Product Modularity and the Rise of Global Value Chains: Insights from the Electronics Industry

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Abstract

In the field of economics, a vast literature has attributed the rise of global value chains to globalization-related forces such as declining costs of transportation, improvements in communications technology, and institutional and policy reforms in developing countries. Through an in-depth review of the industry transformation in the electronics industry, however, we find that an additional relatively unexplored factor is the modularization of electronics products. We analyze the mechanisms through which product modularization may lead to the rise of global value chains and discuss the implications for future research.

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1. Introduction

In the past three decades, the electronics industry has gone through a fundamental transformation of its organization of production. Prior to the 1980s, the industry was dominated by large, vertically integrated firms such as IBM and DEC that produced most parts and components themselves and within their home country. Currently, the industry is dominated by lead firms that only specialize in a single slice of globally dispersed value chains. Similar trends have been documented in telecommunications [Li and Whalley, 2002], automobiles [Sturgeon and Florida, 2000], chemicals [Arora *et al*., 2001] and textiles [Gereffi et al., 2005].

In the field of economics, a vast literature attributes the rise of global value chains to globalization-related forces such as declining costs of transportation, improvements in communications technology, and institutional and policy reforms in developing countries. Yet these explanations may not capture the entire story. Indeed, industry specialists and business scholars have pointed out that the strategic decision by lead firms to modularize electronics products may also have been a critical driver of the industry transformation [Dedrick and Kraemer, 1998; Sturgeon and Lee, 2001; Sturgeon, 2002; Gereffi *et al.*, 2005].

This chapter has two goals. First, we will discuss product modularization and the mechanism through which it may have led to the rise of global value chains. Then we will consider the new insights this provides for our understanding of global value chains, as well as the potential implications for future research in this area.

We have organized our chapter as follows. In section 2, we conduct an in-depth review of electronics industry studies and business research to explain how product modularization could lead to the rise of global value chains in the electronics industry. In section 3, we demonstrate that the economics literature alone cannot fully explain these developments. In section 4, we draw on the business literature to explore some of the costs and benefits of modularity. We argue that the degree of modularity in at least some cases is an active decision variable for firms. Since both the degree of modularity and the organization of the firm are endogenous choice variables for the firm, we consider how underlying factors may have driven both modularity and the transformation of global electronics production. Section 5 concludes with our thoughts on fruitful areas for future research.

2. Transformation in Global Electronics Production

Today's electronics industry landscape bears little resemblance to that of three decades ago. Prior to the 1980s, the industry was dominated by large vertically integrated firms such as IBM, DEC, Fujitsu and Hitachi that produced most parts and components themselves (see Figure 1). Currently, industry leaders are no longer vertically integrated, but are rather firms that specialize in only a slice of electronics products' value chains. Apple and Dell, for example, specialize in the design and marketing of products while outsourcing most of their components production and assembly to external firms. Contract manufacturing firms such as Flextronics and Foxconn are the principal companies in the manufacturing and assembly segment. Microsoft is the dominant firm in the operating system segment. Intel is the market leader in the microprocessor sector.

[Figure 1 about here]

Baldwin and Clark [2000] have used stock market data to illustrate the speed and magnitude of this industry transformation. Figure 2 shows the market values in 1996 constant U.S. dollars of substantially all the public corporations in the computer industry from 1950 to 1996, broken out into sixteen subsectors by four-digit standard industrial classification (SIC) codes.[3] In the beginning of the sample, the market value of the electronics industry was highly concentrated in the SIC category "3570-Computer and Office Equiment". This reflects that at that time market leaders (and especially IBM) were vertically integrated, while firms specializing in electronics subcategories remained relatively rare. Since the 1980s, the market has changed. Now the market value of the electronics industry had spread out over various subcategories such as "7372-Prepackaged software", "3674-Semiconductors and related devices" and "3576-Computer communication equipment".

[Figure 2 about here]

[3] 3570-Computer and Office Equipment; 3571-Electronic Computers; 3572-Computer Storage Devices; 3575-Computer Terminals; 3576-Computer Communication Equipment; 3577-Computer Peripheral Devices, n.e.c.; 3670-Electronic Components and Accessories; 3672-Printed Circuit Boards; 3674-Semiconductors and Related Devices; 3678-Electronic Connectors; 7370-Computer Programming, Data Processing, and Other Services; 7371-Computer Programming Services; 7372-Prepackaged Software; 7373-Computer Integrated Systems Design; 7374-Computer Processing, Data Preparation and Processing; 7377-Computer Leasing.

