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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 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 in their analysis technological change in rather long-term dimensions, and tend to focus on efficiency-related arguments to explain the resulting forces on competition. Expanding on these theories we add three critical aspects to the theory construct that connects technological change and industry dynamics. First, we suggest *re-integating* 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

The study of the implications of 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 tend to view such cause-effect relationships more in longer time frames and more on the industry level, research in the latter steam focuses more on shorter time frames and more on individual firms. Both have explored a variety of technology characteristics and their effects on competition.

More recently, one aspect of technology that has generated particular interest in this field is the role that the overall structure of the product plays for the competitive positions of firms involved in an industry, and subsequently for the entire 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, Verlinden and Westerman 2002), at least 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, Rusnak and Baldwin 2006), numerical controllers (Shibata, Yano and Kodama 2005), and college textbooks (Schilling 2000) have been found to migrate towards higher levels of modularity, and only temporarily, if at all, 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 2006), 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 represents substantial constraints for the industry participants, both for 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 (a) mostly increasing modularity, and (b) the increase in modularity causing increasing vertical specialization in the associated industry, we were intrigued by a case that appeared to not fit that pattern. This case is the bicycle drivetrain component industry during the 1980s. The bicycle drivetrain component industry supplies six different components to the bicycle assemblers: shifters, derailleurs, freewheels, chains, hubs, and brake shifters; each bicycle has one of each. In the early 1980s, the bicycle drivetrain component industry was a fairly competitive industry that exhibited a hybrid industry structure that included both small and large firms. In total, over 50 firms were active in the industry, and over half of those developed and manufactured only three or fewer of the six components. Many of these firms were fairly specialized. At the same time, two firms were producing all six components, 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 row Figure 1). Across the entire industry, all components were interchangeable both within and across firms. In other words, a derailleur from one firm, say Shimano, was as compatible with a chain from its competitor Suntour as it was with a chain from Shimano itself.

By 1990, the industry structure had drastically changed. The total bicycle market had split in two major categories, one for road bicycles (RB) and one for mountain bicycles (MTB); together they 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 row 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.

Insert Figure 1 about here

Insert Table 1 about here

Between these two points in time that describe an industry that had migrated not towards higher levels of disintegration but towards a much higher level of integration – both within and across the individual component segments – one firm had introduced a new product design with an integral architecture including non-compatible components. This firm, Shimano, is the same that became 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 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. More specifically, we re-construct in detail the history of both the product architecture domain and the industry structure domain in our focal industry to establish a time sequence of change events that at the minimum allows to rule out cause-effect relationships in one direction. To establish the credibility of causality in the other direction requires also to control for alternative explanations of the observed change 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, how can our anomaly of technological change be described? In other words, what is the process of product architecture migration towards higher level of integrality instead of modularity? Second, if there is a change towards higher degrees of product architecture integrality, how do these changes affect the structure of an industry and where do the product architecture changes come from? More specifically, what are the causal mechanisms at work here, what is the sequence in which they operate, and what represents the start of this chain of effects? Together, the answers to these questions will contribute to a better understanding of the factors that determine the room available to firms for strategic maneuvering with respect to product architecture change, and more broadly to the role of technological change in industry evolution.

To begin we create a framework for our overall research design and develop detailed measures for both the technology and the industry domain in the next section. 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 explains the observed events. In section five we turn to the gaps that the literature leaves unanswered and develop our theoretical contributions for their explanation. 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, Van de Ven, Dooley and Holmes 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

The research framework fundamentally establishes two separate domains: the product architecture and the industry structure (Figure 2). To establish whether a product architecture has migrated, say, from being rather integral (PA2) to being more modular (PA1) requires the measurement of the product architecture at multiple points in time. Then, to search for possible cause-effect relationships between product architecture and industry structure, the industry structure needs to be measured also at multiple points in time. Once these measurements have been taken, they can be put side by side to identify possible relationships between the two domains (effects (a) through (d) in Figure 2). In addition, forces that can potentially cause change in either or both domains but come from outside need to be identified (effects (e) through (h) in Figure 2).

