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The Power of Integrality: Linkages between Product Architecture, Innovation, and Industry Structure

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## **The Power of Integrality: Linkages between Product Architecture, Innovation, and Industry Structure**

### *Abstract*

A substantial literature stream suggests that many products are becoming more modular over time, and that this development is often associated with a change in industry structure towards higher degrees of specialization. These developments can have strong implications for an industry's competition as the history of the PC industry illustrates. To add to our understanding of the linkages between product architecture, innovation, and industry structure we develop detailed product architecture measurements based on a previously proposed method (Fixson, 2005) and study an unusual case in which a firm – through *decreasing* its product modularity – turned its formerly competitive industry into a near-monopoly. Using this case study we explore how existing theories on modularity explain the observed phenomenon, and show that most consider technological change in rather long-term dimensions, and tend to focus on efficiency-related arguments to explain the resulting forces on competition. We add three critical aspects to the theory that connects technological change and industry dynamics. First, we suggest *integrating* as a new design operator to explain product architecture genesis. Second, we argue that a finer-grained analysis of the product architecture shows the existence of multiple linkages between product architecture and industry structure, and that these different linkages help explain the observed intra-industry heterogeneity across firms. Third, we propose that the firm boundary choice can also be a pre-condition of the *origin* of architectural innovation, not only an outcome of efficiency considerations.

### *Keywords*

Product Architecture, Integrality, Modularity, Technological Change, Intra-industry Heterogeneity, Industry Structure, Competition, Strategy

## 1 INTRODUCTION

Technological change has a rich history in several literature streams. Disciplines ranging from economics, sociology, and technology history (Sahal, 1981; Nelson and Winter, 1982; Rosenberg, 1982; Bijker, 1995) to technology management and strategic management (Anderson and Tushman, 1990; Henderson and Clark, 1990; Utterback, 1994; Macher and Mowery, 2004) have investigated the intricate interconnections between technological innovations and industry evolution. Research in the former stream tends to view such cause-effect relationships in longer time frames and on the industry level, while research in the latter stream focuses on shorter time frames and individual firms. Both have explored a variety of technology characteristics and their effects on competition.

More recently, one aspect of technology that has generated interest is the role that the product structure plays in the competitive positions of firms in an industry, hence in industry structure (Baldwin and Clark, 2000). Product structures, also often labeled product architectures, have been conceptually categorized into two archetypes: integral and modular (Ulrich, 1995; Baldwin and Clark, 2000; Schilling, 2000). The classic illustration for a product with a modular product architecture is the personal computer; other examples include software, some recent textbooks, and sectional sofas. A substantial literature body suggests that many products are becoming more modular over time, and that this development is often associated with a change in industry structure towards higher degrees of specialization (Sanchez and Mahoney, 1996; Langlois, 2002; Jacobides, 2005).

While some research exists that includes the possibility of reversal of the process of modularization towards higher levels of integrality (Fine, 1998; Schilling, 2000; Christensen *et al.*, 2002), the majority of empirical work supports the notion of a product architecture evolution from integral to modular product architectures. For example, computers have been identified as

initially having had a rather integral architecture that later evolved towards significantly higher degrees of modularity (Baldwin and Clark, 2000). Similarly, internet browser software (MacCormack et al., 2006), numerical controllers (Shibata et al., 2005), and college textbooks (Schilling, 2000) have been found to migrate towards higher levels of modularity, and only temporarily, if at all, to revert back to more integral structures in case of external technology shocks. For example, Shibata *et al.* (2005) find that the introduction of the microprocessor unit (MCU) in numerical controls in 1969 resulted in a more integral architecture for only a few years. Once the shock caused by this new technology was absorbed, the modularization process continued.

The prevalent notion of the sequence of events is the following. Early in an industry's life, the initial (engineering) design choices set the ground rules for which 'transfers' can become 'transactions' by making them standardized, countable, and evaluable (Baldwin and Clark, 2008), and in consequence, cause the emergence of interaction patterns across an entire industry. Jacobides *et al.* (2006) call the resulting industry structure the industry architecture. Once this industry structure has emerged, it imposes substantial constraints on industry participants with respect to both firm boundary location choices and product design choices. At the same time, increasing knowledge and technology advancements enable the codification of increasing number of exchanges across interfaces, thus causing further product modularization and firm specialization. In these later stages it becomes very difficult for individual firms to break out of the established industry architecture via changes in the overall product architecture.

Given this fairly broadly shared understanding of (i) mostly increasing modularity, and (ii) an increase in modularity causing increasing vertical specialization in the associated industry, we were intrigued by a case that appeared not to fit that pattern. This case is the bicycle drivetrain component industry during the 1980s. The bicycle drivetrain component industry supplies six

components to the bicycle assemblers: shifters, derailleurs, freewheels, chains, hubs, and brake shifters; each bicycle has one of each. In the early 1980s, the industry was fairly competitive and included both small and large firms. In total, well over 50 firms were active in the industry, and over half of those developed and manufactured only three or fewer of the six components, i.e., many of them were fairly specialized. At the same time, two firms produced all six components and a third firm made four components and had strategic partnerships for the remaining ones. The individual market shares of these latter three firms ranged from 8% to 30% in the individual component market segments (top panel in Figure 1). Across the entire industry *all components were interchangeable both within and across firms*, i.e., a derailleur from one firm was as compatible with a chain from one of its competitors as it was with a chain from its production.

By 1990, the industry structure had drastically changed. The total bicycle market had split into two major categories, one for road bicycles (RB) and one for mountain bicycles (MTB); together those categories accounted for almost 90% of the total market (Table 1). Shimano had become by far the dominating firm for bicycle drivetrain components in both categories, with slightly less than 60% market share in the RB category, and almost 80% market share in the MTB category, in both categories evenly across all six component segments. The rest of the market was occupied by two other firms, Suntour and Campagnolo, and some minor niche firms (bottom two panels in Figure 1). Each of the three major firms offered integrated component sets, i.e., their components were no longer compatible across firms. In fact, they were often incompatible across product lines within the firms.

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Insert Figure 1 about here

Insert Table 1 about here

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Thus between 1980 and 1990, the industry migrated not towards higher levels of disintegration but towards a much higher level of integration – both within and across the individual component segments. In the middle of the decade, one firm had introduced a new product design with an integral architecture including non-compatible components. This firm, Shimano, came to dominate the industry by the end of the decade.

Since anomalies offer particularly valuable opportunities to advance theory building (Eisenhardt, 1989; Carlile and Christensen, 2005) we use this relatively unusual case of decreasing product modularity that is linked to substantial changes in industry structure to explore the linkages between product architecture, innovation, and industry structure in more detail. Specifically, we re-construct in detail the history of both the product architecture and industry structure to establish a time sequence of change events. The sequence of events allows us to rule out the hypothesis that industry structure change brought about the change in product architecture. To establish the credibility of causality in the reverse direction (product architecture change caused industry structure change) requires us also controlling for alternative explanations of the observed events. To do so we collect data on additional variables such as advertising and pricing.

With this paper we attempt to contribute to the answers of two interrelated questions. First, why did the product architecture shift towards higher level of integrality instead of remaining modular? Second, if there is a change towards higher degrees of product architecture integrality, how do these changes affect the structure of an industry? More specifically, what are the causal mechanisms at work here, what is the sequence in which they operate, and what was the start of this chain of effects? Together, the answers to these questions will contribute to a better understanding of the factors that determine firms' strategies with respect to product architecture change, and more broadly to the role of technological change in industry evolution.

In the next section we create a framework for our overall research design and develop detailed measures for both product architecture and industry structure. The product architecture measurement we develop is a refinement of a previously suggested method for product architecture assessment (Fixson, 2005). Using these measures we present the detailed case data in section three. In section four, we apply the framework to explore how the extant literature would explain the observed events and what gaps exist in the explanation. In section five we focus on the gaps in the literature and suggest theory to address them. Section six concludes.

## **2 RESEARCH DESIGN**

Studying the cause-effect relationships between changes in product architecture and changes in industry structure demands a detailed understanding of the change processes themselves that occur within the technical domain and the industry domain. This, in turn, requires a longitudinal research design (Poole et al., 2000). Following Pettigrew's advice that "... theoretically sound and practically useful research on change should explore the contexts, content, and process of change together with their interconnections through time" (Pettigrew, 1990:269) we create a research framework that can discern between the numerous cause-effect relationships over time and develop detailed measures for both domains.

### **2.1 Research Framework**

Our research framework fundamentally establishes two separate domains: the product architecture and the industry structure (Figure 2). In the product architecture domain, any product architecture at any given point in time can be represented by its location somewhere on the spectrum between modular and integral product architectures. A change in product architecture, then, is represented by a shift of this location; for example, from being rather integral ( $PA_2$ ) to rather modular ( $PA_1$ ). Similarly, in the industry structure domain an industry's

structure can be represented by the location on the spectrum between integrated and disintegrated industry structures. A industry's change from one structure to another, then, can be illustrated by a shift of location; for example, from integrated ( $IS_2$ ) to disintegrated ( $IS_1$ ). Next, to search for possible cause-effect relationships between a change in one domain and a change in the other domain, the research framework lists four possible effects – (a) through (d) in Figure 2 – that are separated by directionality and order of change sequences. Finally, to control for effects that originate outside of either domain but potentially cause shifts in either product architecture or industry structure, the framework lists two external causes for each domain – (e) and (f) for product architecture changes, and (g) and (h) for industry structure changes.

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Insert Figure 2 about here  
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## **2.2 Data Sources, Time Period, Sampling Frame and Frequency**

The bicycle market in the U.S. witnessed substantial changes with regards to product offerings between 1980 and 1990. In the early 1980s, road bicycles (RB) were the only type of bicycle that was available. This picture changed with the advent of the mountain bicycles (MTB) in the mid-1980s. Throughout the 1980s the fraction of RBs offered decreased from 100% in 1980 to 44.1% in 1990 while the MTB market share rose over the same period from 0% to 45.2%. All through the decade these two categories represented more than 90% of the U.S. bicycle market (Table 1). Consequently, we focus our analysis on the bicycle component firms that supply drivetrain components for these two categories of bicycles.

To construct the historical accounts of the bicycle drivetrain industry and product architecture we collected both quantitative and qualitative data. For the purpose of triangulation of our data we used a variety of data sources. We collected archival data from magazines, data bases, books, news articles, and academic journals. In particular, we scanned a decade of all issues of the magazine *Bicycling*, which was the leading trade journal in the U.S. during the 1980s. In addition, starting in 1984, *Bicycling* published the *Super Spec Database (SSD)*, an annual listing of all new bicycle models introduced at price points over \$150, including the information on the suppliers of each component. Four additional sources were particularly helpful in understanding bicycle drivetrain technology and the technical changes that occurred during the 1980s. These were the *Proceedings of the International Cycling History Conference*, and the books *Bicycling Science* by David Wilson (2004), *The Dancing Chain: History and Development of the Derailleur Bicycle* by Frank Berto (2005), and *Sutherland's Handbook for Bicycle Mechanics* (1996). To verify our archival findings, we also collected data through face-to-face interviews and via e-mail. We checked data with company representatives, industry observers, technical journalists, and editors of bicycling-related magazines, and we learned details on component compatibility from bicycle mechanics with years of experience in the bicycle repair business.

