Modular Production Networks in Electronics:

The Nexus between Management and Economics Research

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Abstract

In the last two decades, the electronics industry has evolved from a vertically integrated in-dustry to a vertically segmented one. This transformation has often been attributed to the modularization of electronic products. In this paper, we argue that the degree of modularity is an active choice variable for a firm. As a result, it is necessary to focus on the underlying fac-tors that drive both modularity and the organization of production. This provides insights into the transformation taking place in global electronics production, with vertical fragmentation, horizontal consolidation, and the growth of Asian electronics production. (JEL L14, L23, L63)

Keywords: Modularity, electronics, outsourcing, contract manufacturing, East Asia.

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1 Introduction

In the last two 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 (e.g., IBM, DEC, Fujitsu and Hitachi) that produced most parts and components within their country and firm boundaries (see Figure 1). Since the arrival of the personal computer in the early 1980s, however, the industry has increasingly become vertically segmented. The most important electronics companies are no longer national firms that design, market and assemble final products themselves, but rather global firms that operate within one or a few horizontal slices of the industry's value chain. Dell and Gateway, for example, focus on the design and marketing while outsourcing most of their components production and assembly. Contract manufacturing firms such as Solectron and Flextronics 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.

A number of industry studies have attributed the transformation in the structure of global electronics production to the modularization of electronics products. Dedrick and Kraemer (1998) attribute the segmentation of the personal computer industry to new technologies that created open architectures and standardized components. Sturgeon (2002) and Sturgeon and Lee (2001) identify modularity with the co-evolution of vertical outsourcing and horizontal consolidation in electronics manufacturing and the rise of the contract manufacturing industry.

This co-evolution has been accompanied by a rapid increase in the extent of international production. Electronics firms headquartered in developed countries have moved the production and assembly of labor-intensive electronics components to developing countries, primarily in East Asia, to take advantage of low wages. This has gradually turned East Asia into a global electronics manufacturing platform, spurring employment and economic growth. East Asia's share of world electronics production rose from 6 percent in 1985 to 26 percent in 2000.

Existing economic models of the international production provide a framework for analyzing firms' decisions on the location of production and on the boundaries of the firm. However, little work has been done on explaining the co-evolution of vertical outsourcing and horizontal industry consolidation that has been documented in the electronics industry. In addition, few studies have

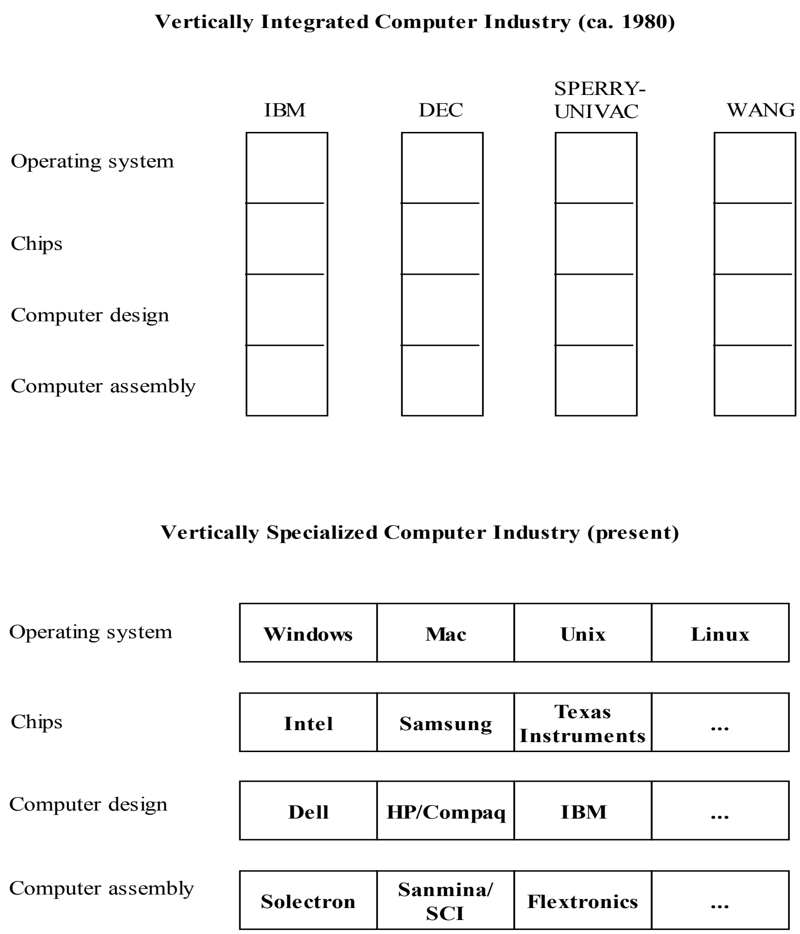

Figure 1: Transformation of the Organization of Electronics Production

looked at the role of modularity therein. Our interest in this paper is to review the management and economics literatures with an eye toward combining elements of both into a rich model of this phenomenon.

