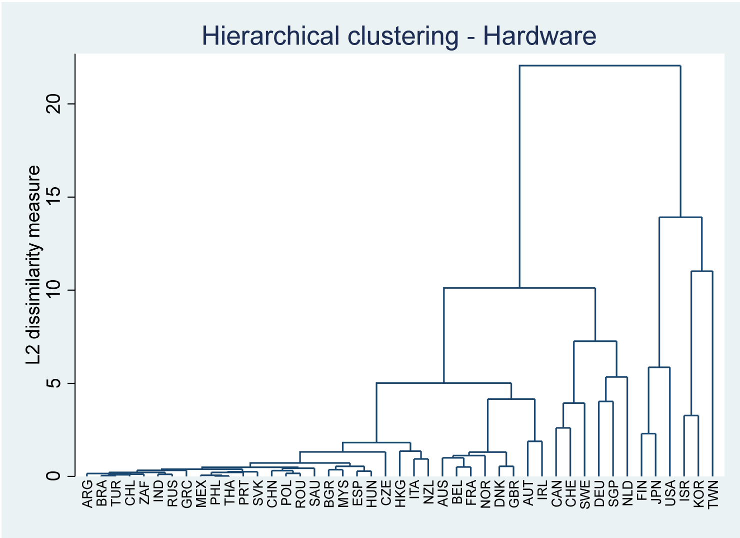
	Average	Median	Std. dev	Min	Max
			Hardware		
GVC	0.494	0.470	0.135	0.210	0.760
GVChange	-0.011	-0.031	0.069	-0.119	0.208
IC	0.000	-4.232	7.993	-5.644	24.137
ICchange	0.000	-0.792	3.386	-7.143	13.298
			Software		
GVC	0.252	0.257	0.086	0.105	0.575
GVChange	0.012	0.016	0.040	-0.078	0.137
IC	0.000	-0.111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

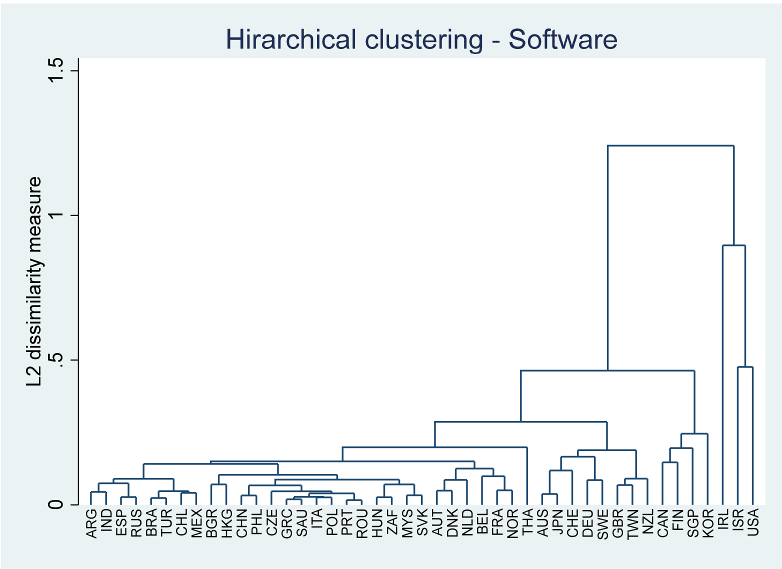
Tab A.3: Correlations: hardware and software

	Hardware				**Software**			
	GVC	GVChange	IC	ICchange	GVC	GVChange	IC	ICchange
GVC	1				1			
GVChange	-0.46*	1			0.22	1		
IC	0.02	-0.05	1		-0.19	0.16	1	
ICchange	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





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