As the time period of our analysis we decided on the decade from 1980 to 1990, with the major product architecture change occurring in the middle of our observation period. The time period also covers drastic changes in industry structure and composition. In general, multiple architectures may exist at the same time in an industry. To account for this possibility, we measure two product architectures at each point in time. One is Shimano's most advanced architecture; the second is representative for the rest of the industry. By representative we mean the typical product architecture, i.e., the most common product architecture (mode), excluding

Shimano's. The actual detailed assessment of the product architecture we conducted in years in which we observed a product architecture change from either Shimano or the rest of the industry. This approach leads to four data sets across the decade:  $t_1=1980$ ,  $t_0=1985$ ,  $t_1=1988$ , and  $t_2=1990$ .

## 2.3 Measures

To develop appropriate measures for product architecture and industry structure we build on existing work, and extend it to produce finer grained measures for our empirical study.

### 2.3.1 *Product Architecture*

Architectures have been identified as a key element for design, operation, and behavior of complex engineering systems (Crawley et al., 2004). We focus here on one type of technical system: assembled hardware products. For such products, Ulrich suggests that the product architecture is “the scheme by which the function of a product is allocated to physical components” (Ulrich, 1995:419). This scheme includes (i) the arrangement of functional elements, (ii) the mapping from functional elements to physical components, and (iii) the specification of the interfaces. Conceptually, product architectures are often categorized into one of two archetypes: modular or integral. While conceptually very powerful, the operationalization of these archetypes has proven to be quite difficult, and various approaches have been chosen to overcome this difficulty (Fixson, 2007). For example, some scholars use indirect measures, i.e., they assess the degree of product modularity indirectly by asking managers to estimate the degree to which certain consequences that are often associated with modularity – for example, the degree to which a buyer can customize a product, or the degree to which a manufacturing process allows late configuration – are more or less true for their own products (Duray *et al.*, 2000; Worren *et al.*, 2002; Tu *et al.*, 2004). Others, particularly in the engineering literature, have developed numerous approaches to measure product architecture characteristics such as modularity, commonality, and platforms directly on the product (Nelson *et al.*, 2001; Fujita and

Yoshida, 2004; Simpson and D'Souza, 2004). The majority of these latter approaches takes a product architecture in its overall structure as a given, and then searches for the optimal solution in the configuration space.

Most real products lie somewhere between the extremes of modular or integral (Ulrich, 1995; Schilling, 2000). What matters then are the relative differences, either between products or between product generations over time. In theoretical explorations of modularity, researchers have emphasized a system's ability to separate and recombine its elements without much loss of functionality (Sanchez and Mahoney, 1996; Schilling, 2000). Separation requires the concentration of some functionality in certain components, and recombination requires certain interface characteristics. To account for these two major dimensions – *function-component allocation* and *interfaces* – we employ a product architecture assessment methodology that measures product architectures independently along these two dimensions (Fixson, 2005). This method builds on Ulrich's earlier description but relaxes Ulrich's definition of product architecture in three important ways.

First, it allows the two dimensions *function-component allocation* and *interfaces* to vary independently from each other. While changes in two or more product architecture characteristics can occur simultaneously, they do not have to. For example, two product architectures could exhibit identical function-component allocation schemes, but differ in the degree to which their interfaces are standardized. As an example, think of the different electric plug and outlet combinations in different countries. In all countries the function allocation between the energy transmitting element, the wires in the wall, and the energy consuming element, say a lamp, are identical. The interfaces, however, i.e., the shape of the plugs and sockets are often country specific.

Second, the assessment method defines the dimension *interfaces* as composed of three separate sub-characteristics: *interface strength*, *interface irreversibility*, and *interface standardization*.<sup>1</sup> Interface strength describes the interface's technical nature (transfer of mechanical forces, materials, signals, etc.) and includes a measure of intensity. Interface irreversibility measures the effort required to disconnect the interface, an aspect important if the product is expected to vary over its own lifetime. Interface standardization we use as synonymous to compatible, i.e., it is a measure that describes the degree to which neighboring components that are manufactured by the same or another firm are compatible with components of the product architecture under investigation.

Finally, the third relaxation of Ulrich's definition guarantees an assessment of the degree of modularity per individual function, instead of creating an average modularity assessment for the entire product or system. The underlying rationale for this approach is that products can be modular with respect to some functions but much more integral with respect to other functions at the same time. For example, the tires of an automobile can be considered highly modular whereas the body structure typically is not. The automobile's product architecture then comprises simultaneously modular and integral aspects.

To illustrate this assessment method we apply it below to the bicycle drivetrain component set that includes shifter, derailleur, freewheel, chain, and hub, plus brake levers at the beginning of our analysis period ( $t_1 = 1980$ ). To measure the function-component allocation we construct a matrix containing the relevant functions ('power transmission' and 'gear shifting,' plus 'brake actuation' for control purposes) in its first column, and all components in the first row.<sup>2</sup> If a

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<sup>1</sup> The interface characteristics *strength* and *irreversibility* were re-labeled from originally *type* and *reversibility*, respectively.

<sup>2</sup> The rationale for the choice of the level of analysis for both functions and components should be meaningful for the analysis goal at hand (Fixson, 2005). Equally important, it should be explicit and stable over time.

component contributes to a function, then the corresponding cell is marked with a '1.' With help of this matrix we then calculate two indices: the component count index simply counts the number of components that contribute to a function, and the entanglement index counts the total number of functions these components are contributing to. Together, these two indices measure the degree to which (and how) a particular function-component allocation deviates from the modular 'ideal' of a one-to-one function-component allocation. Table 2 shows the function-component allocation assessment matrix for Shimano's product architecture in 1980.

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Insert Table 2 about here  
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To measure the interface characteristics *strength* and *irreversibility* we construct a matrix that lists all components in its first column and its first row. Above the diagonal we describe the interface strength by assessing each interface on a scale from -2 to +2 for each of the four categories mechanical, material, energy, and signal (Pimmler and Eppinger, 1994). Below the diagonal, we assess the degree of interface irreversibility by separately estimating the effort required to disconnect the interface and the interface's position in the overall product architecture, i.e., how many other components have to be removed before the interface in question can be disconnected. Figure 3 shows the assessments for Shimano's product architecture in 1980. There are four interfaces in this drivetrain system (out of a possible fifteen): one interface connects the shifter to the derailleur, the derailleur interacts with the chain, the chain with the sprockets of the freewheel, and the freewheel with the hub. To aggregate these

measures to the function level, we sum the assessments for all interfaces of the components involved in each function.<sup>3</sup> The higher the sum, the less modular is the function.

To measure the interface characteristic *standardization* we define an interface as the interaction between two components. For each of the two components the number of alternatives can vary. More specifically, if both components participating in an interface are unique – for either technical, legal, or economic reason – we assign a low degree of standardization to the interface (a measure of 1,1 in the lower left of Figure 4). Other the other hand, if for both components of an interface multiple alternatives exist across the industry we assign a high degree of standardization (a measure of 3,3 in the upper right in Figure 4). As mentioned in the introduction, due to the existing de-facto standardization in the early 1980s, all interfaces in our study fall into the high-standardization category, see for example the derailleur-chain interface.<sup>4</sup> In sum, we view the universe of possible degrees of standardization as determined by the size of the population of alternatives that exists on either side of the interface.<sup>5</sup> To aggregate the measurement to a function level we simply take the average of the interfaces of the components participating in the function.

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<sup>3</sup> This approach implicitly assumes equal weight for each of the four categories of *interface strength*. For the purpose of observing change over time within a given technology this approach is justified.

<sup>4</sup> To assess the degree of standardization we determined two aspects of the component-component pair that constitutes the interface: (i) the technical compatibility between the components, and (ii) the population size of alternatives for one, or both, of the components. Technical compatibility in our framework is a binary decision with ‘no’ cases only present in the lower left corner of Figure 4, whereas all other cases represent a ‘yes.’ To make that binary decision of component compatibility we used two different data sources: We screened all issues of *Bicycling Magazine* from 1980 to 1990 to learn about compatibility issues with newly introduced products, and we studied the compatibility of components relevant to our study with help of Sutherland’s Handbook for Bicycle Mechanics (6th edition), which is a technical report for bicycle mechanics. The handbook details on 450 pages the interchangeability between individual components. For the cases in which technical component compatibility was determined, we categorized the population size into three categories with help of model market share data from the *Superspec Database*. This approach allowed us to place every interface into one of the nine categories of Figure 4.

<sup>5</sup> The concept of *interface standardization* as applied here is based on Fixson (2005). More recently, Jacobides *et al.* (2006) follow a similar line of thought in their separation of complementary and mobility of assets. Their definition of complementary of assets is similar to our view on compatibility of components. Their concept of asset mobility is similar to our idea of population size of components, both describe the number of alternatives.

Table 3 summarizes the complete product architecture assessment results. The numerical assessments can be interpreted against the extreme points of the underlying scales. Both component count index and entanglement index are one-sided anchored ('1' is the minimum, representing 'perfect' modularity). Given that the maximum values are driven by product complexity, the values in Table 3 show relatively low numbers, albeit on different levels for different functions. The values for *interface strength* and *interface irreversibility*, i.e., '6' and '5', respectively, can be considered medium when compared to the possible extreme value of '16.' Finally, the standardization assessment (3,3) for both relevant functions is high within the framework developed in Figure 4.

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Insert Figure 3 about here  
Insert Figure 4 about here  
Insert Table 3 about here  
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Note that while some aspects of our view of product architecture overlap with what has been discussed in the literature as dominant designs (Abernathy and Utterback, 1978; Utterback, 1994; Tushman and Murmann, 1998), some important differences remain. Much of the dominant design literature attempts to assign a design's dominance to a combination of some technical and market measures, whereas we simply use our framework to describe technical product architecture changes over time.<sup>6</sup> In general, our assessment method, while shedding light on

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<sup>6</sup> For example, a similarity between a recent proposed framework for the study of dominant designs and our product architecture assessment method is how a product's functionality is provided by the components. Murmann and Frenken (2006) suggest to understand products and systems as complex hierarchical systems, determined by their physical hierarchy and their operating principle. Their approach to represent "an architecture [...] by a matrix

product architectures, cannot be used to identify dominant designs as the latter encompasses additional conceptual dimensions.<sup>7</sup>

### 2.3.2 *Industry Structure*

As noted, a bicycle drivetrain consists of six complementary components – shifters, derailleurs, freewheels, chains, hubs, and brake shifters. These components define the boundaries of the industry. Following Grove (1996) and Fransman (2002) the industry can be represented as a set of layers, one for each component. We construct two proxy measures to determine changes in the competitive dynamics within and across these layers. As our first measure we use a modified Herfindahl-Index to measure industry concentration within each of the six layers (one for each component). The Herfindahl index is defined as the sum of all firms' market shares squared. The index can take on values between 0 and 10,000. The more competitors are in a market and the more evenly distributed their market shares are, the lower the Herfindahl index. Since direct market share data was unavailable we constructed a proxy to measure industry concentration as follows: We counted all bicycle models offered in any given year. Next, we counted the number of bicycle models for which an individual firm supplied its

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specifying the relations between technical characteristics (the components) and service characteristics (product attributes)” (Murmann and Frenken, 2006:941) is very similar to our mapping of one of the two product architecture dimensions: the function-component allocation scheme. Nevertheless, Murmann and Frenken use their matrix to search for components with high pleiotropy (a component exhibits high pleiotropy if it affects many functions) as they identify those as the defining elements for dominant designs. In contrast, we use our product architecture assessment strictly to describe product architecture changes over time, and we do not claim it to identify dominant designs per se. In addition, Murmann and Frenken's approach of dominant design definition differs also from our approach of product architecture assessment in that they permit interfaces to constitute components, because their focus is on high-pleiotropy elements, and these elements can be either true components or interfaces, whereas we strictly distinguish components and interfaces in our analysis.