The paper is organized as follows. In section 2, we document the emergence of modularity and the transformation of electronics production that has accompanied it. In section 3, we rely on the management literature to discuss some of the costs and benefits of modularity. We furthermore argue that the degree of modularity in at least some cases is an active choice variable for firms. Since both the degree of modularity and the organization of the firm are endogenous choice variables for the firm, in section 4 we focus on some of the underlying factors that might have driven both modularity and the transformation of global electronics production. Finally, in section 5 we review the relevant economics literature on the boundaries of the firm in international production and identify several key issues that need to be addressed in order fully elucidate the role of modularity in such a framework.

2 Modularity and the Evolution of the Electronics Sector

Prior to the arrival of IBM's first modular computer, the System/360, leading computer companies generally built computers with an integral and fully closed proprietary architecture. Each company designed and manufactured their own operating system, processor, peripherals and application software. This implied a high cost of coordinating interoperability between components and induced 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). Every time a manufacturer introduced a new computer system to take advantage of improved technology, it had to develop software and components specifically for that system while continuing to maintain those for the previous systems.

The 1960s arrival of the System/360 with its modular product architecture permanently altered the structure of production. The developers of the System conceived of a family of computers that would include machines of different size suitable for different applications, all of which would use the same instruction set and could share peripherals. To achieve this compatibility, they set up a Processor Control Office, which established and enforced open and codified standards that 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 capabilities at a reduced coordination cost and thus to improve their piece of the system independently from others.

A new level of modularity emerged in the early 1980s, when IBM turned to outside suppliers for key components of its new personal computer. In its race to get into the market pioneered by Apple Computer, IBM decided that it needed to outsource many components including floppy disks (Tandon), power supplier (Zenith), circuit boards (SCI Systems) and the two critical components: the operating system (Microsoft) and the microprocessor (Intel).[1]

Once the *de facto* standards of interoperability and compatibility were set, barriers to entry into the industry were substantially lowered and thousands of IBM clones and component producers entered into the various niches of the computer business. The resulting competition drove down prices in almost all areas (Langlois and Robertson 1995). The change in industry structure also altered the factor intensities of production stages over time. As a consequence of the falling component prices, labor costs became a bigger share of PC production costs (Curry and Kenney 1999). To survive in the new highly competitive environment, electronics producers were forced increasingly to seeking lower production costs by outsourcing and by moving labor-intensive production blocks to developing regions (Dedrick and Kraemer 1998). This international fragmentation of production has led to an increase in trade in components relative to final goods (Bonham, Gangnes, and Van Assche 2004).

An indication of the extent of this transformation can be seen in the changing concentration of electronics production (Baldwin and Clark 2000). 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.[2]

[1]The move to greater modularity is not unique to the electronics industry. Automotive manufacturers are also reducing the number of platforms to achieve economies of scale in design and manufacturing, to increase the range of end products using a smaller number of basic designs and interchangeable modules. (Yusuf 2003 citing a PriceWaterhouseCoopers report.) Sturgeon and Lester (2002) say 75% of a vehicles value added is in only 15 preassembled modules.

[2]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.

