Industry structure and modular product architectures:

An interpretation of the bicycle industry

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Abstract

This paper aims at describing network dynamics through the lenses of modularity. Different types of networks exist as ways of coping with the dynamics of industry demands that are based on modular product architectures. In order to distinguish between different types of mechanisms in which networks (operating with modular product architectures may) evolve, two types of networks are introduced: 'market-driven product architecture network' (i.e., when the industrial network is driven by product architecture that is controlled by the market) and 'firm-driven product architecture network' (when the industrial network is driven by product architecture that is controlled by the firm). The history of the technological development of bicycle, since 1890s to 1990s, illustrates how the bicycle industry survived two cycles of disaggregation-concentration.

1. Introduction

Networks are 'clusters of firms or specialist units coordinated by market mechanism instead of chain of commands' (Miles and Snow, 1992:53). A network allows its parties to operate independently of each other, working towards a common goal. An industrial network exists when companies are linked together by the fact that they either produce or use complementary or competitive products (Håkansson, 1989:16). Different types of network organizations emerge as a way of coping with dynamics of industry demands. From technology perspective, industrial networks exist to produce or use competitive components to sustain and to advance sets of interdependent components of a technological system. The decomposition of a technological system into portions allows division of labor and hence for task specialization to take place[1]. Components can be outsourced and produced independently by different parties of the network. The process of organizing complex products and processes efficiently into simpler portions is referred to as *modularization*.

This paper attempts to describe the dynamics of network structures that exist due to modular product architectures. The bicycle industry, for instance, is fragmented based on various specialized capabilities associated with the manufacturing of various components. Bicycles are built from components sourced from multiple suppliers rather than vertical integration as a more efficient method to keep prices low (Garvin and Morkel, 2001). In his study of the bicycle industry in Taiwan, Chu (1997) argues

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[1] Decomposition of a complex system into smaller, more manageable parts has been well discussed in management and economic literature (e.g., scientific management principles with respect to standardized work designs and specialization of labor (Taylor, 1967), nearly decomposable systems (Simon, 1995; 1996), and Adam Smith's (1776) view on division of labor and task partitioning).

that the success of the bicycle assembly sector depends upon having the support of a network of parts suppliers, which must consist of numerous SMEs with some skills. The focus of this paper is to show that even in well-established industries with stable modular product architectures, modularity (through decomposition of systems and integration of components) plays a special role in changing how industry networks go through periods of concentration and disaggregation. This takes place through the control of interface standards, either by core firms or by the market itself. In other words, the extent of product architecture control, to some degree, leads to industry concentration (i.e., consolidation into vertical structure) or disaggregation (i.e., expansion into horizontal structure). Industry concentration refers to the concentration of the competition in the product category (Ulrich and Ellison, 1999), and is an important determinant of vertical integration[2] (McDonald, 1985). A highly concentrated industry tends to reduce the bargaining power of potential component suppliers, discouraging entry (Porter, 1980). Industry disaggregation into horizontal structure, on the other hand, tends to create fierce, commodity-like competition within individual niches (Fine, 1998).

Standardization of interfaces creates a high degree of independence or 'loose-coupling' between component designs (Orton and Weick, 1990; Sanchez and Mahoney, 1996) and used interchangeably in different configurations without compromising system integrity (Flamm, 1988; Garud and Kumaraswamy, 1993, 1995; Garud and Kotha, 1994). The bicycle industry is one of the oldest industries,

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[2] In economic theory, vertical integration is a response to relatively high costs of market exchange (Williamson, 1981). It also arises as a result of market power on one side of the market (Stigler, 1951), and the degree of vertical integration in an industry depends on supply as well as on demand conditions (Langlois and Robertson, 1992).

with widely established international standards. Over the years, the bicycle industry has survived through cycles of concentration and disaggregation (Fine, 1998; Galvin and Morkel, 2001; Ritchie, 1975). Prior to the establishment of the dominant bicycle design in the 1890s, there were 607 bicycle producers in the U.S. with no particular maker dominating the market, but all complying to the interface specifications of the bicycle. However, by the end of 1905 the bicycle industry had aggregated in which the number of bicycle makers had dropped to 12. The industry concentrated vertically again during the mid-1950s lead by Schwinn Company, but disaggregated horizontally again during the 1980s with the popularity of mountain bikes. Today the bicycle industry is concentrated around Shimano components comprising nearly 47% of the bicycles world wide.

The bicycle industry may provide insights into how certain industries (operating in stable industries with modular product architectures, in which component interface specifications are well accepted within the industry) may evolve over time. If so, how do modular product architectures prompt industries to concentrate vertically and/or to disaggregate horizontally? How does component innovation impact this dynamics?

In this paper I look into historical evidence of technological development of bicycles to explain to the relationship between modularity and industry concentration/disaggregation. All the data used in this paper are collected from secondary sources such as newspapers, books, magazines, trade journals, academic journals, and web sites. The paper is organized as follows. A literature review on modularization is provided in the next section with a discussion of integral and modular product architectures with respect to the role of interface specification and standardization. Next, the impact of modularity in industry network dynamics is elaborated. Here I describe two types of network organizations that may evolve as result of modular product architectures: ‘market-driven product architecture network’ and ‘firm-driven product architecture network’. Finally, the dynamics of industry concentration-disaggregation cycles are illustrated with the evolution of the bicycle industry, followed by some discussions and future research.

2. Modularization

In broadest terms, *modularization* is an approach for organizing complex products and processes efficiently (Baldwin and Clark, 1997) by decomposing complex tasks into simpler portions so that they can be managed independently and yet operate together as a whole. Modularity permits components to be produced separately, or ‘loosely coupled’ (Orton and Weick, 1990; Sanchez and Mahoney, 1996), and used interchangeably in different configurations without compromising system integrity (Flamm, 1988; Garud and Kumaraswamy, 1993; Garud and Kotha, 1994; Garud and Kumaraswamy, 1995). Moreover, modularity intentionally creates a high degree of independence or ‘loose coupling’ between component designs by standardizing components specifications (Sanchez and Mahoney, 1996), hence the tightness of coupling between components and the degree to which the “rules” of the system architecture enable (or prohibit) the mixing-and-matching of components (Schilling, 2000).