<sup>7</sup> For example, for some scholars a dominant design is determined through socio-cognitive sense-making processes between market participants (Rosa *et al.*, 1999). Seen from this perspective, a product design can become (or recede to be) a dominant design without actual changes in its technical parameters.

components. We define the fraction of models for which a firm supplies its components as our proxy for market share within its segment.<sup>8</sup>

Our second measure assesses concentration across the segments; we call it the integration distribution. It consists of six market share indices and is defined as follows. Each bicycle model has one of each of the six components. If all six components are supplied by one firm, we label this model a ‘type 1’ bicycle. If two firms share the supply of the six components, the model is a ‘type 2’ bicycle, and so on. At the other end of the spectrum, if six different firms supply one component each, we classify the model as a ‘type 6’ bicycle. The market share index of each type can vary between 0% and 100%. The set of the six indices, i.e., the integration distribution, reflects the concentration of firms across the component segments. It is most closely akin to the vertical integration measure in sequential supply chains. Similar to the product architecture measurements, we measure the two industry structure proxies at four points in our observation period ( $t_{-1}=1980$ ,  $t_0=1985$ ,  $t_1=1988$ , and  $t_2=1990$ ). In the appendix, we also provide layer maps of the industry, that show the market share for each of the three largest firms (and a fourth group labeled ‘others’) for every component segment in every year over our observation period.<sup>9</sup>

### **3 ANALYSIS: THE BICYCLE DRIVETRAIN COMPONENT INDUSTRY 1980-1990**

Table 4 summarizes our measurements of product architectures and industry structures. It presents in the top half the data from the product architecture domain and in the bottom half the

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<sup>8</sup> We are aware that this is not a true market share measure, neither in sold units nor in monetary value. However, given the large number of models in our Super Spec Database (SSD) and the dramatic changes our data show, we believe it is a useful approximation of changes in the competitive landscape in this industry. Furthermore, other researchers have used this data source in a similar way. For instance, Fine (1998:56ff), discussing Shimano’s market power, uses the SSD and states that “In *Bicycling* magazine’s Super Spec Database of over a thousand 1993 models, 86 percent of the bicycles came with Shimano components.”

<sup>9</sup> While our layer maps look similar to Grove’s (1996:40-44), ours are narrower in industry definition since they include exclusively technical components.

data from the industry structure domain. Within the product architecture portion the top row represents the product architecture of Shimano, the bottom row the rest-of-the-industry. Each architecture assessment comprises the two function-component allocation indices and three interface characteristics. Within the industry structure domain, the top portion shows the within layer concentration, the bottom portion the across layer concentration.

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Insert Table 4 about here  
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### **3.1 1980-1984**

In the early 1980s the standard bicycle drivetrain product architecture was almost perfectly modular. As discussed above we find that in 1980 the components related to ‘power transmission,’ ‘gear shifting,’ and ‘brake actuation’ showed a relatively low level of integrality with respect to their function-component allocation (low values in column  $t_1=1980$  for component count and entanglement indices in Table 4), and the interface assessment produces modest values for interface strength and irreversibility, and high values for interface standardization. Note that the product architecture assessments for Shimano and the rest of the industry produce identical results. In all, during this phase inter-firm component compatibility was very high, and most bicycles were sold with a mix of components from various firms.

The structure of the industry in the early 1980s was fairly heterogeneous and competitive within each segment as well as across the segments. In 1984, over 50 firms were supplying drivetrain components for road bicycles (RB) and over 25 for mountain bicycles (MTB). The RB drivetrain industry had three major contenders and many small companies: Shimano, SunTour, and Campagnolo were the leaders in most drivetrain component markets (layers), with SunTour being slightly ahead of the other two (for details see Appendix Fig A.1.0 and Fig

A.1.1)(Berto, 2005). Shimano and SunTour produced components in all six layers but their market shares varied across layers; between 12% and 20% for Shimano, and between 5% and 40% for SunTour. Campagnolo focused on shifters, derailleurs, and hubs, and purchased most of its freewheels and chains from component firms such as Regina or Maillard. Despite the leadership of these three firms, overall market concentration was relatively low, and varied substantially from layer to layer. The model-weighted Herfindahl indices for the RB market for this time period ranged from 1,000 (hubs) to 2,870 (derailleurs). Similarly, market share of integrated systems was very low. In 1984, only 5.6% of the new RBs introduced came with all six drivetrain components provided by a single supplier ('Type 1'). Over 50% of the new models had their six drivetrain components supplied by four, five, or six different firms

The MTB market was small in the early 1980s. In 1983, MTBs represented only 6.7 % of the U.S. bicycle market (Bicycling magazine), Aug 1983:54). The early assemblers of MTBs such as Breeze, Fisher, and Ritchey used an eclectic mixture of components – including some motorcycle parts – for their drivetrains (Berto, 1998; Bicycling magazine) Aug 1983:54-57). SunTour and Shimano realized that components suitable for mountain biking had to be more robust than conventional road racing-type components, and developed a line of products tailored to the needs of this emerging market. In particular, they redesigned gear shifters so that they could be comfortably positioned next to the thumb on the handlebars (Far Eastern Economic Review) Dec 14 1989: p103). In 1982, SunTour introduced its Component Ensemble (Berto, 1998), and Shimano launched its Deore drivetrain set which was designed for the use in mountain bicycles (Bicycling magazine) May 1982:88). Both Shimano and SunTour entered the MTB market earlier than other major component firms and led the MTB component development during this phase, with a slight advantage for SunTour (Berto, 2005).

### 3.2 1985-1987

Prior to 1985, most bicycles' gear-shifting systems required the rider to carefully adjust the shift lever when switching gears. That changed in 1985 when Shimano introduced its index-shifting technology (Shimano Index System: S.I.S.). With S.I.S., preset positions signaled gear engagement with a 'click' that the bicycle rider could hear and feel. With each click of the shifter the rear derailleur aligned the chain precisely with one of the evenly spaced sprockets on a freewheel or cassette (Bicycling magazine), Feb 1986:154).

To develop S.I.S. Shimano had to redesign four relevant components – shifter, derailleur, freewheel, and chain – and change the linkages between them. In the process, it made the product architecture of this set of components more integral. Table 4 makes the details of this architectural change visible. In the function-component allocation the component count and entanglement measures went up for both 'power transmission' and particularly 'gear shifting.' Of the interface characteristics, strength increased slightly due to somewhat higher precision requirements, and irreversibility did not change because the firms still used the same type of fastening technologies. But standardization declined dramatically because compatibility was eliminated between the components of the S.I.S. architecture and the components of the rest of the industry.

With the exception of the standardization measure, the changes only affected Shimano's product architecture. Note, however, that a move towards integrality by one firm, decreases the standardization measure of the industry because this measure indicates the size of the population of compatible components.

In 1985 the markets for bicycle drivetrain components were still fairly competitive. The within-segment concentration indices varied across segments between 1,150 and 2,700 for RBs,

and between 1,310 and 4,350 for MTBs. Only 13.4% of RBs and 7.0% of MTBs came with all six drivetrain components made by one supplier (column  $t_0=1985$  in Table 4).

Shimano introduced the new index shifting set first to its top RB line Dura-Ace in 1985, then to its moderately priced 600 group in 1986 (Bicycling magazine), Mar 1987:38), and last to its low priced 105 line in 1987. Once S.I.S. was added to all Shimano drive-train sets, none of the four components in its set was compatible with other components made by other firms. Responding to Shimano's success with its new index shifting architecture – from 1985 to 1986 the S.I.S. architecture's RB market share grew from 3% to 23% (Fig A.1.2 and A.1.3) – the main competitors SunTour, Campagnolo, and Sachs/Huret developed their own versions of index shifting. SunTour introduced its index system AccuShift in 1986 (Fig A.1.3), Campagnolo introduced its own version of an index shifting system, Syncro, to the market in 1987 (Fig. A.1.4), and Sachs/Huret also entered the index shifting market with its own solution, ARIS, at the end of 1987 (Fig. A.1.4). All these indexed shifting systems had become integral and required specialized components that were no longer compatible across firms. Over the next few years, all major firms phased out the production of most of their compatible components (represented by market share that falls outside of the solid-lined boxes in the graphs in the Appendix).

Note that the function-component allocation of Shimano's product architecture does not change from  $t_0=1985$  to  $t_1=1988$ , but it does for the rest of the industry. In fact, by 1988 the measurements for the rest of the industry approach those of Shimano. The same is true for the measurements of interface strength (minor change) and interface irreversibility (no change). An exception is again the measurement of the interface standardization as a consequence of the shift in market shares of the now incompatible product architectures.

Although initially introduced in the RB market, the index shifting systems changed the MTB market at a much faster rate. In addition, the MTB market itself grew substantially. By 1988, the fraction of bicycles that were MTBs had grown to 40%. Shimano and SunTour had been major players in the MTB market since the early 1980s, and both transferred their index shifting systems with their integral product architectures from RBs to MTBs starting in 1987 (Fig A.2.4). And throughout the second half of the 1980s Shimano and SunTour were in fierce competition with each other in this sector. However, even though both firms offered similar product lines, Shimano's market share leadership grew with every year. By 1988, Shimano held 77% of MTB market share with S.I.S. compared to 14% that SunTour held with Accushift.

In the second half of the 1980s the industry structure also began to change substantially. By 1988, the Herfindahl indices increased dramatically (in some cases doubled) to a range between 2,400 and 4,420 for RBs, and between 3,060 and 7,620 for MTBs. Similarly, the fraction of bicycles that were outfitted with components from a single firm became the mode, with 38.8% for RBs, and 46.8% for MTBs.

### **3.3 1988-1990**

In 1989, Shimano took its product architecture integration one step further. In the MTB market segment it introduced its HyperGlide (HG) freewheel, which allowed bike riders to change gears under load while pedaling, even when shifting from a smaller to a larger sprocket (Bicycling magazine), Sep 1988:8, Dec 1989:96). The HG freewheel had to be keyed to the hub, thus the components could only be assembled in one alignment (Berto, 2005:298). Thus, Shimano brought an additional component (the hub) into its already integral drive train system and, as a result, further reduced the components' compatibility with either Shimano's other components (that were soon phased out) or those of other firms. This effect can be seen in an increase in standardization for Shimano and a decrease of standardization for the rest of the

industry – due to shrinking population size of alternatives for their components. From 1988 to 1990 the assessment of the industry leader’s function-component allocation scheme increases further for the function gear shifting. With the exception of the interface standardization all other product architecture measures remained unaffected.

By 1990 the MTB market was larger than the RB market. Only three integral product architectures existed in the 1989 MTB market: S.I.S. plus HG, and S.I.S., both from Shimano, and AccuShift from SunTour (Fig. A.2.6). At this point, the direction of technology transfer had also reversed: Shimano offered its HG freewheel for road bicycles in 1990, and SunTour and Campagnolo followed by introducing their versions of HyperGlide to road bicycles.

The end of the decade is characterized by a stark industry consolidation and the market dominance of Shimano. While the pace of industry concentration within the layers slowed down and approached similar levels across the layers – the Herfindahl indices in 1990 ranged from 4,150 to 4,220 for RBs and from 6,380 to 6,790 for MTBs – the distribution of integration indices signals a strong concentration. In both RB and MTB markets over 90% of the bicycles are now equipped with all six drivetrain components made by a single firm (column  $t_2=1990$  in Table 4). This increase in industry concentration coincides with the emerging dominance of a single firm. Over the relatively short period of six years Shimano became the dominant firm in both RB and MTB drivetrain market sectors. In 1990, Shimano’s market shares in each of the six segments reached over 55% in the RB category, and almost 80% in the MTB category.