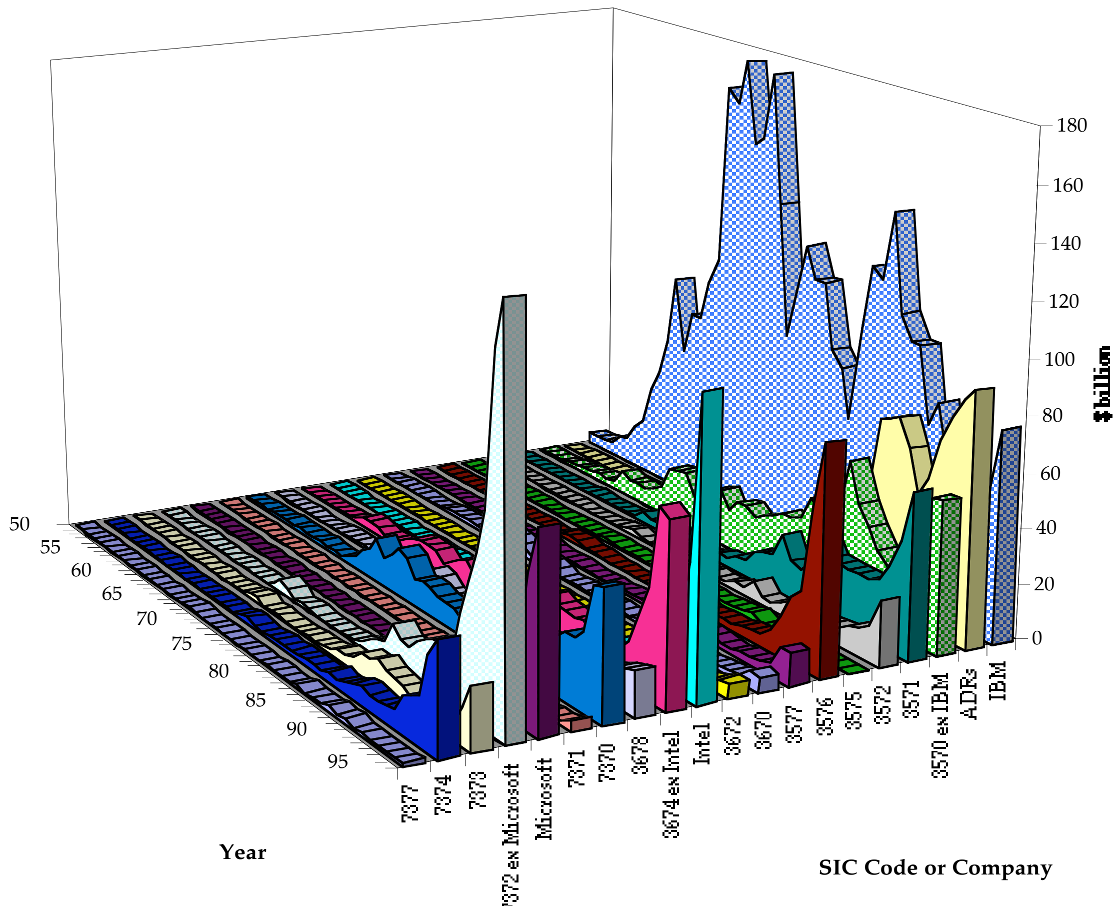

Figure 2: Market Value of the Computer Industry by Sector in constant 1996 U.S. Dollars. Taken from Baldwin and Clark (2002).

The figure shows that there was a period in which the computer industry was highly concentrated, with IBM playing the role of the dominant firm. But we can also see that in the 1980s, the computer industry got away from IBM.

While industry control evolved away from IBM and other industry leaders, market power was not eliminated. Instead, it was largely shifted away from vertically integrated companies to firms that were able to control key segments of the electronics market. Because they were highly specialized, the new component giants could innovate at a furious pace and because they owned defacto standards, they were able to develop a large installed customer base they allowed them to build high profit margins. These "open-but-owned" systems became the hallmark of the PC and later other technology markets, such as the networking industry and telecommunications (Borrus and Zysman 1998).

In this system, firms located anywhere in the value chain can potentially control the evolution of standards and define the terms of competition in their own segment but also in the final good market. Market power has shifted away from the assemblers to key component producers and to pure product development companies (Cisco and 3COM). The link between market power and ownership of the assets of production is no longer key, but rather the use of property rights and licensing strategies is the main basis for competitive advantage.

2.1 The Contract Manufacturing Industry

A similar trend of co-evolution between vertical outsourcing and horizontal consolidation can be found more recently in the rise of the contract manufacturing industry. Over the past decade, the boundaries of electronics firms have been changing, with multinational firms focusing on their core competencies and selling off large parts of their manufacturing capacity, much of which has been consolidated by a new class of large contract manufacturing firms that provide manufacturing—and in some cases design services—for multinationals (Sturgeon 2002; Sturgeon and Lee 2001).[3]

[3] To our knowledge, there have been no empirical studies that have systematically documented the rise and extent of contract manufacturing outsourcing. Nonetheless, semi-structured qualitative interviews conducted by researchers at MIT's Industrial Performance Center indicate that this reorganization has primarily occurred in complex assembly sectors such as electronics and motor vehicles. Sturgeon and Florida (2000) document the rise in component outsourcing in the automobile sector. Sturgeon and Lee (2001) finds that leading electronics firms have systematically sold off their circuit board and product-level assembly to contract manufacturing firms. Macher, Mowery, and Simcoe () focus on the emergence of "fabless" semiconductor firms that rely on contract manufacturing "foundries" for the production of their designs.

Table 1: Revenue Growth at the Top Five Contract Manufactures (Millions of U.S. Dollars)

Company	1995 Revenue	Fiscal 2003 Revenue	Compound Annual Growth
Flextronics	389	14,500	57%
Solectron	1,679	11,014	27%
Sanmina/SCI	3,514	10,361	15%
Jabil	686	4,729	27%
Celestica	600	6,735	35%
Total	6,868	47,339	27%

Source: 1995 revenues from Yusuf (2003). 2003-2004 figures from annual reports for fiscal years ending: Flextronics, March 31, 2004; Solectron, August 31, 2003; Sanmina/SCI, September 27, 2003; Jabil, August 31, 2003; Celestica, December 31, 2003. Flextronics the data is for Fiscal 2004.

During the 1990s, North American electronics firms (Apple Computer, Hewlett-Packard, IBM, Lucent, Maxtor, Nortel, and 3COM) sold off many of their domestic and offshore production facilities to the five largest contract manufacturers. And newer companies like Cisco Systems, Sun Microsystems, etc., outsourced most of their production from the start. European companies like Alcatel, Mokia, Ericson followed by late 1990s, followed by Japanese firms including NEC and Sony (Yusuf 2003; Ernst 2002).