Insert Figure 2 about here

2.2 Measures

To develop appropriate measures for product architecture and industry structure we build on existing work, and extend it to produce finer grained measures that fit our goal for an empirical study. Below we define our measures for both domains in detail.

2.2.1 Product Architecture

Architectures have been identified as a key element for design, operation, and behavior of complex engineering systems (Crawley, De Weck, Eppinger, Magee, Moses, Seering, Schindall, Wallace and Whitney 2004). We focus here on one type of technical systems: assembled hardware products. The architecture of a product is one of its central design elements. 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, Ward, Milligan and Berry 2000; Worren, Moore and Cardona 2002; Tu, Vonderembse, Ragu-Nathan and Ragu-Nathan 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, Parkinson and Papalambros 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.

It has been acknowledged that most real products are somewhere between the extremes of modular or integral (Ulrich 1995; Schilling 2000), and that what matters are the relative differences, either between products or between product generations over time. Pointing towards an operationalization 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 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 across different countries. Second, the assessment method defines *interfaces* as composed of three separate sub-characteristics: *interface strength, interface irreversibility*, and *interface standardization*.[1] Interface strength describes the interface's technical nature (transfer of mechanical forces, materials, signals, etc.) and includes a measure of intensity. The irreversibility of an interface measures the effort required to disassemble the interface, an aspect important if the product is expected to vary over its own lifetime. The third interface characteristic, interface standardization, we use as synonymous to compatible, i.e., the measure 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 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

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[1] The interface characteristics *strength* and *irreversibility* were re-labeled from originally *type* and *reversibility*, respectively, and for the third interface characteristic, *interface standardization,* the coding was reversed. These adjustments were made to ensure that a decreasing number aligns with increasing modularity for all assessments.

rationale for this approach is that products can be modular with respect to some functions but much more integral with respect to other functions.

To illustrate this assessment method we apply it below to the bicycle drivetrain component set that includes shifter, derailleur, freewheel, chain, and hub, plus break 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 'actuating brakes' for control purposes) in its first column, and all components in the first row.[2] If a component contributes to a function, then the corresponding cell is marked with a '1.' With help of this matrix we then calculate two indices: index 1 counts the number of components that contribute to a function, and index 2 counts the total number of functions these components are contributing to. 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.

Insert Table 2 about here

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 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. To aggregate the measures per function we sum the assessments for all interfaces of the components involved in a given function.[3] The higher the individual numbers, the further is the function away from being modular.

To measure the interface characteristic *standardization* 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 (Figure 4). In other words, if there are many compatible components on either side of the interface, we assign a high degree of standardization which decreases when one, or both, populations shrink.[4] The relevant interfaces for the functions 'power transmission' and 'gear shifting' exhibit relatively high levels of standardization.[5] At an evaluation of 3,3, for example, every version of a derailleur is compatible with every version of a chain. (In the original framework the area between 3,3 and 0,0 is occupied by systems where

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[2] 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.

[3] This approach implicitly assumes equal weight for each of the four dimensions of *interface strength.* For the purpose of observing change over time within a given technology this approach is justified.

[4] The concept of *interface standardization* as applied here is based on Fixson (2005). More recently, Jacobides and co-authors (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.

[5] To assess the size of the population of compatible alternatives includes two aspects: (a) whether or not components are compatible, and (b) the population size of the component. For the assessment of component compatibility we screened all issue of *Bicycling Magazine* for data on when manufacturers introduced product architectures with components that were compatible with those of rival product architectures and when they introduced product architectures having components that could only be used in the context of this specific product architecture. In a second step we verified the compatibility of components with help of Sutherland's Handbook for Bicycle Mechanics (6th edition), which is a technical report for bicycle mechanics, sometimes dubbed as 'the Bible for Interchangeability'. The handbook details in 450 pages the interchangeability between individual components. For the assessment of population size we used the model market share from the *Superspec Database*.

every component is compatible with *every other* component, e.g., LEGOs.) Table 3 summarizes the complete product architecture assessment results.