#### **4 HOW PRIOR THEORY EXPLAINS THE EVENTS**

To explore how existing theory would explain the observed events, we return to our research framework (Figure 2). Using the letter system in the framework, we will compare the events

with the predictions offered by existing theory. We separate the analysis below into two segments: change description and explanation of cause-effect relationships.

## **4.1 Descriptions of Product Architecture and Industry Structure Changes**

### *4.1.1 Product Architecture Changes*

The majority of the extant literature predicts a trend towards increasing levels of modularization (towards PA<sub>1</sub>). Some scholars, however, recognize the possibility of a reverse movement towards higher degrees of integrality (towards PA<sub>2</sub>). Their descriptions vary in the extent of the movement and in the level of detail of the change path. For example, in his double-helix model Fine (1998) describes product architectures as oscillating between integral and modular states. Conceptually similar, Schilling (2000) allows systems to migrate towards and away from modularity. The two concepts differ in that Fine seems to imply a series of full swings between the endpoints whereas Schilling allows small shifts as well as equilibria anywhere on the spectrum. Christensen *et al.* (2002), focusing on the interfaces as their unit-of-analysis, distinguish between modular and interdependent interfaces and suggest that while the migration is mostly towards more modular interfaces, under some circumstances the process can reverse its direction. How far it can go in the new direction remains unspecified. Henderson and Clark (1990) identify the introduction of a new product architecture as an architectural innovation. They are silent, however, on whether this shift introduces an architecture that is more modular or more integral than its predecessor.

In our case, the direction of product architecture change is clearly towards higher levels of integrality given that our measurement is anchored at perfect modularity. Since our measure has no equivalent anchor for perfect integrality, however, we cannot say how big the shift was relative to the conceptual extreme. What we can say is that the change process proceeded in steps both for the innovating firm and across the industry, and that this form of change process

caused temporary product architecture heterogeneity across firms. The second detail that our analysis allows to add is that some dimensions of the product architecture changed but not all of them. Our fine-grained description of product architecture change will help in identifying cause-effect relationships below.

#### *4.1.2 Industry Structure Changes*

Similar to the majority opinion on product architecture migration, most scholars describe the prevalent change in industry structure more towards disintegration and specialization. The prevailing findings are that industries begin in an integrated mode and become disintegrated over time. This effect has been observed in industries as different as computers (Baldwin and Clark, 2000), text books (Schilling, 2000), and mortgage banking (Jacobides, 2005). This general direction of industry evolution has been explained by the increasing efficiency through the division of labor that is only limited by the extent of the market (Stigler, 1951), first formulated by Adam Smith over 200 years ago. Providing firm-level explanations, Jacobides (2005) identifies potential gains from specialization and gains from trade as underlying forces that ultimately cause an industry's disintegration. Proponents for the opposing view, i.e., that industries can integrate, are fewer. Chandler (1977) finds increasing vertical integration in his studies of large American corporations, and explains this trend with an increasing need for administration through growing markets and increasingly complex technologies. In an effort to reconcile Chandler's and Smith's views, Langlois (2003) suggests that Chandler's findings of vertical integration are a temporary phenomenon that industries experience on their way to vertical disintegration. Yet others have suggested that industries oscillate between integrated and disintegrated forms of their structure (Fine, 1998), and neither form is ultimately stable. Some empirical studies support this possibility. For example, in their study of the chemical industry Macher and Mowery (2004) find that after disintegrating, the industry split into a commodity

segment and a specialty segment, and firms in the latter began to re-integrate. Similarly, Jacobides and Winter (2005) show how the watch industry re-integrated after the introduction of the quartz movement technology.

More generally, there seems to be a two-level debate ongoing. At the macro level, focusing more on long-term historical dimensions, the agreement appears to be that industries ultimately migrate towards higher degrees of specialization, while at the micro level possibilities are considered for short-term and medium-term industry changes in either direction. It is the latter that we necessarily focus on with our case study over only ten years. One question within the micro level is the sequence of changes in an industry. It has been suggested that firms, first, gain dominance in their segment, and then, second, begin to vertically integrate (Fine, 1998). Our case with its narrow focus on six parallel layers clearly demonstrates the reverse sequence of change events. Shimano not only produced all six segments at the beginning of our observation period, but, more importantly, it introduced an integrated design *before* it began its expansion of market share in all individual segments.

#### **4.2 Cause-Effect Relationships**

To explore whether existing theories can explain the observed events, we first describe the cause-effect relationships of these theories within our framework (Figure 2), and then compare and contrast them to the cause-effect relationships that we observed in our case study. Each chain of causes and effects will cover the path of change, the underlying mechanisms at work, and the drivers behind the change.

In their seminal work on the evolution of the computer industry, Baldwin and Clark (2000) describe the initial creation of the modular architecture as clearly preceding the emergence of the modular industry structure, ‘industry clusters’ in their parlance. This corresponds to a path of first (b) and then (a) in our framework. The mechanisms at work they describe as a set of six

modular operators: splitting, substitution, augmenting, excluding, inverting, and porting. The drivers in Baldwin and Clark's theory are the designers. "Designers see and seek value in new designs." (Baldwin and Clark, 2000:35) Although their theory focuses on creating modular designs, they do acknowledge that designers see design parameter interdependencies, and consider those in their designs. They also assert that a modularization (splitting) requires the designers' knowledge about interdependencies to reach or exceed a certain threshold – one that allows design rules to be established without unduly constraining the performance of the artifact.

Schilling (2000), in her model on explaining interfirm product modularity spends little time on describing a path of events between product architectures and industry architectures. At the heart of her model is the assumption that a product or system attempts to achieve a best fit with its environment by migrating towards or away from modularity. While the model allows for system's inertia and firms' resistance against change, at its core it assumes that the balance of external forces determines the system's degree of modularity. Eleven propositions describe the forces that drive the system towards or away from higher levels of modularity. The greater the functionality achieved through component specificity (P1), the greater the difficulty for customers to assess component quality and interaction (P2), and the greater the difficulty for customers to assemble the system (P3), the lower the degree of interfirm product modularity. The next three propositions suggest that heterogeneity of inputs increases interfirm product modularity through greater differentials of capabilities among firms (P4), greater diversity in technological options (P5), and the interaction of the capability differentials and technological option diversity (P6). These forces and increasing interfirm product modularity may over time become a self-reinforcing cycle (P7). Demand heterogeneity will also cause an increase in interfirm product modularity (P8), and the heterogeneity of inputs and demands will each reinforce the effect of the other (P9). Finally, the speed of technological change (P10) and

competitive intensity (P11) will accelerate any existing migration towards or away from higher levels of interfirm product modularity. In summary, these forces are the drivers of product architecture change, and the type of pressure they generate represents the mechanisms. Only the forces of propositions 4, 6 and 11 suggest a path from industry to architecture (either (a) or (c)), all others fall in the non-industry causes category (either (e) or (f)).

Fine (1998) in his double-helix model describes the changes of product architecture and industry structure as jointly occurring, i.e., (a) and (b), or (c) and (d) happen simultaneously. Instead of the sequence, he focuses more on the mechanisms and drivers that force these changes. For the change towards modularity he identifies advantages of niche competitors, disadvantages of covering broad knowledge fields, and organizational rigidities of large firms as drivers, the first one represents change path (a), the latter two represent change path (b) in our framework. For the change towards integrality he suggests the forces of technical advances, individual firms' market power in individual component markets, and potential profitability from integration into a proprietary system. The first and third forces reflect external change paths (f) and (h) respectively, whereas the second force can be understood as change path (c).

Christensen *et al.* (2002) also discuss the possibility of a change process towards higher degrees of integration. Their starting point is "the occurrence of a 'performance gap'—an upward shift in functionality that customers needed" (Christensen *et al.*, 2002:972), which can be satisfied only by technically integral solutions. This, in turn, favors vertically integrated firms over modular ones. From the perspective of our framework, external demands (f) cause the product architecture to become integral, and selection pressures (c) then changes the population of product architectures in an industry.

Similar to Christensen *et al.*, Jacobides and Winter (2005) incorporate in their framework the possibility that industries can migrate towards higher degrees of integration. Where they

differ from Christensen *et al.* is the origin, i.e., the driver of the process. Jacobides and Winter (2005:405) argue “.. that the cycle pushing toward specialization gets reversed when new and superior capabilities arise from knowledge bases that are misaligned with the existing vertical structure of the industry.” In the language of our framework the arrival of new and superior capabilities is represented by link (f), the new superior design by link (d), and the ensuing selection pressures by link (c). As support they present the case of the Swiss Watch manufacturing industry, which was unable to respond to the introduction of the quartz watch movement. While their case exhibits some similarity to our bicycle drivetrain component case with respect to change direction and effects, it differs in the origin of the innovation and the degree to which it was radical.

Langlois (2003; 2004), in his work to reconcile the views of Smith and Chandler, similarly proposes that external technical change can cause firms to re-integrate. His fundamental argument is that these external technical changes open up new opportunities, but at the same time temporarily increase what he calls ‘dynamic transaction costs,’ i.e., the cost of “informing outsiders and persuading them to cooperate in production” (Langlois, 2006:1400). In those circumstances, the expansion of a firm’s boundaries then is the most economic choice. Within our framework, the linkages are similar to the ones at Jacobides and Winter: the need to lower dynamic transaction costs through integral solutions is represented by link (f), the new superior solution by link (d), and the ensuing selection pressures by link (c).

Finally, Brusoni *et al.* (2001) also emphasize the value for a firm of maintaining an integrated knowledge perspective. However, there is a subtle difference to Jacobides and Winter’s and Langlois’s approach. Whereas both Jacobides and Winter and Langlois see the arrival of new knowledge that is misaligned with current capabilities as the driver for change on a systemic level, Brusoni *et al.* view the integrated knowledge perspective as the mechanism

with which a firm can cope better with technology progress that is uneven across components. In our framework, the increasing degree of integration on the knowledge level then is a cause that is not industry structure-related (f), and its consequences are superior designs (d), and selection pressure (c).

A close inspection of our case study reveals the following cause-effect relationships. Starting with the general product architecture in the industry being modular, and the industry structure disintegrated, one firm introduced an integral product architecture (f). This linkage is similar to Baldwin and Clark's designer seeking value (although in our case they were not seeking option value but rather the value of systemic performance), Schilling's increase in synergistic specificity, and Fine's technical advances. It differs somewhat from the accounts of Christensen *et al.*, Jacobides and Winter, Langlois, and Brusoni *et al.* who all see the integration rather as a response to changes in either customer demand or technological environments to lower transaction costs, as opposed to a deliberate strategic move of one industry participant.

The second cause-effect linkage that we can identify in our case is the effect the new and superior integral product architecture had on the industry: it pushed the entire industry to become more integrated (d). This happened because the superior performance was only possible through the integral design solution, hence, competition forced all firms to play on the new field. From the perspective of the non-leading firms this is represented by link (c). This link however, looks on the inside very different for firms that are already integrated compared to those that are not. We will explain the theoretical underpinnings in the next section.

Finally, we investigate for our case study the effects of supporting activities for the industry structure change (linkage (h)). We identify two reasons that appear to have played major supporting roles in Shimano's success for starting to get the product architecture moving away from modularity. The first was the timing of Shimano's attack, i.e., its temporal context. In the

mid-1980s, the mountain bicycle market began to emerge in the U.S. When riding in rough terrain, it is particularly valuable to keep the hands on the handlebar at all times and focus on the path ahead. Index shifting, together with repositioning the shifters to the handlebar, made that possible. In other words, Shimano introduced its performance improvement through the integral product architecture at a point in time at which it became particularly relevant. Shimano appears to have learned here from an episode a few years earlier: In the early 1980s, when Shimano launched an attempt to introduce incompatible component sets that were designed for better aerodynamics, most customers did not consider this new technology as added value and rejected it. As a result, Shimano retreated and reverted back to interchangeable components.