Modularity is made possible by how information is partitioned into visible design rules (or visible information) and hidden design parameters (or hidden information decisions that do not affect the design beyond the local module) (Baldwin and Clark, 1997). According to Baldwin and Clark (1997), visible design rules are established early in the design process and fall into three categories:

- *An architecture* which specifies end modules[3] and respective functions in the system
- *Interfaces* that describe in detail how the modules will interact, fit together, connect, and communicate
- *Standards* for testing a module's conformity to the design rules and for measuring modules' performances

There are many reasons why firms pursue modularization as a strategy. For one, modular product designs[4] enable firms to increase specialization (Langlois, 2000), encouraging them to pursue specialized learning curves and increasing their differentiation from competitors (Schilling, 2000) as well as benefiting from decreased throughput times with elimination of pre-assembly operations (Wilhem, 1997). Because modularity encourages concurrent and distributed component development processes, it enables the loose coupling of component designs and

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[3] A module can also be a component depending on the level of analysis. For example, the windshield wipers controller (WIPER) for Jeep Grand Cherokee is considered a module for Chrysler (as it is a part of windshield wiper sub-system produced by a first-tier supplier), but the parts embedded in the WIPER are considered components (which can be produced by lower tier suppliers). In other words, whether a part is called a module or a component can be distinguished from the hierarchy of supplier (or tiers) considered by the assembler, although these two terms are often used interchangeably (Hsuan, 1999).

[4] In modular product design, the standardized interfaces between components are specified to allow for a range of variations in components to be substituted into a product architecture (Sanchez and Mahoney, 1996). The aim of a modular product design is to create a product design that can serve as the basis for a number of product variations with different performance and cost characteristics (Sanchez, 1995).

thereby creating loosely coupled knowledge domains (Sanchez, 1999). Modularity also boosts the rate of innovation, and as long as the design rules are followed, more experimentation and flexibility are given to designers to develop and test the modules (Baldwin and Clark, 1997). Other advantages of modularization include cost reduction (Muffatto, 1999; Sanchez, 1995; Cusumano and Nobeoka, 1998), economies of scale and scope (Pine, 1993; Friedland, 1994), increased flexibility (Henderson and Clark, 1990; Christensen and Rosenbloom, 1995; Schilling, 2000; Sanchez, 1995; Wilhem, 1997; Garud and Kumaraswamy, 1995, Sanderson and Uzumeri, 1997), and increased number of compatible suppliers (Langlois, 1992, 2000; Langlois and Robertson, 1992; Tassey, 2000; Reed, 1996; Sanderson and Uzumeri, 1997; Garud and Kumaraswamy, 1993; Morris and Ferguson, 1993; Baldwin and Clark, 1997). The degree of modularity of a system is dependent on product architecture designs.

2.1. Product architectures

Product architecture can be defined as the arrangement of the functional elements[5] of a product into several physical building blocks, including the mapping from functional elements to physical components[6], and the specification of the interfaces among interacting physical components. Its purpose is to define the basic physical

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[5] The *functional elements* of a product are the individual operations and transformations that contribute to the overall performance of the product, and are usually described in schematic form before they are reduced to specific technologies, components, or physical working principles (Ulrich and Eppinger, 1995).

[6] The physical elements of a product are the parts, components, and subassemblies that ultimately implement the product's functions. These elements are inextricably linked to the product concept and are defined at the time of concept selection (Ulrich and Eppinger, 1995).

building blocks of the product in terms of both what they do and what their interfaces are with the rest of the device (Ulrich, 1995; Ulrich and Eppinger, 1995). A bicycle's product architecture, for instance, can be decomposed into 'groupsets', where different components that make a bicycle's mechanical profile (e.g., chains, gear, brakes and pedals) are designed as a complete ensemble. Each component is finished to a particular standard, and shares the same product name and styling (Wilson and Hirst, 1994). Product architectures generally vary from integral to modular.

2.2. Integral product architectures

Integral product architectures are designed with maximum performance in mind, and the implementation of functional elements may be distributed across multiple components. Innovation within integral product architecture tends to be systemic (Chesbrough and Teece, 1996; Teece, 1996). The introduction of systemic innovations requires significant readjustment to other components of the system. It takes place when the benefits of innovation can be realized only in conjunction with related, complementary innovations. Moreover, organization integration facilitates systemic innovations by facilitating information flows, and the coordination of investment plans (Teece, 1996). Integral product architecture innovations tend to favor horizontal industry structure. For instance, Polaroid needed to develop both new film technology and new camera technology in order to profit from instant photography. This type of innovation requires organizational members to be highly dependent of each other. In addition, information sharing and coordinated adjustments must be managed throughout an entire product system. Coordinating architectural innovations is particularly difficult when industry standards do not exist and must be pioneered. When innovation depends on a series of interdependent innovations, independent companies (such as ones linked through arm's-length contracts) will not usually be able to coordinate themselves to knit those innovations together (Chesbrough and Teece, 1996).

2.3. Modular product architectures

Contrary to integral product architectures, modular product architectures[7] (Sanchez and Mahoney, 1996; Ulrich and Eppinger, 1995; Lundqvist et al., 1996) are used as flexible platforms for leveraging a large number of product variations[8] (Gilmore and Pine, 1997; Meyer et al., 1997; Robertson and Ulrich, 1998; Sanchez, 1996; Sanchez 1999), enabling a firm to gain cost savings through economies of scale from component commonality, inventory, logistics, as well as to introduce technologically improved products more rapidly. Some of the motivations for product change include upgrade, add-ons, adaptation, wear, consumption, flexibility in use, and reuse (Ulrich and Eppinger, 1995). Modular architectures enable firms to minimize the physical changes required to achieve a functional change. Product variants often are achieved through modular product architectures where changes in one component do not lead to changes in other components, and physical changes can be more easily varied without adding tremendous complexity to the manufacturing system. Outsourcing decisions are often made concurrently with the design of modular product architectures, and specialization of knowledge is gained through division of labor.