Insert Figure 3 about here

Insert Figure 4 about here

Insert Table 3 about here

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 aspects and some perceptual ones, whereas we simply use our framework to describe technical product architecture changes over time.[6] In general, we feel that the debate on what constitute a dominant design is much larger as it encompasses additional conceptual dimensions.[7]

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[6] 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 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.

[7] For example, for some scholars a dominant design is determined through socio-cognitive sense-making processes between market participants (Rosa, Porac, Runser-Spanjol and Saxon 1999). Seen from this perspective, a product design can become (or recede to be) a dominant design without actual changes in its technical parameters.

A peculiarity that needs to be addressed in the measurement of product architecture change over time is the possibility of heterogeneity of product architecture change across firms. Existing work has focused on explaining "why the dominant design of a product system should migrate toward or away from increasing modularity." (Schilling 2000:320) This focus on the dominant design makes sense in stable or slowly changing industries. However, we consider it possible that during a period of change multiple versions of product architectures exist simultaneously in an industry. To account for this possibility we measure two product architectures at each point in time. One represents the most 'advanced' product architecture, 'advanced' meaning deviating the most from the industry median; the second reflects the median, i.e., the typical, product architecture of the rest of the industry. In our assessment, we label the first with 'Industry Leader' (note that the firm became industry leader only *after* the product architecture change) and the second simply with 'Rest-of-Industry.' To study product architecture change and its effects over time we measure two product architectures each at four points in our observation time frame (t_{-1}=1980, t_0=1985, t_1=1988, and t_2=1990).

2.2.2 Industry Structure

To determine the structure of an industry is difficult because the relevance of surrogates often used to define industry boundaries – the functionality of a product, the components a product consist of, the relationships between components, or the processes required to develop, manufacture, and sell the product – can vary substantially across products, times, and regions (Dalziel 2005; Jacobides et al. 2006). The probably only uncontestable way to describe an industry unambiguously would define an industry around a single product that consists of only one component, and every firm in this industry engages in all relevant processes. Since this view is unrealistic, the four surrogates listed above can be used to define an industry, each presenting its own advantages and challenges. First, describing an industry along its product's functionality appears to be intuitive, but technical developments can make the boundaries very fuzzy. Consider a technology that is used in many different products, e.g., software. Does this mean that a company providing software for automobiles, aircrafts, and power plants is part of these industries? The second option to define an industry structure is along the components that go into a product.[8] The question here is whether the manufacturing of the component is part of the higher level industry. Given that modern high tech products contain many layers of these relationships, the question then becomes how far down lies the industry boundary? For example, is a screw and rivet manufacturer part of the ship building industry? The third conceptual approach is to define industries around compatible products or components. In contrast to the previous definition where one component becomes part of exactly one other product, here two (or more) products form a higher level system and the constellation of this system can change. Many industries in which products rely on the interoperability with other products fall into this category, for example, computer hardware and software, VCR players and tapes, or Video game consoles and CDs.[9] The challenge here is that a change in compatibility – without a change in functionality or component content – could cause an industry boundary change. The fourth possibility to define an industry is to follow the processes required to design, make, and sell a product. This approach is straightforward for individual products. However, recent innovations in business processes make this definition much less obvious. For example, does the computer industry include firms providing internet services? In the literature, all of these four conceptual industry definitions are used, often in combination. For example, Grove (1996:40-44) in his

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[8] This view underlies the discussion on vertical integration and the classic make-vs-buy decision in transaction cost economics (Williamson 1985). The typical example is an assembler who has to decide whether he wants to buy a component that will become part of his assembled product from an external supplier or to manufacture it in-house. This individual decision can shift the firm boundary, and consequently, in its aggregate the industry boundary.