The second reason that helped Shimano to start the product architecture shift in the industry was support for the dealerships. One of the side effects of Shimano's new architecture was that it required new tools to disassemble and assemble the component sets. The costs for the new tools and for learning how to use them represented switching costs for the bicycle repair shops, who also often sold new bicycles. To lower those switching costs Shimano distributed the special tools free of charge to dealers (*Bicycling magazine*), Feb 1985:163-174), and sent technicians to dealers to teach them how to install and fix indexed component sets. These activities made the distribution channels more comfortable with the technology and increased their willingness to carry bicycles with S.I.S. component sets. In contrast, during the aerodynamics episode, Shimano had tried to force the dealers to purchase the special tools required to repair the aerodynamics component sets (*Bicycling magazine*), Feb 1982:66-96). That strategy contributed to the dealers' unwillingness to carry Shimano's aerodynamic component sets – another reason for the failure of the first attempt.

We also studied the influence of marketing and pricing strategies as alternative explanations for the observed changes in industry composition. While in general there are many different

marketing channels available for bicycle component firms, through interviews we found that a major marketing avenue in the 1980s was print ads in bicycling-related publications, in particular in *Bicycling* magazine. To check whether the marketing activities differed substantially across the major firms we counted the number of pages each firm bought for advertisements in the *Bicycling* magazine. The data does not allow us to discern a significant difference in marketing efforts across the three systems firms. We also checked whether the three systems firms employed different pricing strategies. The data we collected allows us to reject this hypothesis, too. All through the decade all three major firms offered component sets across the price spectrum, albeit with Campagnolo leaning slightly to the high-price segments.

The overall sequence of effects, i.e., that once a technology has demonstrated its superiority in the market, every competitor is forced to match the offer is supported by the theories of Christensen *et al.*, Jacobides and Winter, Brusoni *et al.*, and Langlois. In contrast, Fine assumes first the market power by a player in a component segment before industry integration occurs, which is different from what we observe in our case. All theories, however, assume simply that the competitive effects are similar for all industry participants.

In summary, we identify three areas where we can contribute to the extant literature. The first relates to the change path of product architectures, the second concerns the cause-effect relationships between changes in individual product architecture dimensions and their effects on competitors, and the third involves the origin of integral product architecture innovation.

## **5 DISCUSSION**

### **5.1 Theoretical Implications**

The first addition to the literature our case analysis permits us to make is the introduction of a new design operator. Baldwin and Clark suggest that their list of operators – splitting,

substitution, augmenting, excluding, inverting, and porting – is complete to generate “ ... any conceivable modular design or task structure ... from a set of earlier structures via some sequence of operator steps.” (Baldwin and Clark, 2000:144) We do not challenge that notion with respect to *modular* designs, but propose that their set of operators is incomplete for the creation of *any* design. More specifically, we introduce *integrating* as a design operator to complement those suggested by Baldwin and Clark. As the case data demonstrates, the changes in product architecture that Shimano introduced in 1985 clearly reduced the degree of modularity of the bicycle drivetrain component set. Subsequently, the other firms in the industry followed Shimano’s lead and moved to more integral product architectures themselves. While it is possible that product architectures migrate to more modular structures in the long-run, our case clearly shows that there is the possibility for an at least temporary reversal of this process.

Our second contribution is concerned with the unpacking of some causal mechanisms between technical changes and changes in the industry architecture. The introduction of our fine-grained and multi-dimensional product architecture measurement not only allowed us to identify specific product architecture change patterns, but – in conjunction with a careful industry definition – also permitted us to make visible the mechanisms through which changes of individual product architecture dimensions affect individual competitor categories. In the bicycle drivetrain case three different mechanisms affected different types of competitors very differently (Figure 5). The first, triggered by a more integral function-component allocation, increased the systemic performance and consequently forced the competitors who offered all of the six drivetrain components, i.e., systems firms, into a systems competition. In contrast, the second mechanism, triggered by a reduction in interface standardization, drastically reduced the available market size of complementary components to which component firms could attach their own components. With the elimination of interfirm component compatibility, the small

firms essentially lost the population of components that were ‘co-specialized’ with their own components.<sup>10</sup> The third mechanism made the systemic form of competition difficult for all firms still standing because the origin of performance differentials was very difficult to detect, and it took the remaining competitors several years to close the performance gap.

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Insert Figure 5 about here  
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It has been shown before that individual product architecture dimensions are linked to multiple individual *operational* performance dimensions of a firm – such as cost and time (Fixson, 2006); our case here shows that there are equally intricate linkages between individual product architecture dimensions and multiple *strategic* performance dimensions of a firm. Our case data illustrates two different effects on single-component and multi-component firms in a narrowly defined industry. We conjecture that in industries defined with higher levels complexity additional cause-effect relationships are at work.

The third contribution of our case analysis is to shed light on the *origin* of architectural innovations, and their underlying prerequisites. Specifically, we propose that the firm boundary location is not only an outcome of efficiency considerations but can also be pre-condition for some types of innovations.

Most current explanations of an industry’s structure explain firms’ boundary location choices as a consequence of efficiency considerations. First, classic transaction cost and

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<sup>10</sup> A similar effect, i.e., the exclusion of rivals from upstream suppliers or downstream sellers, has been termed

complete contract analysis focuses on how information asymmetry and incentive problems can create hold-up problems (Williamson, 1985; Hart and Moore, 1990; Baker *et al.*, 2002; Gibbons, 2005). The firm's boundary choices are aimed at lowering total transaction costs. Similarly, the more recent focus on mundane transactions also tends to focus on reducing transaction costs, albeit via the possible detour of first creating the capabilities that are necessary to reduce these dynamic transaction costs. In other words, the goal is still to improve long-run process efficiencies by reducing transaction costs, but the skills to do so might be costly to acquire and build (Langlois, 2006).

Another expansion of the classic view that resolving the incentive problem requires ownership (Teece, 1986) has been proposed by Jacobides *et al.* (2006). They suggest viewing competition more systemically, i.e., to rethink existing business models, and to benefit through activities such as inducing competition in neighboring industry layers or investing in assets expected to appreciate through increasing competition. For both of these literature streams, however, the transactional interface and the co-specialization of assets, respectively, are exogenously determined.

In contrast, our case study suggests that the existence of a transactional interface, and the degree of co-specialization is to a large extent an endogenous variable. Engineering decisions – particularly concerning product architecture – affect both the feasibility of transactions and the degree of co-specialization of assets and components. Co-specialization can increase product performance as observed in our case. Alternatively, process cost reductions may be achievable via the larger redesign of a product and its architecture (*cf.* Cooper and Slagmulder, 2004). This

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*foreclosure* in the economics literature (*cf.* (Lafontaine and Slade, 2007)).

explanation is akin to Baldwin and Clark's (Baldwin and Clark, 2008) with respect to the endogeneity of the location of transactional interfaces.

Designer pursuing modularity 'see and seek value' in the options that a modular design generates. Designers pursuing integral solutions seek value in a system setup that is – along some performance dimension – better than more modular setups. Although the type of value premium is dissimilar, in both cases it is the designers that envision the solution space and set the ground rules of how to explore it. Where then, does the competence to do so reside? The analysis of our case data suggests that the competence for architectural redesign is more likely to exist in firms that cover a broader component spectrum. In our case, both the attacking firm and all surviving firms were already in the business of making all relevant components. Knowledge across several segments appears to have been a necessary ingredient for maintaining competitiveness in the wake of this architectural shift. Broader scope apparently helped some firms avoid the 'modularity trap' (Chesbrough and Kusunoki, 1999). But broad scope was not necessarily sufficient as illustrated by how long it took the defenders to create their own competitive integral product architectures. Paralleling Brusoni *et al.* (2001) who suggest that a broad knowledge base is required for system integrator firms to accommodate multiple technology advancement rates across multiple components, we add that the broad knowledge base can also be valuable for a firm in *creating* a new architecture in the first place. In summary, we argue that a firm's boundaries may not only be a consequence of efficiency considerations, but it can also be the origin – or at least pre-condition – of industry-altering architectural innovations.

Overall, our study reveals that the cause-effect relationships between product architecture and industry structure were complex. On the industry level, there was a strong cause-effect relationship from product architecture to industry structure. One firm's successful integral

product architecture forced all firms to become more integrated, albeit through three distinct mechanisms (shift to systemic performance, reduced interface standardization, and difficulty in understanding systemic performance). However, on the individual firm's level – especially at the beginning of the process – there is evidence of causality running the other way: from firm boundary to product architecture. The firm that introduced the new integral architecture was a firm of broad vertical scope, and it had tried the integrating move before. And the only survivors of the industry shakeout were firms of similarly broad scope.

## **5.2 Managerial Implications**

Even if long-run product architecture developments tend to lead to increasing modularization, our case demonstrates that there can be tremendous value in temporary re-integration. The managerial implications following from this insight are twofold. First, there is substantial value in understanding the potentially industry-changing power of product architecture innovation. In other words, engineering decisions on product architecture are not only relevant for product performance and operational performance of the associated manufacturing system, but they also can have truly strategic value for the firm. The devil, however, is in the details and knowing the effect propagation paths and mechanisms is a pre-condition to align engineering and strategy. Second, the necessary – albeit not sufficient – condition for creating product architecture innovations is knowledge that stretches at least across the current product portfolio, often beyond that. This means that while a deep knowledge base has value for being able to compete within a modular architecture, to change the rules of the game requires investments in a broad knowledge base.

Our case study yields some strategic advice for both attack and defense. On the attacker's side, it is valuable to know the conditions that facilitate architectural innovations because they have the potential to alter what Jacobides *et al.* (2006) have called the architecture of an industry

with strong repercussions for the other industry participants. Most previous research has investigated architectural redesign decisions either in early-industry situations (e.g., IBM/360) or for firms that maintain architectural control (e.g., Microsoft over Windows). Our case shows these effects at work in a mature industry in which no single firm controls the product architecture. On the defender's side, it is important to recognize hidden vulnerabilities of the own products due to their reliance on other co-specialized products. Finally, knowing the paths through which changes in individual product architecture dimensions propagate through the industry is valuable knowledge for both attackers and defenders.

## **6 CONCLUSION**

We have analyzed a somewhat unusual case in which decreasing modularity in a mature and modular industry led to an overwhelming dominance of the attacking firm. Our case shows how the introduction of an integral architecture by a then non-dominating firm resulted in a near-monopoly position for the innovating firm within a few years. Changes in two dimensions of the product architecture triggered effects in two different propagation paths, one hitting small component firms, the other larger systems firms. While some supporting activities such as dealer training and free tools were relevant to set the process in motion, the analysis shows a clear link between technological change and industry structure with causality running from the former to the latter.

There are two main limitations of our study. The most obvious is that it is a single case study focusing on only one industry. Generalizations beyond this industry are challenging. Nevertheless, previous single-industry studies on the effects of technical changes on competition (Henderson and Clark, 1990; Christensen, 1992a; Christensen, 1992b; Tripsas, 1997) have contributed helpful insights, and we hope to add to this body of knowledge with our study. A

second limitation involves – as in any empirical study – the quality of the measurement instruments. For both of our main dimensions, product architecture and industry structure, we constructed proxies to measure the change over time of the underlying constructs. Our measures are certainly imperfect and we acknowledge potential distortions this may cause. However, given the overwhelming change that our data indicates, we believe the analysis still provides interesting insights into the powerful effects product architecture choices can have on competitive outcomes.