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[7] Lundqvist et al. (1996) use the term 'remodularization' to redefine modular architecture or architectural innovation of a product, as the reconfiguration of product systems and not necessarily changes in functionality or the technical performance of components.

[8] Ulrich and Eppinger (1995) defined variety as the range of product models the firm can produce within a particular time period in response to market demand.

In a modular product architecture, components can be disassembled and recombined into new configurations, possibly substituting various new components into the configuration, without losing functionality and performance (Langlois, 1992; Sanchez, 1995). Furthermore, one of the most important characteristics of modular product architectures is the modularity distinguished by a great number of components with standardized interfaces facilitating upgradability, reusability, and substitutability. Modular upgradability enables firms to react to customer feedback and alter their systems accordingly by substituting some components while retaining others (Garud and Kumaraswamy, 1993, 1995).

Modular product architecture strategy fits with autonomous innovations[9] (Chesbrough and Teece, 1996; Teece, 1996), which are innovations that can be pursued independently from other innovations, hence modular. For example, to increase horsepower of a new turbocharger in an automobile can be developed without a complete redesign of the engine or the rest of the car. With this type of innovation, centralized virtual organization[10] can manage the development and commercialization tasks efficiently. Information embedded in modular architectures is codified information in the sense that specifications that are captured in industry standard and design rules can often be transferred effectively within and across companies, hence not easily protected (Chesbrough and Teece, 1996). Components with standardized

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[9] Contrary to systemic innovation, autonomous innovation is one which can be introduced without modifying other components of a system (Teece, 1986).

[10] Hoogeweegen et al. (1999:1075) define virtual organization as a "network of organizations from which temporary alignments are formed to combine the specific core capabilities of its members in order to quickly exploit a specific product or service manufacturing opportunity, after which the

and industry-wide accepted interface specifications decouple firms from one another, leading to increased specialization and technological improvement of components independently of innovations from other firms.

One crucial element of modularity is substitutability. According to Garud and Kumaraswamy (1993:365) “economies of substitution occur due to preservation and enhancement of existing knowledge through the use of standardized interface specifications and technological platforms with wide degrees of freedom.” Components have to be compatible in order to be substitutable. Compatibility has “a relational attribute that defines rules of fit and interaction between components across boundaries called interfaces. The overall set of rules that defines acceptable fit and interactions constitutes a system’s architecture” (Garud and Kumaraswamy, 1995). Lack of compatibility among components of any system results in sub-optimal system performance.

According to many scholars, one of the fundamental key characteristics of modularity in product architectures is related to creating flexibility through mixing-and-matching of components (Garud and Kumaraswamy, 1995; Sanchez and Mahoney, 1996; Schilling, 2000; Pine, 1993) to create product variety. Schilling (2000), for instance, captures some of the factors influencing mixing-and-matching of components in system architecture by discussing direct and indirect effects of why a firm should adopt modular strategy versus integral strategy. She discusses trade-offs between disaggregation and integration by using the term ‘synergistic specificity’ to describe the degree to which a system achieves greater functionality by its components being

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temporary alignment is dissolved and the members become available for another virtual and temporary assignment.”

specific to one another. For instance, high levels of synergistic specificity oppose the system's shift to a more modular design.

2.3.1. Interface Specification and Standardization

Interfaces are linkages shared between and among components of a given product architecture. Interface specifications define the protocol for the fundamental interactions across all components comprising a technological system. For instance, the specification for the majority of road bike wheels are manufactured to 27 inch-diameter and mountain bikes to 26 inches (Galvin and Morkel, 2001).

Component interfaces can be classified and specified according to the following (Sanchez, 1999):

1. Attachment interfaces – define how one component physically attaches to another.
2. Spatial interfaces – define the physical space (dimension and position) that a component occupies in relation to other components.
3. Transfer interfaces – define the way one component transfers electrical or mechanical power, fluid, a bi-stream, or other primary flow to another.
4. Control and communication interfaces – define the way one component informs another of its current state and the way that other components communicate a signal to change the original component's current state.
5. Environmental interfaces – define the effects, often unintended, that the presence or functioning of one component can have on the functioning of another (e.g., heat, magnetic fields, corrosive vapors, radiation, etc.).

6. Ambient interfaces – define the range of ambient use conditions (e.g., ambient temperature, humidity, elevation, etc.) in which a component is intended to perform.
7. User interfaces – define specific ways in which users will interact with a product.

Modularity in bicycles takes place through standardizing attachment and spatial interfaces (Galvin and Morkel, 2001). The degree to which interfaces become standardized and specified defines the compatibility and substitutability between components, hence the degree of modularity. Standardized components have well specified interfaces, hence product architectures comprised of standardized components are considered modular product architectures. According to Langlois and Robertson (1995:5), "standardization of interfaces creates 'external economies of scope' that substitute in large part for centralized coordination among the wielders of complementary capabilities. This allows the makers of components to concentrate their capabilities narrowly and deeply and thus to improve their piece of the system independently of others." Standardization also impacts innovation and technology diffusion, influencing industry structure and hence determining which firms benefit (or not) from technological change (Tassey, 2000). Interface standards allow multiple proprietary component designs to coexist. With standardized interfaces, substitution of old components with technologically advanced components is possible. A bicycle can be treated as a close-assembled system (Tushman and Rosenkopf, 1992) assembled from components sourced from multiple suppliers. The number of components and the way these components are attached (functionally and spatially) to one another through standardized interfaces allows for interchangeability of parts across models and determines the degree of modularity in bicycles. The dominant design of today's bicycles was institutionalized in the 1890s, and most of the bicycle components have defined interfaces for over 50 years, making the bicycle industry one of the oldest industries to have international standards for its components. The bicycle industry can be described as fragmented with relatively little architectural[11] and radical innovation (Galvin and Morkel, 2001).

In general, standardization of parts enables tasks to be performed independently, encouraging supplier specialization to take place often fostering the emergence of network organizations. The rate at which interface specifications change (which has deep implications for component integration and decomposition) influences the way product architecture is controlled, hence impacting how firms organize within the industry to compete or to cooperate around the new set of interface specifications.