Industry specialists and business scholars attribute the industry transformation to the modularization of electronics products [Dedrick and Kraemer, 1998; Sturgeon and Lee, 2001; Sturgeon, 2002; Gereffi *et al.*, 2005]. To understand this, it is useful to first define product modularity. Ulrich [1995] describes a product as a combination of components or "modules" that interact with one another according to the design rules of its product architecture. Depending on the number of interdependencies between modules, products can vary on a continuum from integral to modular [Schilling, 2000; Gawer and Cusumano, 2002]. If modules are highly interdependent, then a product is integral (Figure 3, top panel). In that case, any change made to a module needs to be coordinated with other modules to ensure that there is no significant reduction in the functionality of the final product. In contrast, if modules are independent from one another, then a product is modular (Figure 3, bottom panel). Changes can now be made to one module independently from other modules as long as the changes are compatible with the codified interfaces that govern the operability of the system.[4]

[Figure 3 about here]

In the past three decades, electronics products have rapidly evolved from an integral to a modular product architecture. Prior to the arrival of IBM's System/360 computer, leading electronics companies built computers with a fully integral architecture. Each company designed and manufactured its own operating system, processor, peripherals and application software. This implied a high cost of coordinating interoperability between components and required firms to produce almost all necessary components – semiconductors, hardware and operating systems – in-house and principally within one country [Dedrick and Kraemer, 1998; Chandler, 2001].

For the production of the System/360 in the 1960s, IBM for the first time adopted a modular product architecture. The developers of the System/360 conceived of a family of computers that would include machines of different sizes suitable for different applications, all of which would use the same codified instruction set and could share the same peripherals. Future IBM products would all adhere to this modular system. To achieve the compatibility of components, IBM set up a Processor Control Office, which established and enforced open and codified standards that

[4] PCs and cell phones are good examples of modular products. They are essentially a limited number of standard parts or modules (e.g., resistors, capacitors, and memory chips), which get mounted onto printed circuit boards in different combinations.

determined how the different modules of the machine would work together [Baldwin and Clark, 2000; Langlois, 2002]. This allowed the makers of components to concentrate their innovation efforts at a reduced coordination cost and therefore to improve their module of the system independently from others.

This adoption of a modular product architecture would permanently alter the structure of production in the electronics industry. As we will see in the next sections, it would first move the electronics industry *from vertical integration to horizontal concentration.* Second, it would lead to a transformation *from local to global value chains*.

2.1. From vertical integration to horizontal concentration

In the early 1980s, product modularization led IBM to give up its vertically integrated production structure. In its scramble to bring to market its personal computer (PC) as a cheaper alternative to the popular Apple II, the industry giant turned to external suppliers for key components. The production of floppy disks was outsourced to Tandon, power supply to Zenith and circuit boards to SCI Systems. Furthermore, the production of the operating system and the microprocessor were outsourced to Microsoft and Intel.

The PC was a dramatic success. As a result, the codified standards of interoperability, which IBM had set and made public to ensure a smooth collaboration with its external partners, rapidly became the *de facto* industry-wide standards, reducing the barriers to entry into the industry. Firms were now able to specialize in a single slice of the value chain without needing to coordinate extensively with other firms in the value chain. This enticed thousands of IBM clones and component producers to enter into the various niches of the computer business, reshaping the industrial landscape. Product modularity had led to the vertical disintegration of the electronics industry [Sanchez and Mahoney, 1996; Baldwin and Clark, 2000].

Beyond leading to vertical disintegration, product modularity also increased market concentration within value chain segments [Sturgeon, 2002]. With the standards of compatibility and interoperability fixed across the industry, firms could now produce generic modules for multiple clients and purposes. Microsoft could sell their operating system to multiple PC producers. Printers were compatible with most computer brands. Common semiconductors could be used inside cell phones, television sets, personal digital assistants and computers. This allowed component producers to take advantage of economies of scale and scope in engineering and manufacturing to grab market share in their industry segment, leading to heightened market concentration within value chain slices.

Over time, vertical disintegration was pushed even further, with companies starting to specialize in only parts of modules. In the production of many electronics products, for example, design became separated from manufacturing [Sturgeon, 2002; Shih et al., 2009]. As a result, brand-name electronics firms such as Apple, Hewlett-Packard, IBM and Nokia all sold off their production facilities to a new type of electronics company, the contract manufacturer. These firms do not design or sell any brand-name products themselves. Rather, they specialize in using the same generic production routines to produce a wide range of electronics products, ranging from computers, communications equipment, consumer electronics, electronic instruments, industrial electrical, medical, and military/aerospace [Sturgeon and Lee, 2001; Sturgeon, 2002].[5]

2.2. From Local to Global Value Chains[6]

Product modularization also led to a transformation from local to global value chains. As a part of the product modularization process, firms have widely relied on information technology (IT) such as business-to-business (B2B) technology to transfer codified information between product modules [Sturgeon, 2002]. This, in turn, has made it easier to perform tasks in geographically dispersed locations [Baldwin and Clark, 2008]. In line with the theory of comparative advantage, firms could keep their capital-intensive activities in developed countries, while offshoring labor-intensive activities to developing countries [Dedrick and Kraemer, 1998].