An interesting direction to extend this research would be to investigate product architecture changes and their consequences in larger, more complex supply networks. Many studies do not distinguish clearly between vertical, horizontal, or sequential industry structures. In this study we deliberately focused on a rather horizontal industry structure of limited size in order to isolate product architecture effects caused by the integration of components on the same product hierarchy level. On the other hand, it has been suggested that in a vertical industry the profits flow away from modular sectors to the next level that is more integral (Christensen *et al.*, 2001), and some empirical studies indicate that a firm boundary shift, caused by a product architecture change, might occur in one direction within a OEM – first-tier supplier relationship, but not at all or even in the reverse direction within the relationship between first-tier and second-tier suppliers, i.e., in the dyad below (Fixson *et al.*, 2005). This suggests that industry structure changes are not homogenous along a supply chain, just as product architecture changes are not likely to be homogenous within the product hierarchy. Future research should address these complex relationships, perhaps by combining it with better industry structure measurements for complex industries (Dalziel, 2007).

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## 8 TABLES & FIGURES

Table 1: Bicycle models offered in the U.S. between 1980 and 1990

Total Number of Bicycles offered in the U.S.											
Category	1980*	1981*	1982*	1983*	1984	1985	1986	1987	1988	1989	1990
<b>Road</b>	5	12	27	18	215	134	143	134	147	179	346
<b>MTB</b>	N/A	N/A	N/A	N/A	N/A	43	48	59	94	134	369
<b>Hybrids</b>	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	58
<b>Others</b>	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	30
<b>Total</b>	5	12	27	18	215	177	191	193	241	313	803

Source: Superspec Database  
 \* *Bicycling Magazine* began to annually publish its Superspec database (SSD) in 1984. Prior to that year it announced new bicycles individually in every issue. For the years 1980 to 1983 we counted all individual new bicycle announcements and aggregated them for each year.

Table 2: Measuring function-component allocation (Shimano at  $t_1=1980$ )

		Components						Component Count Index	Entanglement Index
		1	2	3	4	5	6		
Functions		Brake levers	Shifter	Derailleur	Free- wheel	Chain	Hub		
1	Power transmission				1	1	1	3	1
2	Gear shifting		1	1				2	1
3	Brake actuation	1						1	1
Function count		1	1	1	1	1	1		

Table 3: Summary of product architecture assessment

			<b>t<sub>1</sub> = 1980</b>		
			Power Transm.	Gear Shifting	Brake Actuation
Shimano	PA Dimension 1	Function-Component Allocation Scheme			
		Component Count Index	3	2	1
		Entanglement Index	1	1	1
	PA Dimension 2	Interface Characteristics			
		Strength	6	6	N/A
		Irreversibility	5	4	N/A
	Standardization	3,3	3,3	N/A	

Table 4: Changes of product architecture and industry structure in the bicycle drivetrain component industry, 1980-1990

			t <sub>1</sub> = 1980			t <sub>0</sub> = 1985			t <sub>1</sub> = 1988			t <sub>2</sub> = 1990			
Functions			Power Transm.	Gear Shifting	Brake Actuation	Power Transm.	Gear Shifting	Brake Actuation	Power Transm.	Gear Shifting	Brake Actuation	Power Transm.	Gear Shifting	Brake Actuation	
<b>Product Architecture</b>	Shimano	PA Dimension 1	Function-Component Allocation Scheme												
			Component Count Index	3	2	1	3	4	1	3	4	1	3	5	1
			Entanglement Index	1	1	1	2	2	1	2	2	1	2	2	1
		PA Dimension 2	Interface Characteristics												
			Strength	6	6	N/A	7	7	N/A	7	7	N/A	8	7	N/A
			Irreversibility	5	4	N/A	5	4	N/A	5	4	N/A	5	4	N/A
	Rest of Industry	PA Dimension 1	Function-Component Allocation Scheme												
			Component Count Index	3	2	1	3	2	1	3	4	1	3	4	1
			Entanglement Index	1	1	1	1	1	1	2	2	1	2	2	1
		PA Dimension 2	Interface Characteristics												
			Strength	6	6	N/A	6	6	N/A	7	7	N/A	7	7	N/A
			Irreversibility	5	4	N/A	5	4	N/A	5	4	N/A	5	4	N/A
Standardization	3,3	3,3	N/A	3,3	3,3	N/A	2,2	2,2	N/A	1,1	1,1	N/A			
<b>Industry Structure</b>	Within Layer Concentration [model-weighted Herfindahl Index]	RB	Shifter	2,750 *		2,670		4,420		4,200					
			Derailleur	2,870 *		2,660		4,420		4,220					
			Freewheel	2,580 *		2,700		4,170		4,180					
			Brake	1,800 *		1,800		3,250		4,210					
			Chain	1,650 *		1,700		3,260		4,190					
			Hub	1,000 *		1,150		2,400		4,150					
		MTB	Shifter	N/A		4,180		7,460		6,810					
			Derailleur	N/A		4,350		7,620		6,810					
			Freewheel	N/A		4,140		7,000		6,550					
			Brake	N/A		3,630		5,420		6,790					
			Chain	N/A		2,110		6,170		6,550					
			Hub	N/A		1,310		3,060		6,380					
	Across Layer Concentration [Integration Distribution]	RB	Type 1	5.6% *		13.4%		38.8%		94.2%					
			Type 2	16.3% *		19.4%		25.9%		3.5%					
			Type 3	20.5% *		17.2%		15.0%		0.6%					
			Type 4	19.1% *		17.2%		10.2%		0.0%					
			Type 5	24.2% *		17.9%		6.1%		0.0%					
			Type 6	8.8% *		11.9%		0.0%		0.0%					
		MTB	N/A	5.6% *		3.0%		4.1%		1.7%					
			Type 1	N/A		7.0%		46.8%		94.3%					
			Type 2	N/A		20.9%		23.4%		4.1%					
			Type 3	N/A		18.6%		4.3%		0.0%					
			Type 4	N/A		27.9%		13.8%		0.0%					
			Type 5	N/A		16.3%		5.3%		0.0%					
Type 6	N/A		2.3%		0.0%		0.0%								
N/A	N/A		7.0%		6.4%		1.6%								
			t <sub>1</sub> = 1980			t <sub>0</sub> = 1985			t <sub>1</sub> = 1988			t <sub>2</sub> = 1990			

\* = Data from 1984

Fig. A.1.1. Product Architectures and Market shares (Road 1984)

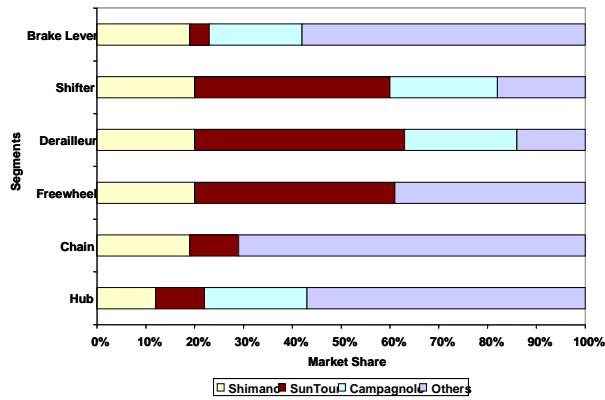


Fig. A.1.7. Product Architectures and Market shares (Road 1990)

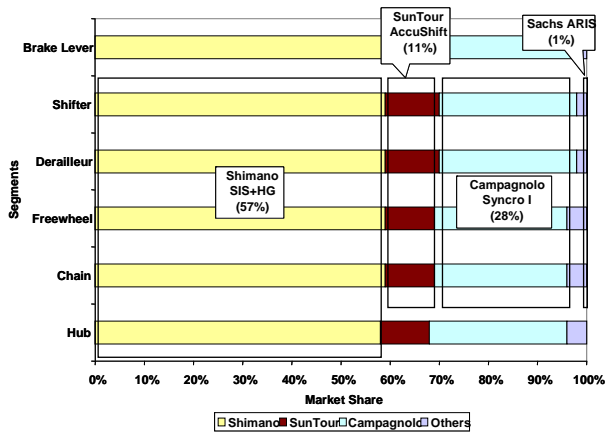


Fig. A.2.7. Product Architectures and Market shares (MTB 1990)

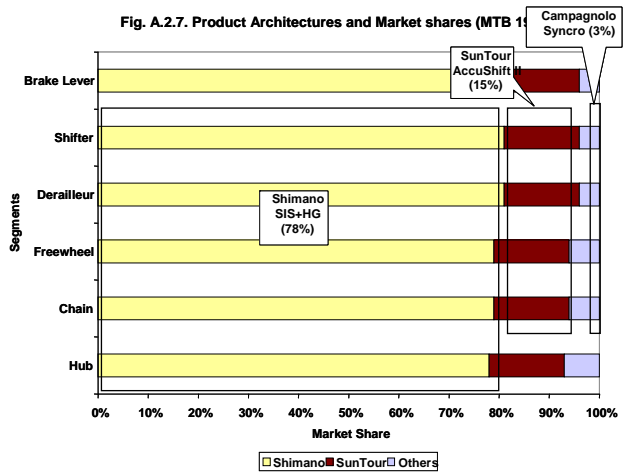


Figure 1: Industry structure of the bicycle drivetrain component industry in 1984 (top) and in 1990 (bottom)

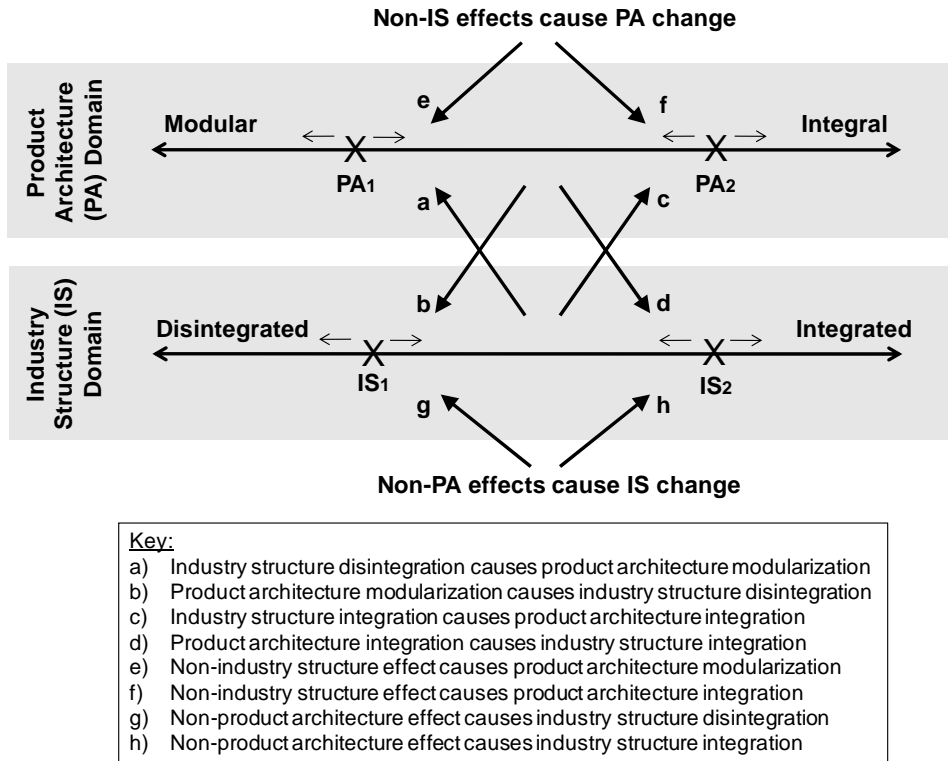


Figure 2: Research framework

**Product Architecture Shimano: t-1=1980**

INTERFACES: Characteristics *Strength* and *Irreversibility*

		Components					
		1	2	3	4	5	6
		Brake Levers	Shifter	Deraillleur	Freewheel	Chain	Hub
Components							
1	Brake Levers						
2	Shifter			2 2 0 0			
3	Deraillleur		1 1			1 1 0 0	
4	Freewheel					1 2 0 0	1 2 0 0
5	Chain			1 1 1 1			
6	Hub				2 1		