3. Modularity and Industrial Network Dynamics

Modularity is an attractive strategy for many firms to benefit from cost savings due to economies of scale, task specialization, and independent task organization. Although modular products are vulnerable to competition, a firm's market power and architectural control can still be protected when it has control of unique assets[12], or

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[11] Architectural innovations are (Henderson and Clark, 1990:10) "innovations that change the way in which the components of a product are linked together, while leaving the core design concepts untouched." The emphasis of an architectural innovation, often triggered by a change in a component, is the reconfiguration of an established system to link together existing components in a new way.

[12] Assets are stocks of resources that are owned or controlled by the firm (Amit and Shoemaker, 1993; Dierickx and Cool, 1989). Firm-specific assets are resources that are difficult to imitate, such as quality, miniaturization, and systems integration capabilities. These resources are typically

accessibility to complementary assets[13] (Teece, 1986). But to protect such assets from competitors (e.g., reverse engineering, spin-offs, etc.) is not an easy task. The extent of control and accessibility to complementary assets determines, to some degree, whether a firm lean towards an integral or a modular solution to product architecture designs.

There is performance, time, and cost trade-offs associated with modular and integral product architecture designs. As described by Baldwin and Clark (1997), modular systems are much harder to design than comparable interconnected systems because the designers of modular systems must know a great deal about the overall product or process in order to develop the visible design rules necessary to make the modules function as a whole. This means that interface designs with respect to integration of parts must be done carefully in terms of defining and organizing the modules. Muffatto (1999) further points out that rigidity can be introduced by modularization if cost benefits were exploited and flexibility must be maintained on model changes, as this does not encourage standardization through module development.

Different types of network organizations[14] emerge as a way of coping with the dynamics of industry demands. According to Robertson and Langlois (1995), when

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assembled in integrated clusters spanning across multiple technologies or product lines, and may extend outside the firm to embrace alliance partners (Teece et al., 1997).

[13] There are three types of complementary assets: generic, specialized, and co-specialized. Generic assets are not tailored to the innovation. Specialized and co-specialized assets have unilateral and bilateral dependence, respectively, between the innovation and the complementary assets.

[14] Robertson and Langlois (1995) use the term ‘core networks’ to describe networks that are organized around a single firm or a large assembler, such as the relationships between Japanese and US auto manufacturers and their assemblers.

there is modularity, both vertical and horizontal networks may arise. Vertical specialization arises when there are few economies of scale in assembly and consumer prefer the ability to choose components rather than pre-packaged sets. But firms can not control the practices of their competitors and manufacturers because assembly requires a high degree of standardization to permit compatibility. This gives rise to the emergence of horizontal networks.

Modularity through system decomposition with standardization of interfaces tends to generate momentum for industries to disaggregate into autonomous, specialized units. Innovation takes place at the component level, and when a new innovation is created (either with integration of existing components or with entirely new technology) that is accepted and demanded by the market, then a new momentum is generated for the innovating firm(s) to integrate in order to gain technological control of the innovation. Other firms will resist to such change creating inertia to slow down the momentum.

The extent of network concentration (when the industrial network is driven by product architecture that is controlled by core firms) or disaggregation (when the industrial network is driven by product architecture that is controlled by the market) of an industry is, in part, led by the degree to which the standardized interfaces of components within modular product architectures are accepted as industry standards (Figure 1).

******** Figure 1 about here ********

3.1.1. Market-driven product architecture (MDPA) network

One of the main motivations behind market-driven product architecture (MDPA) network is to create strategic flexibility. Strategic flexibility denotes a firm's ability to respond to various demands from dynamic competitive environments (Sanchez, 1995). Strategic flexibility in product competition represents a fundamental approach to the management of uncertainty (Sanchez, 1995), and it requires an organizational climate that nurtures learning and knowledge creation (Adler, 1988; Garud and Kotha, 1994; Garvin, 1993; Kotha, 1995; Nonaka, 1991, 1994) which requires the tapping of tacit knowledge and often highly subjective insights, intuitions, and ideals of the firm's employees (Nonaka, 1991).

Since the 1980s, the increasing competitive global business environment is moving away from centrally coordinated, multi-level hierarchies and toward a variety of more flexible structures that closely resembled network (Miles and Snow, 1992). Many established firms de-layered management hierarchies and started to shift towards outsourcing a wide range of activities. New firms sought to gain competitive advantage through alliances with independent suppliers and/or distributors instead of vertically integrating. Firms turned to contracts and other exchange arrangements to link together external components into various types of network structures. Some characteristics of network include:

- Use of collective assets of several firms located at various points along the value chain
- Dependence more on market mechanisms than administrative processes to manage resource flows. Network members recognize their interdependence

- Proactive, voluntary behavior among participants to improve the final product or service rather than simply fulfilling contractual obligations
- Cooperation and mutual shareholding among groups of manufacturers, suppliers, and trading and finance companies

Modular product architectures enable firms to gain strategic flexibility. When interface specification of a system is published and accessible publicly (such as open source software systems), any firm is invited to innovate. Firms operating within the network have loose control of product architectures. In other words, no single firm has the power to change the product architecture as the components are compatible and can be sourced from multiple suppliers who operate independently of one another. As a result, innovation takes place at the component level, or autonomous innovation (Chesbrough and Teece, 1996; Teece, 1996). For instance, Shimano has taken the lead in the market with innovations such as 'index shifting', which uses tight cables to make gear changes more precise, and 'step-in-pedals', which clip onto a rider's shoe like a ski binding (Kerber, 1998).