This has given rise to a spectacular growth of the contract manufacturing industry. Technology Forecasters estimate that the contract manufacturing industry grew more than 20 percent a year between 1993 and 2001, three times the growth rate of the electronics industry. After a short spell in negative territory during the dot com bust, the industry is forecasted to return to +15 percent territory in the next few years (Barnhart 2004). The electronics contract manufacturing industry was a $10 billion industry just a decade ago. Today it is greater than ten times the size and market analysts project a $250 to $270 billion industry by 2007 (PricewaterhouseCoopers 2004). More than 15 percent of the more than 700 billion dollar market is now handled by contract manufacturers.

The industry's rapid growth went hand in hand with a consolidation of the market shares by the largest contract manufacturers (Solectron, Flextronics, SCI/Sanmina, Celestica and Jabil Circuits). (All but Flextronics are North American based.) Between 1994-1999, Solectron acquired 13 plants, Celestica 12 plants, Flextronics 10 plants, Sanmina/SCI 14 plants (Nationsbanc Montgomery Securities as cited by Shankland 1999). Presently, Flextronics owns 62 plants worldwide, Solectron owns 51, and the recently merged Sanmina/SCI has 100 factories around the world (Electronic Business 2004). In 2001, the top five contract manufacturing firms carried 59 percent of the total market share (Weber 2002). As shown in Table 1, as a group, the big five firms have grown at a compound annual rate of 27% since 1995.[4]

Sturgeon (2002) and Sturgeon and Lee (2001) have argued that the trends of vertical outsourcing and horizontal integration in international production are related. Contract manufacturer can take advantage of increasing returns by applying the same set of generic production routines for all final good firms. North American contract manufacturing firms use the same production processes across a wide range of products, ranging from computers, communications equipment, consumer electronics, electronic instruments, industrial electronics, medical, and military/aerospace (Yusuf 2003). Sturgeon (2002) argues that this trend demonstrates the emergence of a new American model of industrial organization: the *modular production network*.

Production sites for low-product-mix, high volume components are in Asia, Eastern Europe and Mexico primarily. High-product-mix, medium-to-high volume production sites are located in Canada, US, and Western Europe, and engineering centers are often located near major customers design centers. Final assembly, product configuration and service centers tend to be located near major transportation hubs in the developed countries (Yusuf 2003).

Perhaps surprisingly, the CM firms have been slow to move production into East Asia. Initially, most of the acquired plants were in North American or Western Europe, in part because of the need for close proximity to markets during the IT boom in the late 1990s. As the focus has shifted to cost considerations, and as China has emerged as a major production site, East Asia has begun to see more CM presence (Ernst 2002).

CM firms have begun to offer a wider range of services as their own experience has grown. On area of recent growth has been in outbound logistics where some CM firms are taking over customization and shipping from OEM firms (Hannon 2004). They are also considering moving into component design and supply, rather than simply manufacturing. Both are attempts to increase profit margins compared to basic manufacturing where profit margins can be as low as 2% (Sperling 2004).

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[4]Similar trends have been found in other global industries such as semiconductors (Langlois and Steinmueller 1999), telecommunications (Li and Whalley 2002), automobiles (Sturgeon and Florida 2000) and chemicals (Arora and Gambardella 2001).

2.2 The Rise of East Asia as a Global Electronics Production Base

Over the last two decades, East Asia (Asian NIEs, ASEAN4 and China) has gradually developed into a dominant global manufacturing base of the electronics industry, producing electronic products primarily destined for developed countries (Dedrick and Kraemer 1998; Lowe and Kenney 1999; Borrus and Haggard 2000). Production, expenditure and trade data clearly illustrate this trend. While East Asia's share of world electronics production was only 6 percent in 1985, it reached 26 percent in 2000 at a value of 348.6 billion U.S. dollars (slightly less than the United States). (See Table 2) This is production phenomenon; electronics expenditure has continued to be concentrated in the developed world, with the share of electronics expenditure to GDP remaining substantially higher in the U.S., Japan and the EU than in developing East Asia.

Initially, the shift of production toward East Asia took the form of foreign direct investment. U.S. and Japanese electronics firms established affiliates in the region for the sole purpose of export production. As the presence of foreign affiliates in the 1980s mushroomed in the wake of the electronics sector's increasingly competitive climate and stronger relations were built with non-affiliated host country firms, East Asia was gradually integrated into the worldwide networks of electronics production.

East Asia was initially seen as a favorable place to move labor-intensive electronics production blocks for a number of reasons. First, the East Asian countries were known to have not only an abundant supply of low-wage labor but also a large and growing pool of high-skilled engineers. In addition, East Asia had a relatively stable political and macroeconomic environment, conducive to long-term investment projects and business relations (Yusuf 2001). In addition, East Asia had already demonstrated volume manufacturing capability in the consumer electronics industry during the late 1960s (Lowe and Kenney 1999).