STRENGTH of Interfaces (upper triangle)  
(adapted from Pimmler and Eppinger 1994)

*Nature:*  
Spatial 

S	E
I	M

 Energy  
Information 

S	E
I	M

 Materials

*Intensity:*

Required 2  
Desired 1  
Indifferent 0  
Undesired -1  
Detrimental -2

IRREVERSIBILITY of Interfaces  
(lower triangle)

Effort 

1
---

  
Depth 

1
---

*Effort to reverse:*      *Depth of interface:*  
easy 1                      shallow 1  
medium 2                    medium 2  
difficult 3                    deep 3

NUMBER of Interfaces

real 4  
theoretical max. 15  
theoretical min. 5  
real/max 27%  
min/max 33%

**Evaluation Aggregation per Function**

	Power Transmission	Gear Shifting	Brake actuation
Interface Strength	6	6	0
Interface Irreversibility	5	4	0

Figure 3: Measuring interface strength and interface irreversibility (Shimano at t<sub>1</sub>=1980)

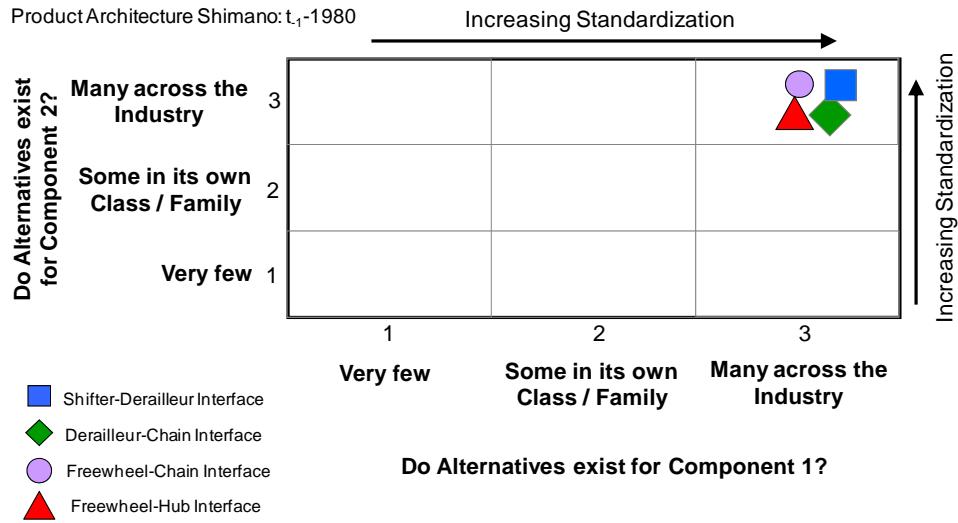


Figure 4: Measuring interface standardization (Shimano at  $t_1=1980$ )

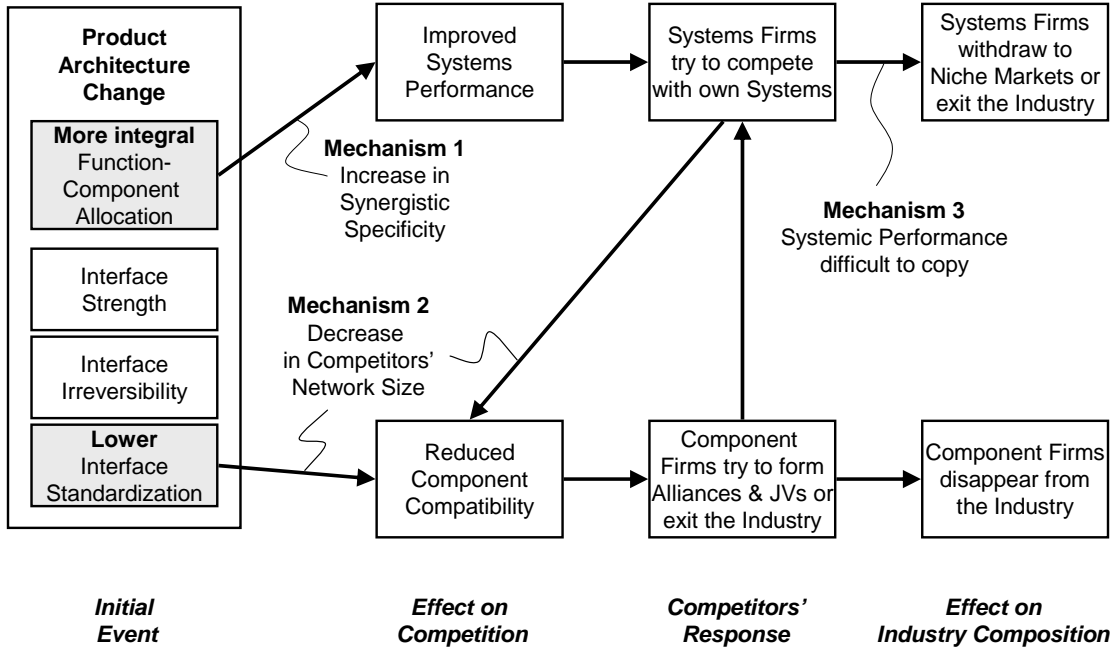


Figure 5: Three mechanisms through which product architecture changes affected competition

# APPENDIX

Fig. A.1.0 Product Architectures and Market shares (Road 1980-1983)

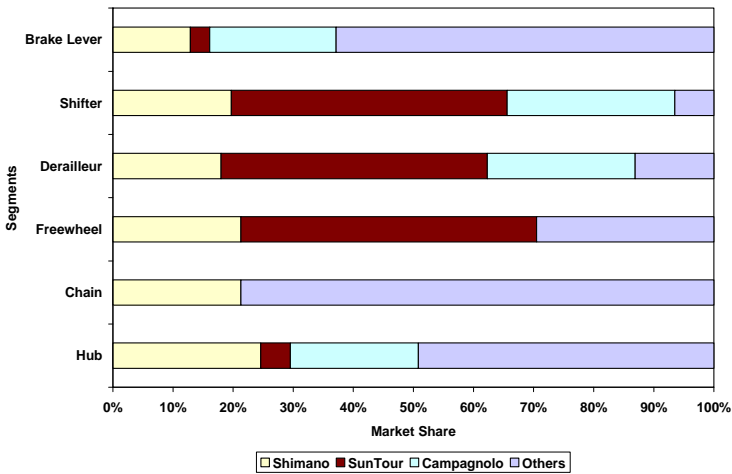


Fig. A.1.1 Product Architectures and Market shares (Road 1984)

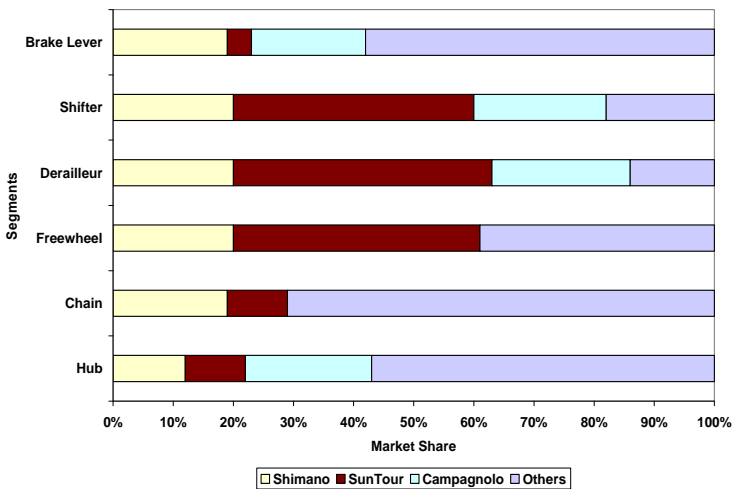


Fig. A.1.2 Product Architectures and Market shares (Road 1985)

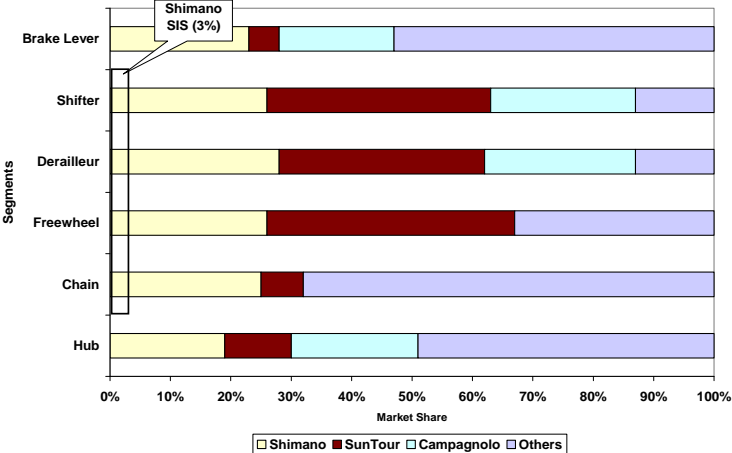
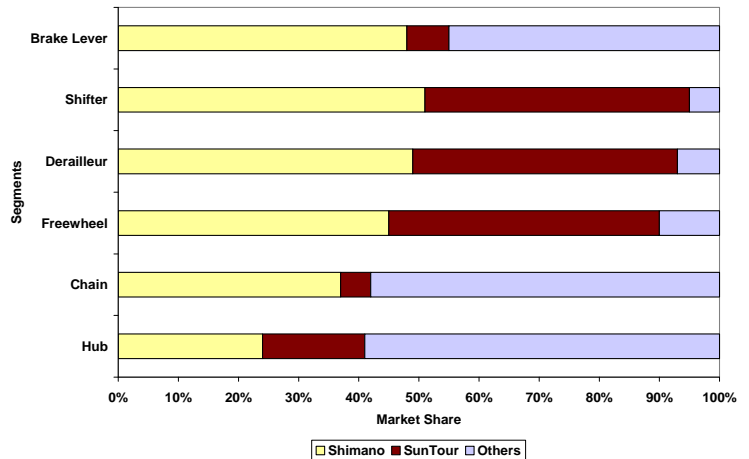


Fig. A.2.2 Product Architectures and Market shares (MTB 1985)



The figures in this appendix are to be read as follows. The six rows in each figure represent the market segments for brake levers, shifters, derailleurs, freewheels, chains, and hubs. In each segment, the different colors show the market share of the three major bicycle drivetrain component firms (Shimano, SunTour, and Campagnolo) and the remaining firms grouped into 'Others.' In addition, we label the new introduction of an integral architecture with a solid-lined box, reflecting the loss of compatibility of the components of the new architecture to the neighboring components. These boxes are labeled with their brand names and their market share.

Each figure represents a calendar year for either the road bicycle or the mountain bicycle market. The figures are organized in two columns: the figures for the road bicycle market on the left, the figures on the mountain bicycle market on the right. This way of presenting the data allows cross-market comparison within a year (horizontally), and market share and product architecture changes over time (vertically).