East Asia (Newly Industrialized Economies (NIEs), ASEAN-4 and China)[7] was seen as an especially favorable place to move labor-intensive electronics production blocks. First, the region had already demonstrated success in consumer electronics production as early as the 1960s [Lowe and Kenney, 1999]. The region was known to have not only an abundant supply of low-wage labor but also a large and growing pool of high-skilled engineers. Second, East Asia had a relatively stable political and macroeconomic environment, conducive to long-term

[5] Shih *et al.* [2009] describe a similar separation between design and manufacturing in the semiconductor industry.
[6] See Gangnes and Van Assche [2009; forthcoming] for an in-depth discussion of East Asia's growing role in electronics value chains. See also Bonham *et al.* [2007] on the implications for trade patterns.
[7] The Newly Industrialized Economies (NIEs) consist of Hong Kong, Singapore, South Korea and Taiwan; the Asian-4 are Indonesia, Malaysia, Philippines and Thailand.

investment projects and business relations [Yusuf, 2001]. Third, East Asian countries changed their policy stance from import substitution to export promotion, providing an improved environment for international business linkages.

As a result, East Asia rapidly turned into a global manufacturing base in electronics, producing electronic products primarily destined for developed countries [Dedrick and Kraemer, 1998; Lowe and Kenney, 1999; Borrus *et al.*, 2000]. In figure 4, we use electronics production data from Reed Electronics Research to illustrate the speed and process of East Asia's rise [Reed Electronics Research, 2007]. The expansion occurred in three waves. The first wave saw the NIEs rapidly expand their electronics production. These countries initially specialized in labor-intensive activities in consumer electronics products such as audio and video assembly, moving later into electronic data processing and other more sophisticated areas. Growth in the ASEAN-4 countries took off in the early 1990s, when rising labor costs in the NIEs made ASEAN countries an attractive alternative. The third and perhaps most dramatic wave has been the surge of electronics production in China, which surpassed that of the NIEs in 2003.

[Figure 4 about here]

This rapid expansion has turned East Asia into the uncontested production hub for electronics products. As it is shown in Table 1, East Asia's share of world electronics production has gone from a mere 4.5 percent in 1985 to 41.2 percent in 2006, currently more than double the shares for Japan, the European Union and the United States.

[Table 1 about here]

2.3. Smile of value creation

As a result of the industry transformation *from vertical integration to horizontal concentration* and from *local to global value chains*, scholars characterize modern value chains in electronics as a smiling curve [Shih, 1996; Everatt et al., 1999] or as the smile of value creation [Mudambi, 2007, 2008]. Figure 5 illustrates how for many electronics products, developed-country firms have held on to high-value activities at the upstream (design) and downstream (marketing) ends of the value chain and have kept them in advanced economies. Conversely, they have outsourced low-value activities in middle of the value chain (manufacturing) to external companies and these activities have moved to emerging economies. This has prompted concerns within developing countries about the limits to gains from electronics trade and the need for industrial upgrading to higher value added activities [Gangnes and Van Assche, 2009]. But it has also incited the fear within developed countries that firms are outsourcing too much of their manufacturing capabilities and that this is undermining developed countries' technological edge [Pisano and Shih, 2009].

[Figure 5 about here]

3. Perspectives From the Economics literature

Despite a vast economics literature that analyzes the rise of global value chains, few studies have considered the role of product modularization. In this section, we briefly review the existing economics literature and discuss how it fails to explain certain trends in the electronics industry's industrial transformation.

Economists have developed three streams of theoretical models to explain the changing international organization of production witnessed in electronics and other global industries. A first stream has focused on the drivers of the transformation *from local to global value chains*, while ignoring changes in the boundaries of the firms. The pioneering studies by Jones and Kierzkowski [1990, 2000] began with a Hecksher-Ohlin framework but divided the value chain for a good into two separate production blocks. If the production blocks are separable and have different factor-intensities, they argue, firms in labor-scarce developed countries have an incentive to relocate labor-intensive production blocks to labor-abundant developing countries. Firms will only do so, however, if the benefits of fragmenting their production process exceed the extra trade, communication and governance costs of coordinating activities across borders.[8] This framework thus allowed Jones and Kierzkowski [1990, 2000] and its successors to identify three globalization-related drivers for the international fragmentation of production: reductions in transportation costs, declines in communication costs, and pro-trade policy reforms.

To explain the concomitant rise in offshore outsourcing, a second stream of literature has introduced elements of the theory of the firm into general-equilibrium trade models (see Spencer,

[8] Other contributions include Venables [1999] and Jones and Findlay [2000, 2001].

2005, and Helpman, 2006, for a review of this literature). In this type of study, a firm concurrently makes a two-dimensional choice: (i) whether to produce its components in-house or to outsource its production to another firm, and (ii) whether to make its components domestically or offshore. The studies generally find that the same drivers of international production fragmentation also make outsourcing more attractive: reductions in trade costs [Antràs, 2003; Antràs and Helpman, 2004]; improvements in communication technology [Grossman and Helpman, 2002]; and trade liberalization [McLaren, 2000; Ornelas and Turner, 2008]. Furthermore, they find that improvements in the institutional environment of developing countries can further induce offshore outsourcing [Antràs and Helpman, 2008].

The two streams of literature have provided important insights into the drivers of international production fragmentation and outsourcing. Yet, when compared to the industrial transformation that we have documented in the electronics industry, they face two shortcomings. First, they have little to say about the concomitant change in product technology. Specifically, they do not consider that the modularization of products may have made it easier for firms to separate production blocks and move them in different locations, therefore inducing the documented offshoring and outsourcing trends. Second, they cannot explain the increase in market concentration seen in many slices of the value chain. Indeed, a standard assumption in the studies described above is that inputs are completely specific so that component suppliers can only sell their output to a single final good firm. This assumption rules out that market concentration may differ across value chain slices.