There were a number of favorable factors that further stimulated the fragmentation process into East Asia. First, in the early 1980s, East Asian countries generally changed their policy stance from import substitution to export promotion, thus providing an improved environment for international business linkages. Barriers to trade and investment were reduced, and domestic economic activities such as insurance, banking and transportation were deregulated. These reductions in barriers to trade are particularly conducive toward international production fragmentation because, in a fragmented world, a good needs to cross multiple occasions during the production process (Hummels,

Table 2: Developments in Electronics Production

	Electronics Production ($ Mill)		CAGR (%)	**Share of World Electronics Production** (%)		**Electronics Production /GDP** (%)	**Electronics Expenditure /GDP** (%)
Country	**1985**	**2000**	**1985–2000**	**1985**	**2000**	**2000**	**2000**
East Asia (EA)	30,262	348,591	14	6	26	13.7	5.7
NIEs	20,561	181,653	12	4	13	-	-
Hong Kong	3,680	8,083	4	1	1	5	8.8
Korea	6,501	76,059	14	1	6	16.5	6.6
Singapore	4,458	47,318	13	1	3	51	9.7
Taiwan	5,922	50,193	12	1	4	-	-
ASEAN4	4,120	85,903	17	1	6	-	-
Indonesia	580	10,791	17	0	1	7.1	2.2
Malaysia	1,851	44,539	18	0	3	49.7	6.8
Philippines	1,063	11,693	13	0	1	15.6	3.8
Thailand	626	18,880	20	0	1	15.4	3.6
China	5,581	81,035	15	1	6	9.4	5.4
United States	-	385,145	-	-	28	3.9	8.1
EU 15 (Excl.)	-	230,272	-	-	17	3	7.8
Japan	89,390	263,451	6	19	19	5.5	8.3
Total Market	481,708	1,366,369	6	100	100	-	-

Source: Electronics expenditure data: *World Development Indicators*; Electronics Production: *Yearbook of World Electronics Data*; GDP: *International Financial Indicators.*

Rapaport, and Yi 1998).

Two other technological advances helped to facilitate East Asia's emergence as a global production center for electronics. First, global transportation costs (particularly for air freight) have declined substantially in recent years, and surface ocean shipping has also increased in speed (Hummels 2000), reducing the cost of getting time-sensitive goods from Asia to the U.S. Secondly, the dramatic reduction in the cost of communication enhanced the coordination, management and monitoring of activities in different locations (Yusuf 2003), as discussed further below.

The gravitation of electronics production toward East Asia is also reflected in changing trade structure between the U.S., Japan and developing East Asian economies. Similar to electronics production, East Asia's electronics trade in the last two decades has taken off at a rate substantially higher than the rest of the world. Between 1980 and 2000 East Asia's electronics exports and imports grew by 21 and 20 percent a year, respectively, while global electronics exports and imports both grew at an annualized rate of 15 percent. As a result, East Asia's share of world electronics exports has risen from 14 percent in 1980 to 40 percent in 2000. East Asia as a whole is now the world's largest exporter of electronics, by far surpassing the United States and Japan (Table 2).[5]

The growth in East Asia's electronics trade has also seen a rise in intraregional trade, which reached 40 percent of electronics exports and almost 60 percent of electronics imports in 2000. This illustrates that the movement of production to East Asia has been accompanied by a growth in production networks within the region. The pattern of trade is also consistent with production relationships in which East Asian economies trade intermediate goods within the region and sell final goods outside of the region. (See, e.g., Bonham, Gangnes, and Van Assche 2004.)

3 Modularity as an Economic Decision

In the management literature, a product is often described as a combination of components or "modules" that interact with one another according to the design rules of its product architecture (Ulrich 1995). 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 3a). In this case, any change made

[5] East Asia's share of exports remains higher than that of the United States even if we exclude intraregional East Asian trade, since nearly two-thirds of East Asia's electronics exports are interregional (Table 3).

Table 3: Developments in Electronics Trade

	Electronics Exports ($ Mill)		**Export Share (%)**		**Electronics Imports ($ Mill)**		**Import Share (%)**		**Growth Rate 1980-2000**	
Country	**1980**	**2000**	**1980**	**2000**	**1980**	**2000**	**1980**	**2000**	**EX**	**IM**
EA (Incl.)*	11,513	413,818	14	40	8,953	288,600	11	28	21	20
EA (Excl.)*	9,110	249,966	11	24	6,549	124,749	8	12	19	17
NIEs	10,011	257,798	12	25	6,349	169,997	8	17	19	19
Hong Kong	2,493	50,302	3	5	2,047	49,479	2	5	17	18
Korea	1,797	61,743	2	6	1,131	32,845	1	3	20	19
Singapore	2,826	76,630	3	7	1,915	50,793	2	5	19	19
Taiwan	2,895	69,123	4	7	1,256	36,880	2	4	18	19
ASEAN4	1,438	109,694	2	11	2,031	66,594	2	6	26	20
Indonesia	102	7,631	0	1	308	1,015	0	0	25	6
Malaysia	1,252	55,759	2	5	1,006	38,077	1	4	22	21
Philippines	71	26,798	0	3	372	12,724	0	1	37	20
Thailand	13	19,506	0	2	345	14,778	0	1	47	22
China	64	46,326	0	5	573	52,009	1	5	41	27
United States	15,961	144,100	19	14	12,610	211,701	15	21	12	16
EU 15 (Excl.)*	11,367	98,661	14	10	15,965	143,213	19	14	12	12
Japan	18,057	110,857	22	11	2,043	59,533	2	6	10	19
Total Market	82,483	1,026,321	100	100	82,483	1,026,321	100	100	14	14