One of the most important areas of modularity is the role of standard setting as means of competition (Morris and Ferguson, 1993; Langlois, 1992, 2000; Tassey, 2000; Link and Tassey, 1987; Galvin and Morkel, 2001). In his study of the microcomputer industry, Langlois (1992) describes how modular systems allow well-coordinated division of labor in the market, which in turn allows for the rapid creation of new capabilities. Modularity permits more entry points for new firms to innovate and thus adding to the diversity in the system. He argues that a decentralized and fragmented system can have advantages in innovation leading to rapid trial-and-error learning, especially when technology is changing rapidly and there is a high degree of technological and market uncertainty. When product variety and quick response require fluid response mechanisms, multi-tasking overcomes the rigidities that set in from the division of labor (Adler, 1988; Walton and Susman, 1987). Specialization and division of labor should lead to a low degree of vertical and horizontal integration (Robertson and Langlois, 1995).

In devising a modular approach to product architecture as a competitive advantage, there should be a balance between the gains achievable through recombination (e.g., mixing-and-matching) of components and the gains achievable through specificity (e.g., higher performance through components) in determining the pressure for or against the decomposition of a system (Schilling, 2000). Although modular designs increase flexibility in the end product by allowing a variety of possible configurations to be assembled (Sanchez, 1995; Garud and Kumaraswamy, 1995; Baldwin and Clark, 1997), it also increases the coordination effort (in logistics, marketing, retail, etc.) of these components. Too much product variety for customers to choose from may actually create frustration and can backfire, especially when customers are not able to distinguish the performance, quality, and value among different components. Nissan, for instance, retreated from customization when it became evident that buyers did not want eighty-seven different varieties of steering wheels (Pine et al., 1993).

Chesbrough and Kusunoki (2001:203) use the term ‘modularity trap’ to describe the situation in which “a firm that has successfully aligned its organization with a modular phase of technology encounters difficulty capturing value from its innovation activities when the technology phase shifts from modular to integral.” In modular phase of the technology, virtual organizational strategies[15] best match their internal organization to the modular technological characteristics of that phase. Moreover, much of their innovation activities are coordinated via the market place where independent firms come together to buy and sell technology and the components that are used to make the various items (Chesbrough and Teece, 1996). However, when technologies shift into a more integral form, virtual organization's capability to focus within a specific configuration of technology, especially when there is a lack of systems expertise, becomes a significant liability. Some firms tend to exert some kinds of control by bundling components (e.g., Shimano), hence gaining some control over the modularity of bicycles in terms of how components should interface with another. For instance, Champagnolo and Shimano try to enforce different international standards for similar components.

3.1.2. Firm-driven product architecture (FDPA) network

Architectural momentum towards industry aggregation takes place when a product architecture becomes so modular that it is not efficient for one single firm to produce the system. Any firm operating in such network can innovate as long as the interfaces among components remain constant. However, when significant technological component improvements are well perceived and demanded by the market, often the core firm gains the control of the product architecture making it more efficient for the industry to vertically aggregate.

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[15] According to Chesbrough and Teece (1996) virtual companies coordinate much of their business through the marketplace, and they can harness the power of market forces to develop, manufacture, market, distribute, and support their offerings in ways that fully integrated companies can not duplicate.

As mentioned, the setting and development of interface specifications have a tremendous impact on industry standards. When interface specifications of a well established architecture operating in a stable industry are altered in such a way (either through radical innovations, or through integration of existing components into a new component) that creates incompatibility with existing components, compelling customers to lock-in into its technology and respective interface specifications. When such specification gain market acceptance, inevitably it changes the competitive environment in which the industry operates. The firm with technological control of this new innovation – that is, the core firm – generates certain amount of momentum, prompting the industry to concentrate into a vertical structure forcing other parties of the industrial network to operate around this new specification. I refer to such group of firms competing in this industrial setting as the 'firm-driven product architecture network'.

In the bicycle industry, currently the core firm is Shimano, a Japanese components manufacturer for bicycles. Mainly through mergers and acquisitions, Shimano is the dominant parts supplier in the U.S. market controlling about 80 percent of the world market for hubs, gears, chain wheels, and other key components (Frazier, 2000). In 1995, Shimano gained market share in the U.S. by integrating traditionally modular components, particularly the drive train. For instance, the rear hub and cog set were integrated in a way that other brands of cogs and hubs were incompatible with Shimano's components. Shimano also integrated its shift levers into the braking system, requiring bicycle assemblers to purchase Shimano brake and shift levers as a single unit. Furthermore, bike makers that rely on Shimano parts become distributors making gross profit margins ranging from 25% to 50% (Kerber, 1998).

In order to become less reliant on core firm's components, some firms try to create differentiation by manufacturing the whole bicycle. This in turn intensifies the competition within the supplier network, perhaps forcing the bicycle industry to disaggregate into a market-driven product architecture network. Galvin and Morkel (2001:31) suggest that 'long-term, constant international standards are effectively able to replace communication and other forms of coordination, eventually leading to fragmentation of the industry and low levels of innovation beyond the component level.'

4. Concentration-Disaggregation Cycles of the Bicycle Industry

Consistent with Utterback's (1994) model of the dynamics of innovation[16], the early bicycle industry was characterized by great uncertainty over which bicycle design would become standard for the industry (Pinch and Bijker, 1987). The dominant design for bicycles was set during the 1890s. Prior to 1890s, the development of American bicycle industry, in general, can be analyzed into four eras of successive generations: ordinaries, high-wheel safeties, solid-tire safeties, and pneumatic-tire safeties. During the 1890s, firms entered and exited the industry at a fast rate, and the industry sales per capita rose and fell, reaching a peak in 1897 that would not be reached again until 1965 (Dowell and Swaminathan, 2000). Most of the components in today's bicycles have international standards for over 50 years making the bicycle

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[16] Before the establishment of a dominant design, firms have the opportunity to experiment more by increasing product variety, and thus are more likely to come up with the dominant design (Utterback and Suarez, 1995).

industry one of the oldest industries (Galvin and Morkel, 2001). See Appendix A for a chronology of bicycle development.

In some 125 years of history, the bicycle industry has gone through two phases of concentration-disaggregation cycles, from vertical in late 1800s to horizontal (in early 1900s), then back to vertical due to Schwinn (in mid-1900s) and horizontal (in early 1980s). Today, we witness a vertical industry structure dominated by Shimano.