[9] In fact, the literature on network effects and network externalities tends to apply this logic for industry description (Katz and Shapiro 1985; Economides 1996).

description of the seismic changes of the computer industry between 1980 and 1995 includes layers representing hardware parts (e.g., chips), software (e.g., operating systems), and business functions (e.g., sales and distribution). Similarly, Fransman (2002) includes as layers of the infocommunications industry (hardware) equipment and software, network, connectivity, navigation and middleware, and applications.[10]

In complex industries these definition difficulties might be unavoidable. However, to investigate the exact mechanisms through which product architecture change might affect firms, and in aggregate the industry structure, we opt for a narrower industry structure measurement, one that is mostly akin to the third option above. More specifically, since the bicycle drivetrain component industry consists of six horizontal segments we construct two proxies to measure changes in the competitive dynamics within and across these segments. As our first measure we use the Herfindahl-Index to measure industry concentration within each of the six segments (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 components. We define the fraction of models for which a firm supplies its components as our proxy for market share within its segment.[11]

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[10] Some authors do make the distinction between different logics for defining an industry clear. For example Macher and Mowery (2004) in their study on the computer industry point out the difference between the interdependence between complementary components on one hand, and the interdependence between subsequent process steps (i.e., design and manufacturing) on the other.

[11] 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

Our second measure, an index to assess concentration across the segments we call integration index. This index focuses on the composition of the product bicycle, rather than the firm. The index 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 bicycle a 'type 1' bicycle. If two firms share the supply of the six components, the bicycle 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. For each of the types, the value of the integration index can vary between 0% and 100%. The integration index 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 indices at four points in our observation time frame (t-1=1980, t0=1985, t1=1988, and t2=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.[12]

3 THE CASE: THE BICYCLE DRIVETRAIN COMPONENT INDUSTRY

3.1 Industry Selection and Data Sources

To explore the effects of product architecture change on competition we selected the bicycle drivetrain component industry from 1980 to 1990 for several reasons. First, and most importantly, while historically the bicycle as a whole has been understood as a modular product

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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."

[12] While our layer maps look similar to Grove's (1996:40-44), ours are narrower in industry definition since they include exclusively technical components.

(Galvin and Morkel 2001), the dominant product architecture of the drivetrain component sets exhibited during the 1980s a significant change in the direction of our interest: from modular to integral, thus represented a relative anomaly, an opportunity to contribute to theory building (Eisenhardt 1989; Carlile and Christensen 2005). Second, while the limited complexity of the product – as compared to computers or jet engines – better allows us to study effects of interest, it is not too limited to allow useful insights. Others have used the related bicycle industry for insightful studies (Randall and Ulrich 2001; Ulrich and Ellison 2005). Finally, despite the significant changes in product architecture and industry composition, this industry exhibited a relatively stable industry boundary during the study period which enables better control for industry-level factors on competition (Dalziel 2005; Jacobides 2005).

The bicycle market in the U.S. has 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).[13] 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

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[13] The percentages refer to the SSD database which covers all bicycles over a price point of $150.

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, 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.

3.2 Bicycle Drivetrain Components and the associated Industry 1980-1990

In the early 1980s the standard bicycle drivetrain was what could be called perfectly modular. In 1980, the components for the functions 'power transmission,' 'gear shifting,' ' and brake actuation,' showed a low level of integrality with respect to their function-component allocation (low values in column t_{-1}=1980 for index 1 and index 2 in Table 4). The interface assessment reveals that the interface strength was medium (medium value), the irreversibility was medium (medium value), and the interface standardization was relatively high (low values). The product architecture assessments for industry leader 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 RBs and over 25 for MTBs, some firms were active in all six segments, others only in one or two. The RB drivetrain industry of the early 1980s had three major contenders and many small companies. Shimano, SunTour, and Campagnolo were the leaders in most drivetrain component market segments, 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 segments but their market shares varied across segments; 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, the overall market concentration was relatively low, and varied substantially from segment to segment. The Herfindahl indices for the RB market for this time period ranged from 1,000 (hubs) to 2,870 (derailleurs). Similarly, the industry concentration across segments was very low. In 1984, only 5.6% of the new RBs introduced came with all drivetrain components provided by a single supplier (labeled as 'Type 1'), and 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, 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, 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 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).