Fig. A.1.3. Product Architectures and Market shares (Road 1986)

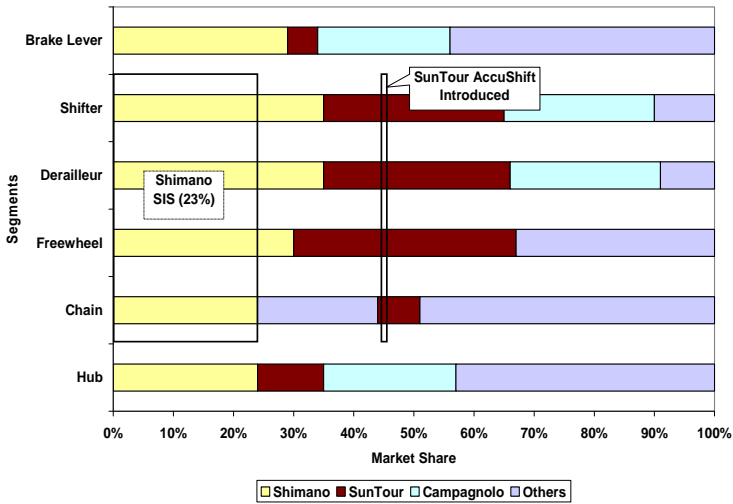


Fig. A.2.3. Product Architectures and Market shares (MTB 1986)

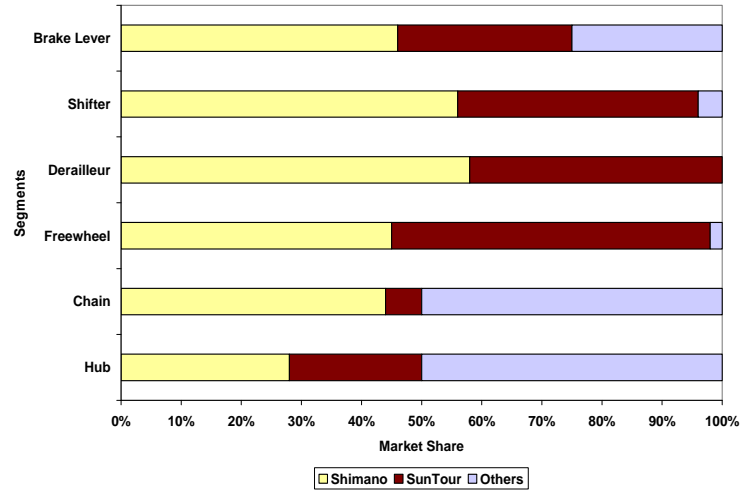


Fig. A.1.4. Product Architectures and Market shares (Road 1987)

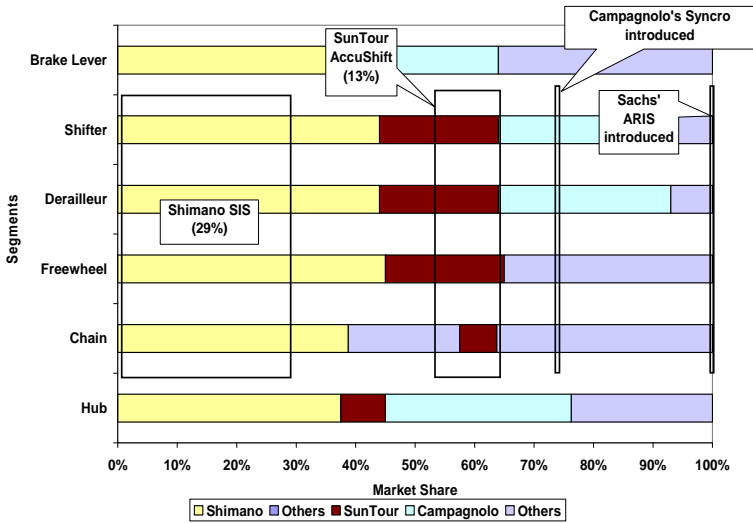


Fig. A.2.4. Product Architectures and Market shares (MTB 1987)

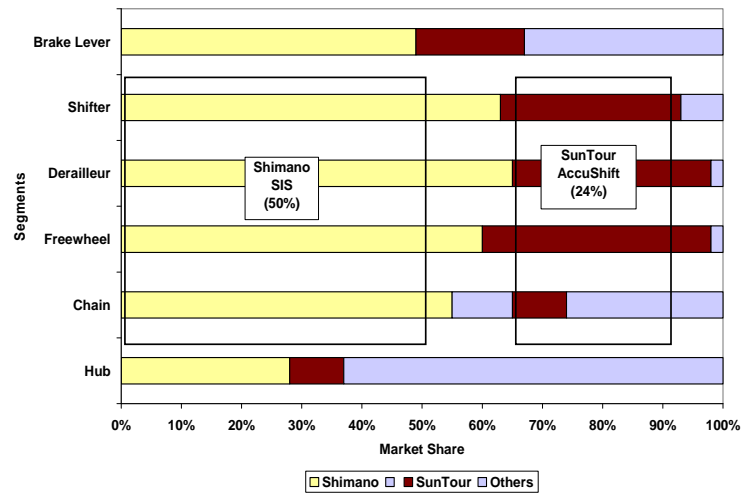


Fig. A.1.5. Product Architectures and Market shares (Road 1988)

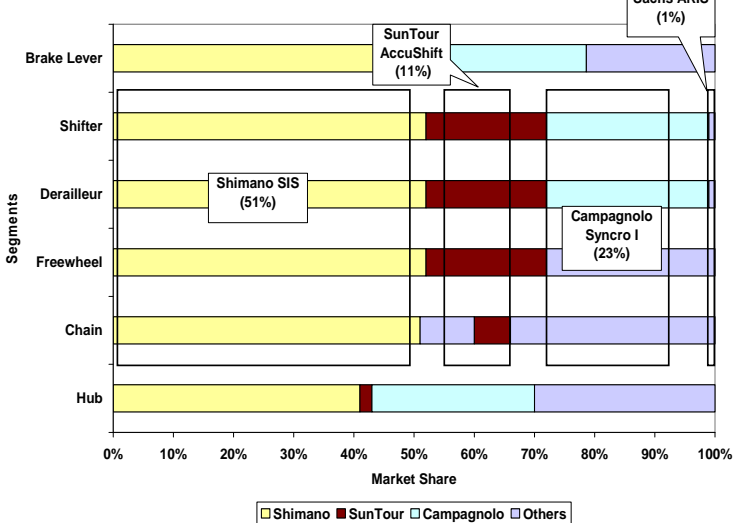


Fig. A.2.5. Product Architectures and Market shares (MTB 1988)

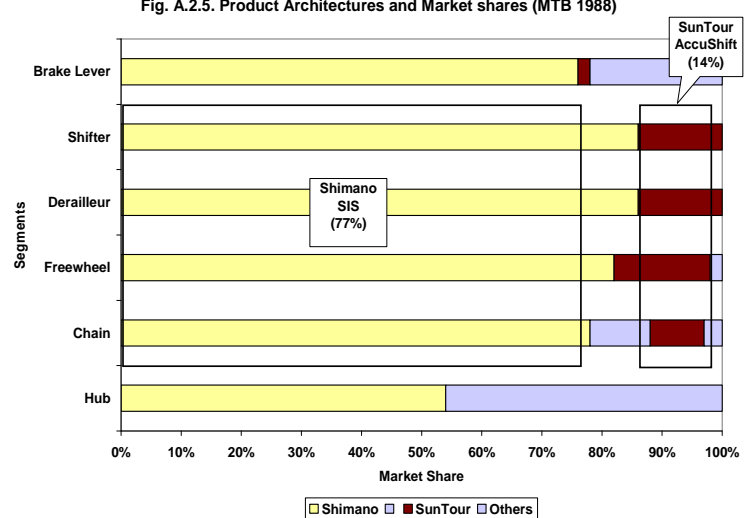


Fig. A.1.6. Product Architectures and Market shares (Road 1989)

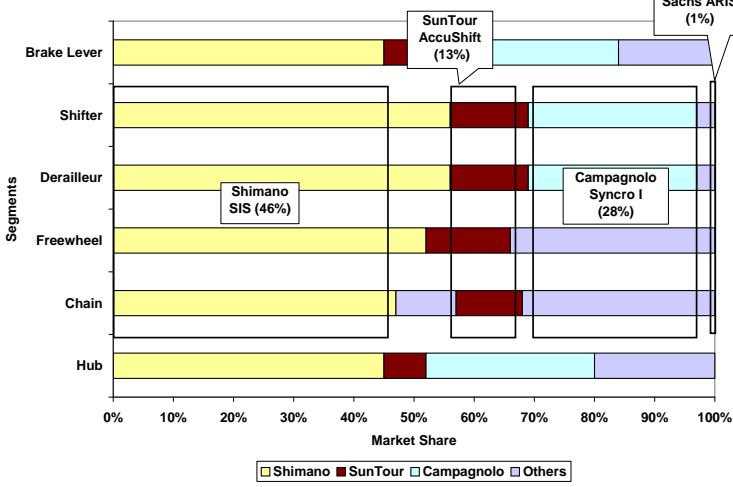


Fig. A.2.6. Product Architectures and Market shares (MTB 1989)

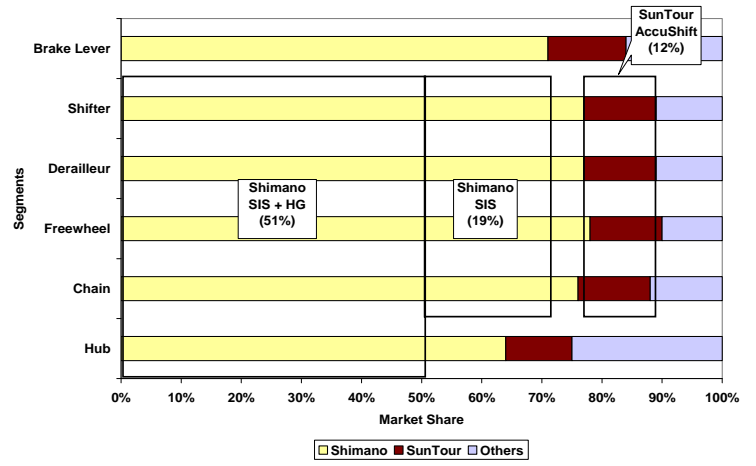


Fig. A.1.7. Product Architectures and Market shares (Road 1990)

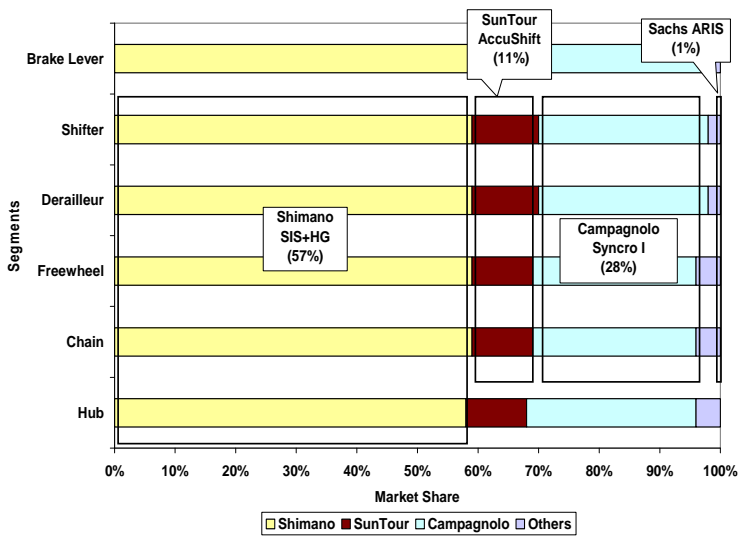


Fig. A.2.7. Product Architectures and Market shares (MTB 1990)