4.1. Industry disaggregation, early 1900s

The architecture of bicycle has changed little since the late 1890s, and technological improvements have taken place at the component level as way to create differentiation. For instance, the derailleur gear system was introduced in the early 1920s. The earlier technology consisted of a chain that shifted between rear sprockets of different sizes using levers, cables and springs (Wilson and Hirst, 1994). The modern derailleur system is much advanced from the earlier days, but the working principles remain mostly the same.

Due to standardization of interfaces of key components, the design process became separate from the production process, making possible for mass production to take place. This led to the fragmentation of industry into autonomous units with low barriers of entry, leaving no particular producer(s) controlling the product architecture. Prior to the establishment of the dominant design of the bicycle, different types of bicycles were mass-produced by some 607 producers in the U.S. alone. Competition was intense as autonomous innovation continued to be pursed by independent producers, which pushed out the weaker innovators out of the market. In 1905, there were only 12 bicycle companies in the U.S., mainly assemblers. This is an indication that the bicycle industry was aggregating. The disaggregated industry structure lasted until the dominance of the Schwinn Company, which took advantages of the modular product architecture of bicycles to gain market leadership.

4.2. Industry concentration, 1900s – 1970s[17]

During the early 1900s, the bicycle's inherently modular design allowed a large number of suppliers to compete, in innovation as well as in prices. The parts maker standardized their products so they could keep their costs low and profit margins high, consequently they avoided improvements in materials, engineering, or design. For instance, for nearly 30 years, the U.S. Rubber Company sold essentially one type of single-tube tire to American bicycle manufacturers. Similarly, the Torrington Company sold spokes, pedals, and handlebars.

In 1925 the parts makers and chain stores started to trade directly with one another, and components were delivered directly to the bicycle manufacturer who merely packed the goods with his simple frame sets, consisted of a diamond-shaped frame, forks and cranks. This enabled the emergence of many look-alike bikes in the market. Schwinn Company decided to make better bikes, focusing on quality and innovative designs. It started by changing the industry specification of tires into a new one. So far the American tire market was dominated by U.S. Rubber, which had monopoly of single-tube tires. The European bicycles, however, had used wide cord tires whose double tubes provided a softer ride, referred to as the 'balloon tires'. Schwinn persuaded independent bike dealers and hardware store owners to sell Schwinn bikes with 'balloon tires', which in 1935 became the American industry standard. Schwinn continued to introduce new technology into its bikes in order to gain control of product architecture, and during the 1930s it was awarded more than forty patents. However, with the modular nature of the bicycles, product architecture control as means of sustaining market share was difficult. Schwinn peaked with 25.5% market share in 1950. When competitors introduced their own imitations in addition to imports, its market share dropped to 13.7% in 1955.

Schwinn Company was creative in bicycle designs that satisfy consumer tastes, although the company supplied only its name on the bicycles, and purchased all the components from outside vendors. During the 1960s it introduced banana seats and a provocative looking, 'high-rise' bicycle for children called Sting-Ray which led the company back to be the market leader accounting for more than 60% of all bikes sold in the U.S. The company continued to enjoy its market leadership during the 1970s with other bike models (e.g., Varsity and and Continental). By 1970s, Schwinn had become the dominant manufacturer of derailleur-equipped bicycles, accounting for 80% of U.S. production.

For decades Schwinn had been the standard-bearer in quality with little domestic competition, and it had told its dealers that the company could supply all their needs, from parts to finished product. However, Schwinn could not keep up with the over demand and satisfy its dealer and started to import bicycles from Japan. In the mid-1970s, Schwinn created the multi-speed mountain bike. The bike incorporated newer components from around the world: and English saddle, Japanese gears, French and German hubs, for instance. This revolutionary product changed the basic product architecture of bicycles in terms of standardization of component interfaces that

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[17] The information about the Schwinn Company is extracted from Crown and Coleman (1996).

changed the competitive landscape of the bicycle industry, and eventually led the industry to disaggregate into a horizontal structure.

4.3. Industry disaggregation, 1980s

In the 1980s, the bicycle industry witnessed another transformation by the introduction of mass-produced mountain bikes. Autonomous innovation was taking place with no particular company controlling the product architecture of mountain bikes, which led bike producers to focus on improving suspension with the front and back forks technology borrowed from motorcycles. For example, Grip Shift, developed by SRAM, is a mechanism that allows bicyclists to shift gears by rotating a dial on their handle bars rather than pushing tow levers up or down (Fine, 1998). Other developments include aluminum frames and titanium frames (Griffith, 1994). In 1995 approximately 50% of mass merchant level sales of bicycles were mountain bikes, accounting for approximately 10 million of the industry's 12 to 15 million annual unit sales overall in U.S. (McEvoy, 1995).

Under the disaggregated industry structure, firms tend to turn to their functional strengths to gain competitive advantage. The National Bicycle Industrial Co Ltd. (NBI) of Japan, for instance, has focused on its manufacturing competence to create customization for its customers. In 1987, NBI implemented an agile manufacturing system (that is based on just-in-time inventory, computer-aided design and manufacturing and robotic processing concepts) to produce personalized bicycles. Over 11 million combinations are available with production time ranging from eight to ten days, and some 50 to 60 semi-custom bikes are turned out daily (Bell, 1993)[18].

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[18] This type of manufacturing strategy is referred to as *mass customization* (Kotha, 1985).

4.4. Industry concentration, 1990s

Although Schwinn filed for chapter eleven in 1992, bicycle industry was disaggregating into a horizontal structure that started during the early 1980s with the introduction of mountain bikes in the U.S., and Shimano became the new market leader. In 1993, over 86% of bicycles in U.S. (listed in the *Bicycling* magazine Super Specs database) came with Shimano components. Moreover, of the 536 mountain bikes in the database, about 95% had Shimano components (Fine, 1998).