A third stream of papers has recently made some inroads in explaining the role of technological change by focusing on the growing role of IT in international business, which has been an important part of the modularization process. Leamer and Storper [2001] distinguish between tasks that require codifiable information and those that require tacit information. Tacit information, they argue, cannot be conveyed in symbols, and therefore require face-to-face communication. Conversely, codifiable information can be expressed in a symbol system and can therefore be more easily transferred from a distance. Autor *et al.* [2003], Levy and Murnane [2004] and Blinder [2006] build on this insight to point out that tasks performed by a computer can be more easily performed remotely with relatively little risk of miscommunication and a modest cost of monitoring.[9] If then firms decide to adopt more IT for their international transactions (perhaps because of product modularization), this can induce the documented rise in offshoring [Blinder, 2006; Grossman and Rossi-Hansberg, 2008].

The two shortcomings mentioned above remain, however, in this stream of literature. The studies cannot explain the increased horizontal concentration in value chain segments. Furthermore, they treat the technological change as exogenous, thus failing to address the question of why firms (in some industries) decide to adopt modular product architectures. As we shall see in the next section, this is a complex question that requires a theory of product modularity.

4. Modularity as a Strategic Decision

A firm's decision regarding which product architecture to adopt is a complex strategic question that needs to consider multiple facets. Firms face various trade-offs when choosing between an integral and modular product architecture. On the one hand, they face a static trade-off that affects their cost structure in the short run. On the one hand, they face a dynamic trade-off that affects their innovation efforts. We consider these two trade-offs in turn.

Consider first the static trade-off. The key benefit of an integral product architecture is that it can lead to synergistic productivity gains related to components being specific to one another [Schilling, 2000]. Conversely, an important advantage of a modular product architecture is that it reduces input specificity by allowing the same generic components to be shared across multiple product families and/or firms. This leads to three benefits. First, component sharing can lower the price of components by allowing its producers to take advantage of economies of scale and scope [Baldwin and Clark, 2000]. Second, it increases flexibility by allowing firms to more easily substitute certain components of a technological system while reusing others [Garud and Kumaraswamy, 1995; Schilling, 2000]. Dell, for example, relies on its modular production structure to provide clients with customized laptop computers by altering the combination of components in the computer. Apple iPad customers can easily customize their devices by choosing which applications to download. Third, lower input specificity can reduce the hold-up friction in outsourcing relations [Van Assche and Schwartz, 2010]. Component suppliers are no

[9] The authors use slightly different terms. While Leamer and Stolper [2001] distinguish between codifiable versus tacit information, Autor *et al.* [2003] and Levy and Murnane [2004] talk about routine and nonroutine tasks. Blinder [2006] emphasizes the need for physical contact when delivering the output of a task.

longer destined to sell their product to one or few customers, therefore improving their outside option and reducing the hold-up problem that is inherent to a setting of asset specificity and incomplete contracts [Williamson, 1985; Grossman and Hart, 1986; Hart and Moore, 1990].

Firms also face a dynamic trade-off when choosing their product architecture. According to Baldwin and Clark [1997, 2000], one of the main benefits of modularizing a product architecture is that it can reduce the complexity and increase the predictability of innovation. Product modularity reduces the interdependencies between modules, therefore allowing researchers and engineers to independently concentrate their capabilities on innovating a single module. This, however, does not come without risks. Modular systems may in the long term lead to fewer innovative breakthroughs than integral systems [Fleming and Sorenson, 2001]. Furthermore, outsourcing modules to external suppliers may make firms lose their ability to control key intellectual property [Zirpoli and Becker, 2011] and may eventually lead to the creation of future competitors [Arrunada and Vazquez, 2006]. If many firms outsource too much, it may even undermine a country's technological edge [Pisano and Shih, 2009].

A theoretical framework that models one or more of these trade-offs will generate new insights into the drivers of product modularization. Furthermore, introducing such as framework into a general equilibrium model of international production may also allow us to gain new perspectives on the changing organization of international production, and the implications for innovations and growth.

Two recent papers demonstrate the potential of this research stream. Van Assche (2008) developed a theoretical model to analyze under which circumstances the modularization of products can explain the concurrent trend *from vertical integration to horizontal concentration* and *from local to global value chains.* For this purpose, he built a two-country general equilibrium model in which firms not only choose their ownership structure (integration vs. outsourcing) and location of input production (home vs. offshore), but also their product architecture (integral vs. modular). In doing so, they need to consider the static trade-off: while the integral architecture increases productivity, the modular architecture reduces input specificity. Using this setup, he demonstrates that technological change that makes it easier to use generic components (such as an IT revolution) not only leads to the adoption of modular product architectures, but also induces the two concurrent trends *from vertical integration to* *horizontal concentration* and *from local to global value chains*. Specifically, it then becomes optimal for vertically integrated firms to outsource component production to foreign input suppliers that uses the same generic production process for multiple final good firms.