Source: Statistics Canada *World Trade Database*

*****"Incl." indicates that the aggregate includes intraregional trade; "Excl." indicates that intraregional trade is excluded.

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 3b). Changes can now be made to one module independently from other modules as long as the changes are compatible to the codified interfaces that govern the operability of the system.[6]

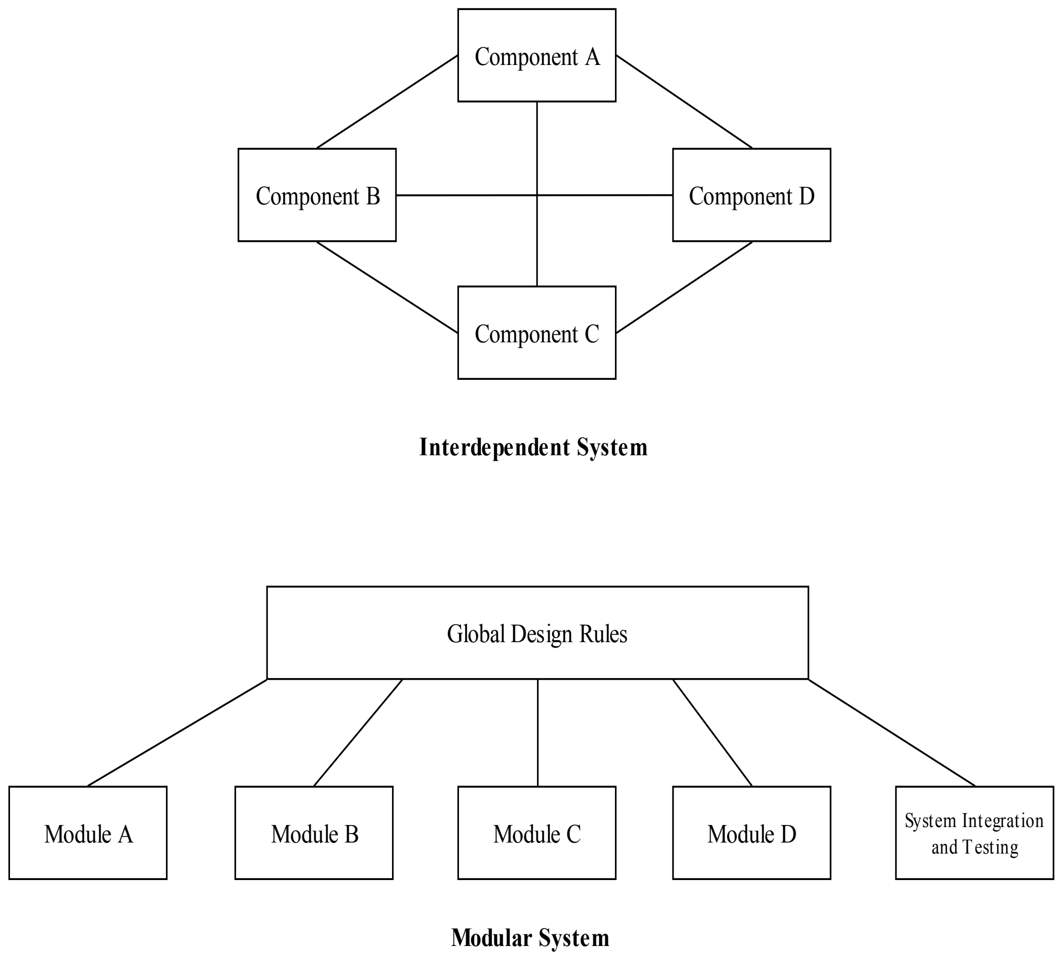

Figure 3: Interdependent versus Modular System (based on Baldwin and Clark, 2000)

Modularizing a product involves reducing the interdependencies between the modules and standardizing the interfaces between components in the product architecture. While modularization leads to both static and dynamic benefits, it also poses additional costs and risks. As a result, the

[6]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.

degree of modularity becomes an active choice of the management.

The direct costs of modularization lie on the fixed costs of designing modularity into the product architecture (Baldwin and Clark 2003). First, the interdependencies between modules need to be accurately identified. Second, a new set of design rules for the product's architecture needs to be created that reduces the inter-modular interdependencies without affecting the overall functionality of the final product. These new design rules need to define the function of each module, specify the inter-modular interfaces, and specify a set of tests to establish the performance of each module separately and the operability of the system as a whole (Baldwin and Clark 2000, p. 86).