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, Feb 1986:154). The key for the development of S.I.S. was to redesign an entire group of components. Shimano redesigned the four components shifter, derailleur, freewheel, and chain, and changed the linkages between them. In short, it made the product architecture of this set of components more integral. Table 4 makes the details of this architectural change visible. Their integral design increases the values of index 1 and index 2 of the function-component allocation for both 'power transmission' and particularly 'gear shifting' (recall that higher values indicate a larger distance from modular function-component allocations). Of the three interface characteristics, one changes slightly (strength) due to somewhat higher precision requirements, one did not change at all (irreversibility) because the firms still used the same type of fastening technologies, and one changed dramatically (standardization) due to the eliminated compatibility between the industry leader's components and the components of the rest of the industry. With the exception of the standardization measure, the changes only affected the product architecture of the industry leader. The reason why also the standardization assessment of the product architecture of the rest of the industry is affected lies in the fact that this measure indicates the size of the population of compatible components. The industry leader changed its design, and initially reduced its standardization level drastically. At the same time, however, by removing its components from the ‘compatibility market’ it also reduced the level of standardization for everybody else, albeit initially to a lesser degree.

In 1985 the markets for bicycle drivetrain components were still fairly competitive. The within-segment Herfindahl 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 in 1985 in its top RB line Dura-Ace, to its moderately priced 600 group in 1986 (Bicycling, Mar 1987:38) and 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 involved was any longer compatible with other components made by other firms. Responding to Shimano’s success with its new index shifting architecture, 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.

Note that the function-component allocation assessment for the industry leader does not change from t_0=1985 to t_1=1988, but it does for the rest of the industry. In fact, the measurements for the rest of the industry approach those of Shimano. The same it 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.

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). Throughout the second half of the 1980s Shimano and SunTour were in fierce competition with each other. However, even though both firms offered similar product lines, Shimano's market share leadership grew with every year. By 1988, Shimano held 77% 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. Compared to 1985, 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.

In 1989, Shimano took the product architecture integration one step further, and introduced its HyperGlide (HG) freewheel, allowing bike riders to change gears under load while pedaling, even when shifting from a smaller to a larger sprocket (Bicycling, Sep 1988:8, Dec 1989:96). The HG freewheel had to be keyed to the hub so they could only be assembled in one alignment (Berto 2005:298). From a product architecture perspective, Shimano had now integrated 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 or those of other firms. 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.

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). By 1990 the MTB market was larger than the RB market. As a consequence, 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. In 1990 Shimano held 57% of the RB drivetrain market with S.I.S., SunTour 11% with Accushift, and Campagnolo 28% with Synchro (Fig. A.1.7).

While the industry concentration process slowed down in the closing years of the decade, the concentration became very homogenous across the segments. The Herfindahl indices in 1990 for RB ranged from 4,150 to 4,220 for RBs and from 6,380 to 6,790 for MTBs. This homogeneity across segments becomes also visible in the integration index. In both RB and MTB markets over 90% of the bicycles are equipped with all six drivetrain components made by a single firm (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 markets. 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.

Insert Table 4 about here

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4 ANALYSIS: 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. Following our two research questions the analysis is divided in 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 1). Some scholars, however, recognize the possibility of a reverse movement towards higher degrees on integrality (towards PA 2). 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 and co-authors (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. The 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. 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 segments 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 events observed in our case studies, 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.

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 forces that drive these changes, i.e., the mechanisms and drivers. 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 change paths (f) and (h) respectively, whereas the second force can be understood as change path (c).

Christensen and co-authors (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 " .. 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 that was unable to respond to the introduction of the quartz watch movement. While the case exhibits some similarity to our bicycle drivetrain component case with respect of 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 and co-authors (2001) also emphasize the value for a firm to maintain 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 see the integration rather as a response to changes in either customer demand or technological environments in order to lower transaction costs than 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 competitors to play on the new playing 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.[14]

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, Feb 1985:163-174). The company also 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.[15]

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[14] The counterexample is a case from 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 value creating for them and rejected it. Shimano retreated and reverted back to interchangeable components.

[15] In contrast, during the aerodynamics episode, Shimano tried to force the dealers to purchase the special tools required to repair the aerodynamics component sets (Bicycling, Feb 1982:66-96). This strategy contributed to the dealers' unwillingness to carry Shimano's aerodynamic component sets.