In a similar spirit, Thoenig and Verdier [2010] built a general equilibrium model in which innovating firms can choose whether or not to codify the transfer of information with its suppliers (which is a necessary part of the modularization process). They, however, focus on the dynamic trade-off of product modularization. On the one hand, they argue, codification of information enables verifiability by a third party and therefore allows the design of more efficient contracts. On the other hand, codification leads to increased possibilities of informational spillover to third parties who might exploit these spillovers to out-compete the initial contracting group. They find that in industries with high technological competition, companies should codify their information transfer less, therefore formally demonstrating that product modularization may make firms lose their ability to control key intellectual property [Zirpoli and Becker, 2011] and may lead to the creation of future competitors [Arrunada and Vazquez, 2006].

Further research is needed in this area. A number of issues remain unadressed. One technical issue that has not yet been analyzed is how product modularization affects hold-up problems in outsourcing relations. Introducing this feature into a model à la Antràs and Helpman [2004] may enrich our understanding of what type of firms are more likely to choose modular product architectures, and how this affects their organizational form.

Another issue that remains poorly understood is what the positive and normative implications are for competition policy. If product modularization induces an industry to move from vertical integration to horizontal concentration, this may (or may not) increase the bargaining power of the component producer and provide it with monopoly power, thus affecting the market structure. This may require us to rethink competition policy in a modular world.

Tied up with this is also the question how this affects innovation and the global distribution of benefits from production and trade. For a firm, what is the optimal degree of product modularization? From a development perspective, how does product modularization affect developing country firms' ability to upgrade and catch-up technologically?

5. Concluding Remarks

We have in this chapter demonstrated that the rise of global value chains in the electronics industry is not solely due to globalization-related drivers such as reductions in trade costs and communication costs, but also stems from a fundamental change in the technological architecture used to produce goods. Product modularization has enabled firms to slice up their value chains and to outsource segments to external firms that can be located anywhere around the world. This, in turn, has led to an increase in market concentration within value chain segments.

Further theoretical research is needed to understand the role of product modularity in the organization of international production. We have argued that the degree of modularity is not completely exogenous, but is to a certain extent a strategic choice variable for the firm. This then begs the question why firms have decided *en masse* to modularize their product architectures, and whether this has been an optimal decision for a firm and for society. We have argued that a better understanding of this will lead to important new insights into innovation and the global distribution of benefits from production and trade.

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Figure 1: Transformation of the electronics industry