On the benefit side, modularization can reduce the complexity of innovation. Since modularization reduces the interdependencies between modules, it makes it easier to make changes to components independently, provided that they are compatible to the interface specifications. This feature can significantly reduce the costs of coordinating activities across modules since it allows designers to concentrate their capabilities on a single module. In addition, it reduces the costs of maintenance, repair and upgrading of a product and encourages experimentation on the modular level.

Modularity also bestows greater flexibility on a system by enabling firms to mix and match compatible components to produce heterogeneous final products (Schilling 2000). This is especially beneficial in industries with a strong consumer demand for differentiated products. 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. Handspring has defined its PDA with a slot to fit in modules that turn the handheld device into an MP3 player, a camera, or a telephone (Biersdorfer 2001). It also allows companies in industries with high technological uncertainty to more flexibly respond to rapidly changing markets and technologies by creating variants derived from different combinations of existing or new modular components. Finally, by using the same generic set of components for various end configurations, a firm is able to take advantage of economies of scope and scale. In that case, the firm can move down the average cost curve of producing modules by applying the same set of standard production routines for various products.

If multiple firms in an industry agree to adopt the same open standards at the modules' boundaries, modularization can affect the location of firm boundaries. Independent component producers can then start taking advantage of economies of scale and scope in engineering and manufacturing to produce the same generic modules for multiple clients. As Sturgeon (2002) and Van Assche (2004) illustrate, this feature of modularity can explain the co-evolution of vertical outsourcing and horizontal consolidation in the electronics industry. We will discuss this issue further, below.

Modularization can also affect transaction costs. By codifying the interfaces between modules and specifying performance tests to which components need to adhere, the direct costs of writing, monitoring and enforcing contingent contracts are reduced. This can partially resolve problems associated with incomplete contracts. In addition, by enhancing the industry-wide interchangeability of modules, component suppliers are no longer destined to sell their product to one or few customers. This improves their outside options and thus reduces the hold-up problem that is inherent to a setting of asset specificity and incomplete contracts (Hart and Moore 1990; Hart 1998; Williamson 1985).

However, reduced asset specificity does not necessarily come without a cost for the outsourcing firm. By improving the component producer's outside options, modularization raises the *ex post* bargaining position of that firm. As the case of Microsoft clearly demonstrates, this in some cases can lead to market power within a vertical layer of production and dominance over other vertical layers of production (Bresnahan 1999).

Furthermore, outsourcing part of the value chain may hamper lead firms' ability to innovate and to create and control key intellectual property. Independent component producers can then acquire some of the core competencies through imitation and become a key competitor to the original equipment manufacturer. Taiwanese contract manufacturing firms substantially increased the complexity of the products they produce as they learned from their component work on PCs. Flextronics has recently started to manufacture its own components, thus moving the company one step closer toward becoming an original design manufacturer (Sperling 2004).

The enumeration of the costs and benefits from modularizing a production process highlights the implications of modularization for intra- and inter-firm relationships. As a result, a firm's decision on production design is wrapped up with its choice of the optimal boundaries of the firm. We turn to these questions in the next section.

4 Modularity and the Organization of Production

It is often argued that modularity in the design of products leads to modularity in the design of the organization that produce such products. Sanchez and Mahoney (1996), for example, contend that modular products are best produced by modular organizations, while non-modular products are best produced by non-modular organizations. Baldwin and Clark (2000) attribute the rise of *Wintelism* to modularity in the electronics industry. Since the degree of modularity is at least partially an economic decision by companies, however, the causation can go both ways. Pre-existing organizational structures and capabilities can also influence the degree of product modularity. Langlois (2002), for example, indicates that electronics firms such as Apple for a long time kept their product non-modular to circumvent the risks of imitation and loss of proprietary control associated with modular organizations. To understand the transformation of global electronics production and the role of modularity therein, it is necessary to focus on underlying factors that can explain both.

As we have seen above, Baldwin and Clark (2000) and Langlois (2002) have argued that the initial decision of IBM to modularize its product and outsource the production of its operating system to Microsoft and of its semiconductors to Intel was based on the increasing complexity of innovation and the need to bring product to market quickly. The resulting modularization with its standardized interfaces reduced the two firms' asset specificity. It allowed Microsoft and Intel to provide the same generic operating systems and semiconductors to IBM and its clones, thus induces a co-evolution of vertical outsourcing and horizontal consolidation.