Like Schwinn, Shimano also took component innovations seriously as a means to compete in the modular product architecture market of bicycles. For instance, index gears was developed by Shimano and had a profound impact on mountain bike sales (Wilson and Hirst, 1994). Furthermore, not only new components were developed, in order to keep its market leadership, Shimano integrated different components into groupsets to improve performance and quality of the bikes, and to control compatibility among components as a means to make retailers lock in to Shimano's system. For instance, STI (a dual control lever) is a system where the gear shifting lever is integrated into the brake lever, was introduced in 1990 and has attracted a great deal of interest among professional cyclists (Wilson and Hirst, 1994). Champanolo, the Italian producer, on the other hand, designs its components with standard gauges and sizes so that the customer is not dependent upon it for replacement parts (Wilson and Hirst, 1994).

Today the bicycle industry is concentrated around Shimano components accounting for nearly 47% of the bicycles world wide. In 2000, about 70% of Shimano's revenue are contributed from bicycle components business (Worldscope Database). During the early 1990s, 84.5% of Shimano sales came from bicycle components (Wilson and

Hirst, 1994). How long can the bicycle industry remain in its current concentrated structure? There are signs indicating that the industry may face new changes. Some bicycle industry analysts predict that, manufacturers that can not compete on low prices or that can not differentiate their bikes from others equipped with Shimano parts will be forced out of the market, or forced to consolidate (Kerber, 1998). Moreover, Shimano is facing competitive pressure from Taiwanese assemblers.

5. Conclusion and discussions

This paper attempted to describe network dynamics through the lenses of modular product architectures. It was argued that even well established industries with stable product architectures, the control of component interface specifications creates momentum for industries to concentrate into vertical structure or to disaggregate into horizontal structure. The extent of network concentration (when the industrial network is driven by product architecture that is controlled by core firms) or disaggregation (when the industrial network is driven by product architecture that is controlled by the market) of an industry is, in part, led by the degree to which the standardized interfaces of components within modular product architectures are accepted as industry standards.

Different types of network dynamics emerge as ways of coping with the dynamics of industry demands as well as creating strategic flexibility for firms operating within the networks. In order to distinguish between different types of mechanisms in which networks operating with modular product architectures may evolve, two types of networks were introduced: 'market-driven product architecture network' and 'firm-driven product architecture network'. In market-driven product architecture network, the goal is to create strategic flexibility for firms and to manage uncertainty. Firms operating within the network have loose control of the product architecture. Component specifications are widely published, and no single firm has the power to change the product architecture. As a result, technological development tends to be incremental, fostering autonomous innovations. Much of the innovation activities are coordinated via the market place where independent firms come together to buy and sell the technology and components that are used to ensure proper functionality and performance of the product architecture. It was argued that modularity through system decomposition with standardization of interfaces generates momentum for industries to disaggregate into autonomous, specialized units. The decomposition of technological systems into more manageable portions allows for division of labor and task specialization to take place.

Firms, in general, seek to earn profits and wish to gain market share. Firms that wish to control the market in some way often resist the momentum created by 'market-driven product architecture network'. This takes place when a product architecture become so modular that it is not sufficient for one single firm to produce the system. When interface standards of modular product architecture is altered in new ways, often through the integration of components into a new component, it limits the compatibility of components with other systems. The firm with the technological control of the new component eventually become the core firm of the industry with certain amount of control over the technological development of the product architecture. The firms operating under this type of network is referred in this paper as the 'firm-driven product architecture network'.

As an example of how industries may go through cycles of concentration and disaggregation based on modular product architectures, a history the technological development of the bicycle is illustrated. As the 125-year history of development of bicycle reveals that the industry has gone through two cycles of concentration-disaggregation. During the disaggregation era, the industry resembled that of ‘market-driven product architecture network’. However, during the concentration era, core firms had some control of the product architecture, by Schwinn Company (during 1900s – 1970s) and Shimano (during 1990s). As bicycle industry is one of the oldest industries, can we apply the same logic to analyze newer industries that also compete based on modular product architectures, whether the product architecture in early 2000 is ‘firm-driven’ (e.g., automobiles, mobile phones, personal computers, etc.) or ‘market-driven’ (e.g., open source software systems, e-commerce)?

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Worldscope Database (2002).

Appendix A

Chronology of bicycle development

	Technological and Process Advancements	Industry and Market Landscape
1800s	• Velociferes or celeripedes had the bodies of either horses or lions – steered by feet	
About 1817	• Draisienne – no animal heads, lighter wheels and framework, front wheel pivoting on the frame so it could steer around corners	
About 1819	• Johnson's hobby horse – lighter, usage of bigger wheels, 50 lbs	
About 1832	• Drais improved velocipede – systematic application of power, inspired from the principle of the steam engine	
1860s	• Two-wheeled 'boneshaker' velocipede: cranks and pedals directly attached to the hub of the front wheel, wooden spokes, metal rims • Intensive activity in technology (e.g., machine with two speeds and freewheel) • Macmillan's velocipede – the 'earliest bicycle': backwards-and-forwards movement of the legs into a circular motion in the wheel, variable gear, pedals close to the front wheel • 'Bicycle' (two-wheeled velocipede): ball-bearings fitted to the front wheel • Do-it-yourself plans for component parts from blacksmiths, coach-builders and wheelwrights	• Emergence of 'technical' worker • Common pool of ideas, but no agreement on the fundamentals of the bicycle • A rush of inventions to improve the velocipede • Inventor specialized in making the velocipedes alone, and marketed and sold them himself • Mechanization of the industry • Mass production methods developing • Patent of the first American bicycle in 1866 • Cycling races • Bicycle clubs • There were at least 40 velocipede makers in England by the end of 1869