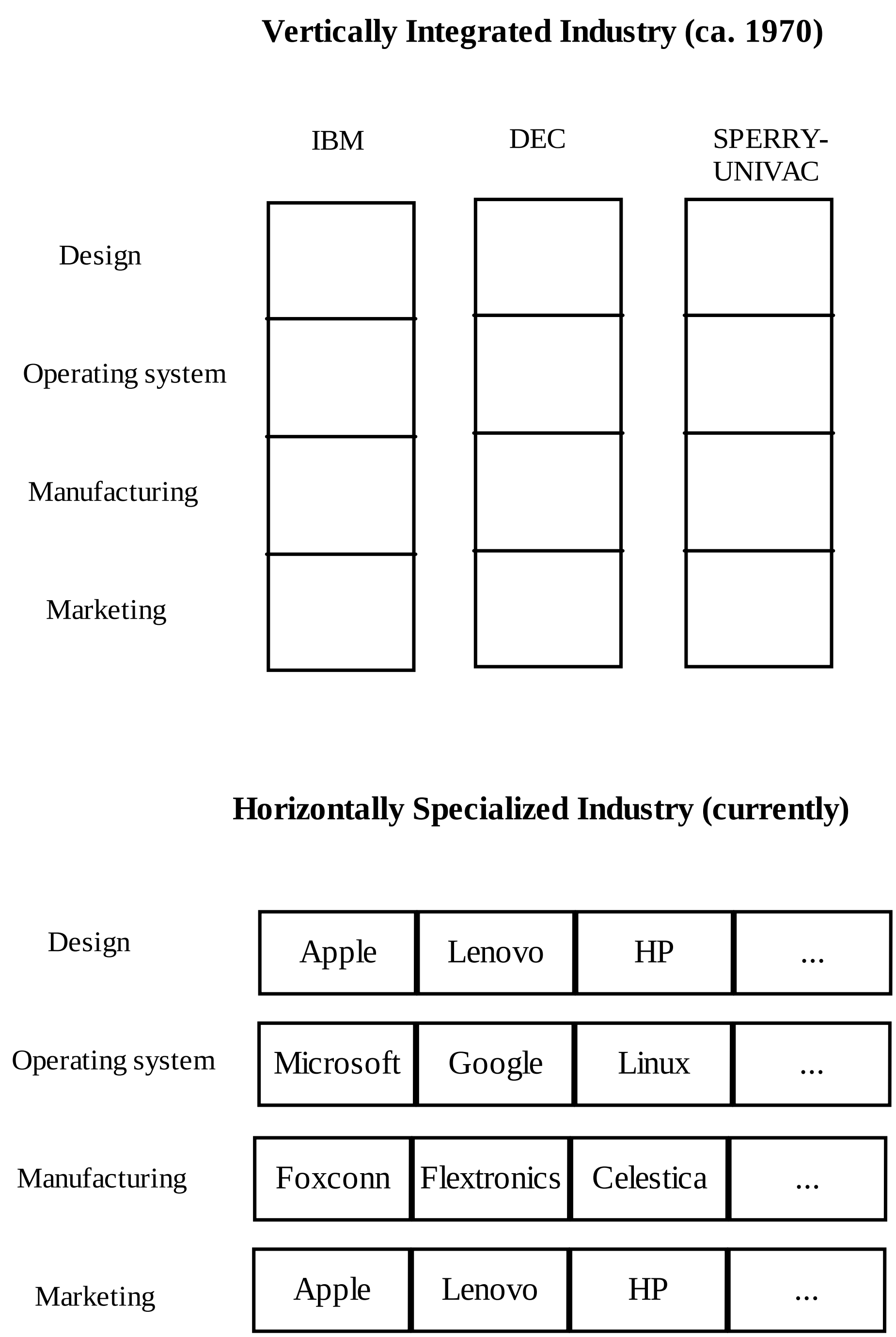
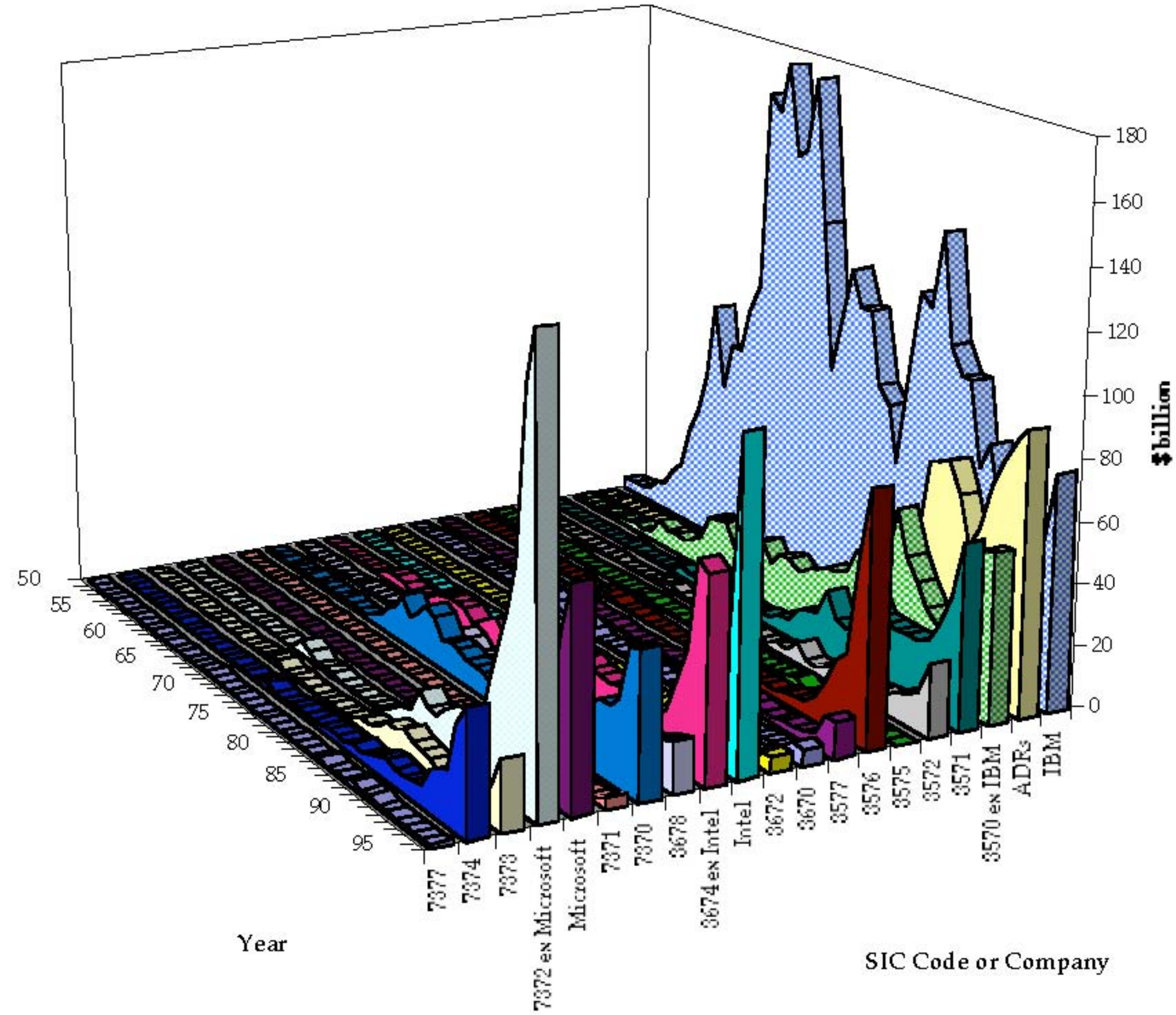