Sturgeon (2002) has identified the adoption of Information Technology (IT) as an important driver for the most recent wave of product modularization and organizational change in the electronics industry. The use of IT (e.g., internet and electronic commerce) enables firms to more easily standardize and automate the transfer of complex data to other firms. If a group of firms adopt the same language to transfer data, then their heavy reliance on codified and standardized information and communications technologies at the interfaces between firms can reduce coordination costs and contract incompleteness. Codification and standardization of information flows are not sufficient to induce a co-evolution between vertical outsourcing and horizontal consolidation however. It will also depend on the component producers' ability to take advantage of economies of scale and to increase its outside options. If component producers are able to produce the same generic components for multiple clients, then this can induce a co-evolution since it not only reduces asset specificity of a component but also allows the component producer to move down its average cost curve.

This has implications for the optimal location of production of the various components. Luethje (2002) observes that original equipment manufacturers continue to keep the highest value added modules in the developed countries, while moving low value added modules to developing countries. One reason for this is comparative advantage; another may be that the threat of imitation is larger in developing countries since property rights are less established and less strongly enforced. In any event, this raises the concern that the potential for developing country producers to move up the value chain may be limited (Ernst 2004; Yusuf 2003).

5 Agenda for further Research

To move beyond a descriptive analysis of the role that modularity may play in international production decisions, we would like to incorporate key aspects of this story into structural economic models. By introducing modularity into firms' optimization problems, the role of modularity in the location of production and the boundaries of the firm can be elucidated, and we may obtain new insights about how policy, institutions, and markets influencing international production arrangements.

An emerging international trade literature has focused on the determinants of the location of production and the boundaries of the firm by incorporating elements of transaction cost theory into industry-equilibrium trade models. The literature generally finds that many factors that are identified with globalization can explain the recent wave of international outsourcing. In McLaren (2000), firms face a trade-off between the friction of incomplete contracts under arm's length trade and extra governance costs in integrated companies. The author finds that trade openness induces outsourcing since it thickens the market for inputs, thus improving the intermediate good firms' outside options and reducing their hold-up problem. In Grossman and Helpman (2002), firms in arm's length relationships not only face the friction of incomplete contracts but also a search friction. In particular, final good producers must find a suitable supplier of inputs, while input producers must find potential customers. Grossman and Helpman find that improvements in matching—which for example can be induced by increased internet connectivity—can give rise to an increase in outsourcing activity. Antràs (2003) and Antràs and Helpman (2004) extend the Grossman-Helpman framework to a two-input setting and find that a widening wage gap between the North and the South, or a reduction of the trading costs of intermediate inputs raises the prevalence of outsourcing. In addition, sectors that are relatively intensive in headquarter services integrate, while sectors that are relatively intensive in components outsource.

While these studies have laid important building blocks for a general theory of international production, they face a few important shortcomings for our purposes. First, they do not provide a theoretical explanation for the co-evolution of vertical outsourcing and horizontal consolidation that has been documented in the electronics sector. Since these studies implicitly assume that intermediate good firms and subsidiaries provide components to at most one final good firm, the degree of concentration in the intermediate good sector is not allowed to co-evolve with vertical outsourcing. Second, these studies do not analyze the role of product modularity on the organization of production.

In a recent paper, Van Assche (2004) has addressed both issues. The author set up an industry-equilibrium model in which the boundaries of the firm were endogenous in both the horizontal and vertical dimensions of international production. Modularity in the model is assumed to be negatively related to the degree of input specificity of intermediate goods. The model demonstrates that the modularization of a product precisely the sort of co-evolution of vertical outsourcing and horizontal consolidation that we see in the intermediate good sector. If products are modular and if intermediate good firms can exploit economies of scale, then it can become profitable for a vertically integrated firm to outsource component production to an intermediate good firm that uses a generic production process to produce intermediate goods for multiple final good firms. As such, this paper links the emergence of modular production networks to the *de facto* standardization of inputs and production processes that has been taking place in high technology industries such as electronics.

Further research is needed to gain broader insights into the role of modularity in the organization of international production. As we have mentioned above, the degree of modularity is not necessarily exogenous as is assumed by Van Assche (2004), but instead may be endogenously determined by the management of the firm. A model that endogenizes both the degree of product modularity and the organization of production may therefore provide novel insights on how these two decisions interact at the firm and market level.

There are also particular aspects of modularity that may be better studied in such a model setting. As we have discussed above, modularity has the potential to reduce the problems related to contract incompleteness, so introducing modularity in this context may prove instructive. In addition, modularity may help to resolve the severity of the hold-up problem by improving the component producers' outside options. A model in which a component producer's outside option is endogenous and dependent on the degree of modularity adopted by the final good firm thus might provide an additional explanation of the co-evolution of vertical outsourcing and horizontal integration.

The co-evolution of vertical outsourcing and horizontal integration may also have far-reaching positive and normative implications related to market structure. If co-evolution increases the bargaining power of the component producer so much that it becomes a dominant firm with monopoly power, this might not only act as a deterrent against modularizing a product, but also have important implications on competition policy. The international production arrangements that emerge also influence the location of work and the opportunities for product and skill upgrading, and so may imply prescriptions for development policy.

This represents a broad and promising area for further analytical research. That research will eventually inform empirical research in this area, as well.

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