	Technological and Process Advancements	Industry and Market Landscape
1870s	• Larger front wheel, smaller back wheel, wooden wheels • Ordinary or 'high' bicycle: saddles as close as to the upright forks • 'Ariel' the first English Ordinary: novel system for tensioning a metal-spoked wheel, back wheel brake, rubber tires, 50 lbs • 'Tangent' system: wheel held rigid by the spokes that were tensioned in four different directions • 'Balance gear' or 'Double-driving gear' or later as 'differential': innovation mainly from tricycles, breaking the main driving axle with a system of bevel wheels and pinions, driven by a chain from a chain-wheel connected to the end of the cranks (a continuous chain) • 'Bicyclette' (patented in 1879): big front wheel, small back wheel, chain-wheel and continuous chain-drive	• Specialist and professional bicycle manufacturers, disappearance of amateurs • Bicycle Union formed in 1878 in London • Two-wheel bicycle accepted almost universally as the most efficient system • 'Ariel' set new standard in bicycle manufacture - first all-metal English bicycle to be mass produced • In 1874 there were about 20 firms making bicycles in England • In 1878 there were more than 68 makers in England
1880s	• Between 1886 and 1887 the large front-wheeled direct-steer became the standard • The Ordinary bicycle was dominant until about 1885 • Rear-driven 'safety' bicycle • Rover 'safety' (1886): Disappearance of 'dwarf' rear drivers, driven by chain to the back wheel • Pneumatic tires replaced the solid tires	• Application of mass production assembly line • Tricycle union founded in 1882 • Rivalry between different types of 'safety' bicycles
1890s	• The establishment of dominant design • Ergonomic design improvements • Design process became separate from production made possible by standardization	• The bicycle was used on a mass scale • Bicycles mass produced on assembly lines • In 1898, there were 607 bicycle producers in US

	Technological and Process Advancements	**Industry and Market Landscape**
	• Fixed wheel, slightly drooped bars, leather saddle, optional plunger brake, pneumatic tires, and encased chain	• ***Horizontal industry structure***
Early 1900s	• Freewheel, cable-operated brakes, two- and three-speed hub gears, aluminum alloys • *Derailleur* system: chain is shifted between rear sprockets of different sizes using levers, cables and springs • Standardization of components – for three decades, the US Tubber Company sold essentially one type of single-tube tire to American bike manufacturers • In 1935 the wide-cord tires with double tubes became the American industry standard • Cantilever frame (future standard)	• In 1905 there were 12 bicycle companies in US, mainly assemblers • Consolidation of parts markers • Low cost strategy • Bicycles sold through chains stores (e.g, Montgomery Ward, Sears)
Mid-1900s	• Innovative bicycle designs from Schwinn: the banana seat, Sting-Ray, Varsity, Continental • “High-Rise” bikes	• In US the use of bicycle slumped due to increased demand for automobile • ***Vertical industry structure*** (due to Schwinn) • In 1950, Schwinn had 25.5% market share • Some 15,000 outlets selling Schwinn bikes
1970s	• Creation o mountain bikes by Schwinn	• Schwinn the dominant player • US production of 6.9 million (in 1970) to 15.2 million bicycles (in 1973) • About 80% of derailleur-equipped bicycles in the US was manufactured by Schwinn

	Technological and Process Advancements	**Industry and Market Landscape**
1980s	• Improvement of suspension with the front and back forks technology of mountain bikes • Improvements in aerodynamics • Index gears by Shimano • Grip Shift by SRAM	• ***Horizontal industry structure*** during early 1980s • Sales surge of mountain bikes
1990s		• Schwinn filed for Chapter 11 bankruptcy protection on August 16, 1992 • ***Vertical industry structure*** (due to Shimano) • Nearly 47% of bicycles sold in the world has Shimano parts

Sources: McEvoy (1995), Fine (1998), Galvin and Morkel (2001), Ritchie (1975), Frazier (2000), Griffith (1994), Dowell and Swaminathan (2000), Pinch and Bijker (1987), Whitt and Wilson (1983), Crown and Coleman (1996), Wilson and Hirst (1994), Smith (1972)

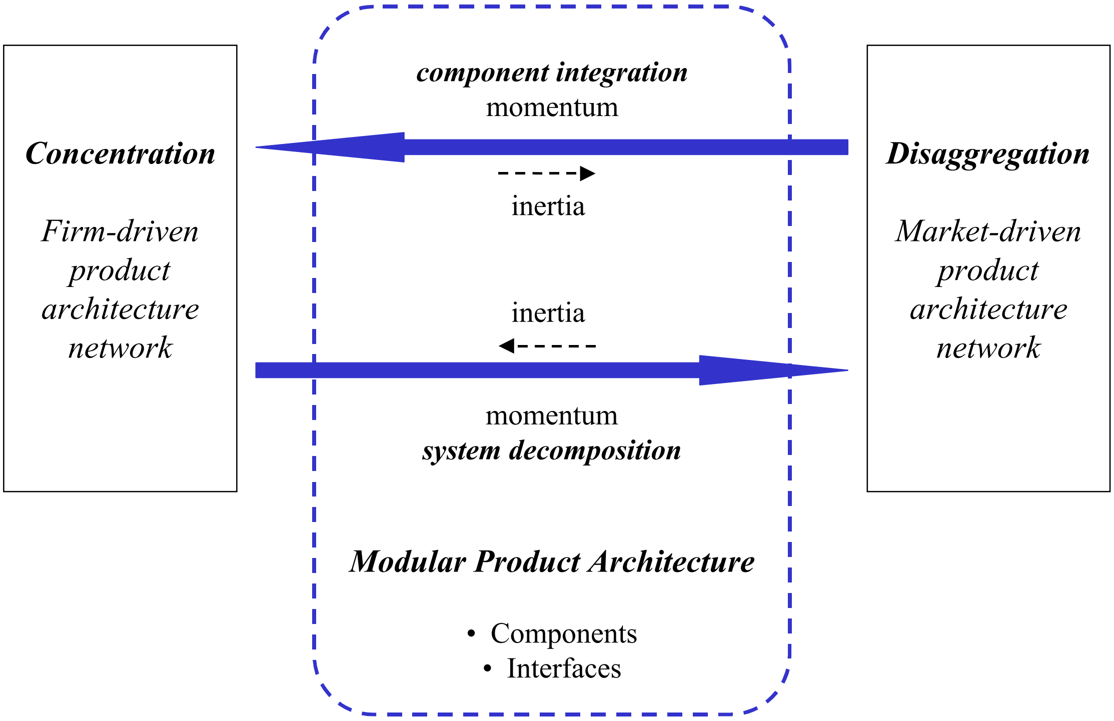

Figure 1. Modularity and Industry Dynamics.