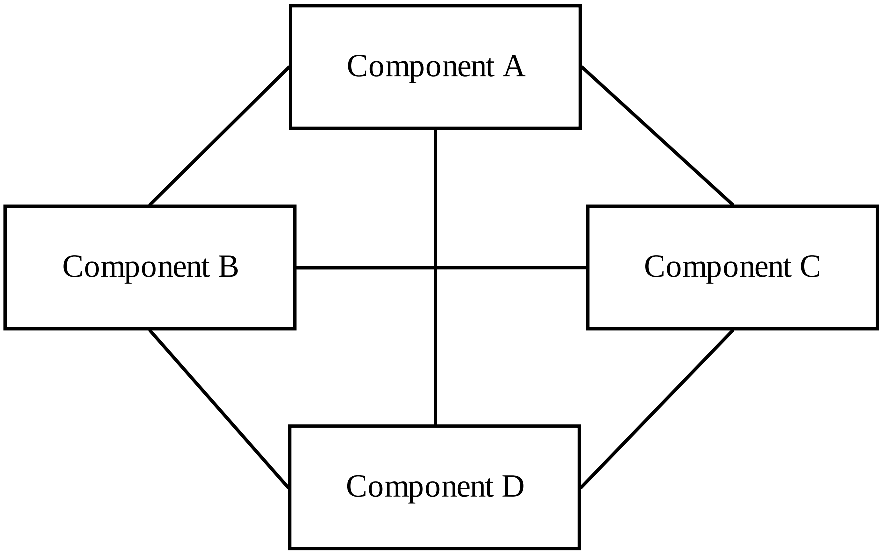
Figure 2 : Market Value of the Computer Industry by Sector in constant 1996 U.S. Dollars.



Source : Baldwin and Clark [2002].

Figure 3 : Modular versus integrated product

Integrated Product



Modular Product

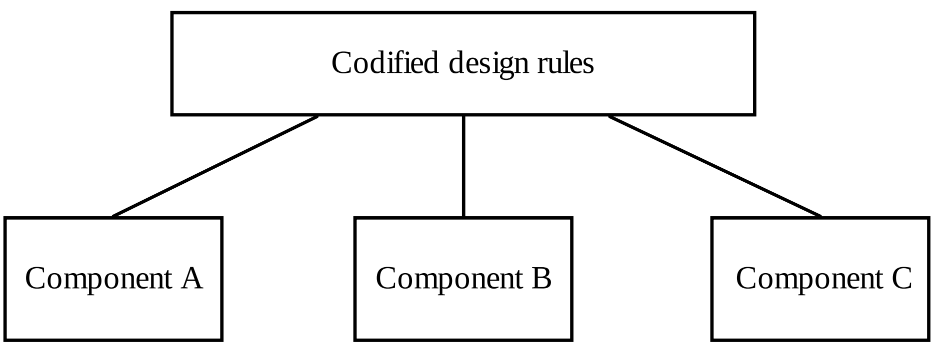
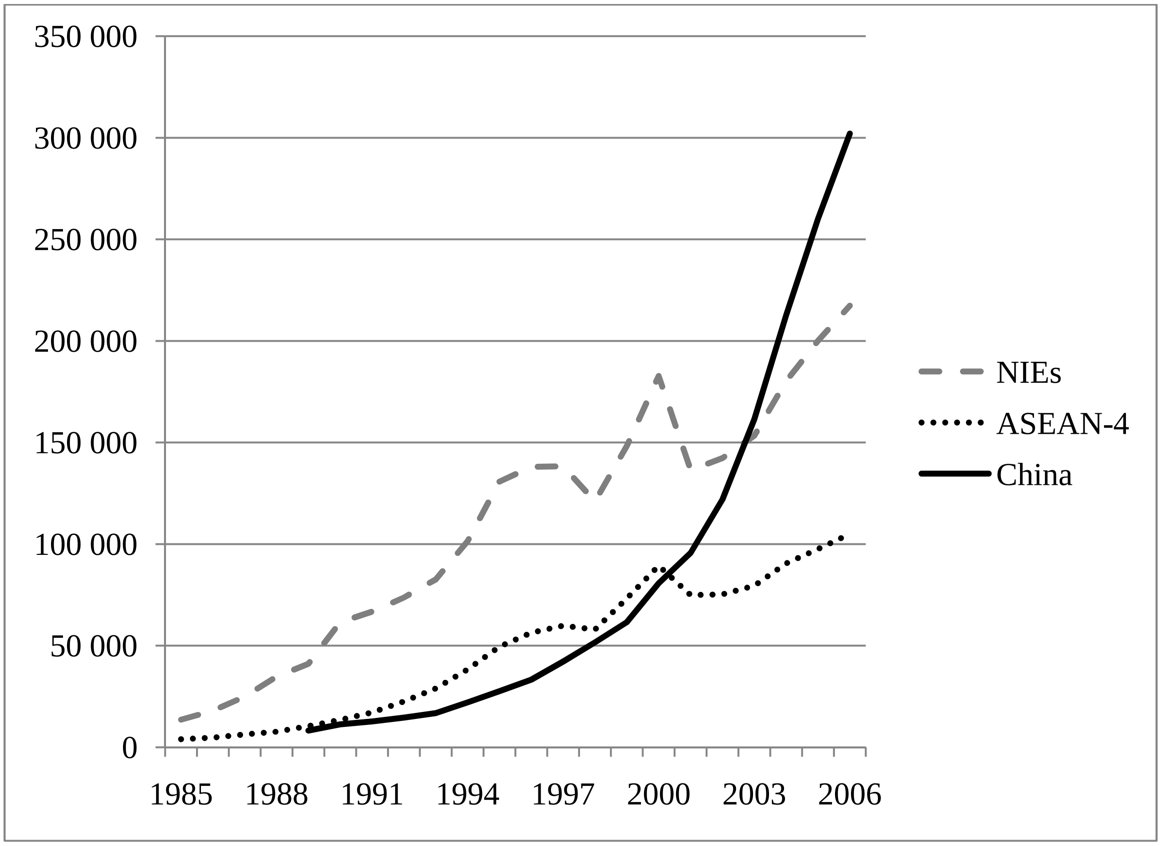
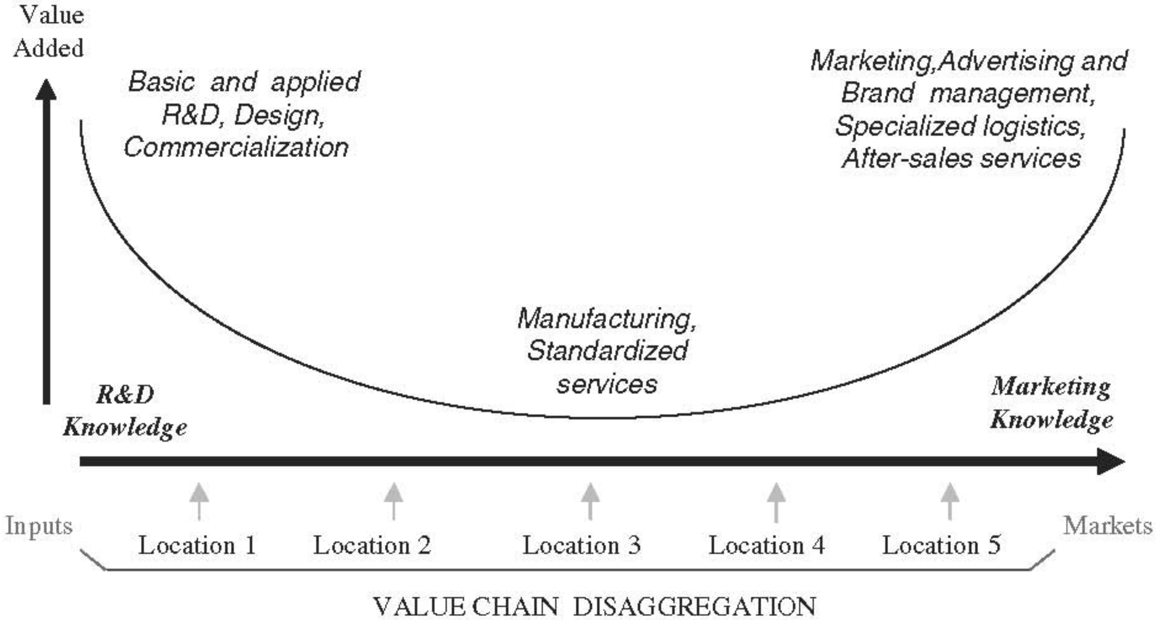


Figure 4: East Asian electronics production (US$ millions)



Source: Authors' calculations, using data from Reed Electronics Research.

Figure 5: The Smile of Value Creation



Source: Mudambi [2008].

Table 1: Growth of Electronics Production, 1985-2006

	Electronics Production Value (US$ Millions)		CAGR (%)	Share of world electronics production (%)	
Country	1985	2006	1985-2006	1985	2006
East Asia	17,323	624,433	18.6	4.5	41.2
NIEs	*13,552*	*217,402*	*14.1*	*3.5*	*14.4*
South Korea	5,881	117,426	15.3	1.5	7.8
Singapore	4,032	51,760	1.2	1.1	0.3
Taiwan	—	44,460	—	—	0.3
Hong Kong	3,639	3,756	0.2	1.0	0.2
ASEAN-4	*3,771*	*104,988*	*17.2*	*1.0*	*6.9*
Malaysia	1,829	52,711	17.4	20.5	3.5
Thailand	435	24,875	21.2	0.1	1.6
Philippines	831	15,167	14.8	0.2	1.0
Indonesia	676	12,235	14.8	0.2	0.8
China	—	*302,043*	—	—	*19.9*
United States	175,014	293,896	2.5	45.7	19.4
EU-15 (Excl.)	64,715	232,528	6.3	16.9	15.4
Japan	87,038	196,573	4.0	22.7	13.0
Mexico	—	39,931	—	—	2.6
Total Market	383023	1,514,816	6.8	100.0	100.0

Source: Reed Electronics Research