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 were 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 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 *re-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 related to the first. The introduction of our fine-grained and multi-dimensional product architecture measurement not only allowed to identify specific product architecture change patterns, but – in conjunction with the careful industry definition – also permitted making the mechanisms through which changes of individual product architecture dimensions affect individual competitor categories visible. For the bicycle drivetrain case we identify three different mechanisms that affected different types of competitors very differently (Figure 5). The first mechanism, 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 system 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. Through this elimination of interfirm component compatibility, the small firms essentially lost the population of components that were 'co-specialized' with their own components. 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.

Insert Figure 5 about here

It has been shown before that individual product architecture dimensions are linked to multiple individual *operational* performance dimensions such as cost and time of a firm (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 in a narrowly defined industry. We hypothesize that in industries defined with higher levels complexity additional cause-effect relationships are at work.

The third contribution as a result of our case analysis is to direct the focus of attention on the role of the *origin* of architectural innovations, and their underlying prerequisites, for shaping industry structures. More specifically, we propose that the firm boundary location is not only outcome of efficiency considerations of but can also be pre-condition for some type of innovations.

Most current explanations of what determines an industry's structure rely on explaining the firm boundary location choice as a consequence of efficiency considerations, either immediate or indirect, or of playing to the advantage of an existing industry architecture. Classic transaction costs analysis focuses on how information asymmetry and incentive problems on co-specialized assets can create hold-up problems. The firm boundary choice then is concerned with lowering the total of these immediate transaction costs *given* these pre-defined friction losses in the system. 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, 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 and co-authors (2006). They suggest viewing competition more systemically, i.e., to rethink the business model, and to benefit through activities such as inducing competition in neighboring industry layers or investing in assets expected to appreciate through increasing competition. For all of these explanations, however, the co-specialization of assets seems to be an exogenously determined aspect.

In contrast, while we agree that the ultimate value of co-specialization is determined by the market, we suggest that the degree of co-specialization is to a large extent an endogenous variable. Engineering decisions – particularly those concerning the product architecture – affect the degree of co-specialization, both for assets as well as products and components. The value increase through co-specialization can lie in a performance increase as observed in our case. An alternative effect could be cost reductions that are made possible not through efficiency improvements but only through a redesign of the larger product architecture (cf. Cooper and Slagmulder 2004).

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 a more modular one. Although the type of value premium is dissimilar, in both cases it is the designers that envision a 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 be a necessary ingredient to maintain competitiveness in case of an architectural shift. It helps to avoid the ‘modularity trap’ (Chesbrough and Kusunoki 1999). That it is not necessarily sufficient to create architectural innovations, however, is illustrated by the fact how long it took the defenders to create 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 might also be invaluable for a firm in *creating* a new architecture in the first place. In summary, we argue that the firm boundary might 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, for the direction of the cause-effect relationship between product architecture and industry structure then the insight from our case study requires a nuanced distinction. On the industry level, there has been a strong cause-effect relationship in the direction from the product architecture to the industry structure. The successful integral product architecture forced all firms to become more integrated, albeit through three distinct mechanisms. However, on the individual firm’s level – especially at the beginning of the process – there exists the possibility for a causality in the other direction. Not for the industry as a whole, but for an individual firm it might be that the firm boundary choice precedes the product architecture choice. When the integral architecture is successful, it sets in motion the strong causality running from product architecture to industry structure mentioned above.

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 the 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 effects propagation paths and mechanisms is a pre-condition to align engineering and strategy. Second, the necessary – albeit not necessarily 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 play in a game, to change the rules of the game requires investments in a broad knowledge base.

Together, the insight of the existence of multiple, separate effect propagation paths, and the concern for the capabilities requirement for product architecture innovations, allow distilling 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. 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 an unusual case in which decreasing modularity in a mature and modular industry led to an overwhelming dominance of the attacking firm. Our case data show how the introduction of an integral architecture by a then non-dominating firm resulted in a near-monopoly position of 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 in the direction from the former to the latter.

There are mainly two limitations of our study. The most obvious limitation comes with a single case study focusing on only one industry, which always makes generalizations beyond this industry 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 very helpful insights, and we hope to add to this body of knowledge with our study. A second limitation is – as in any empirical study – the quality of the measurement instrument. For both of our main dimensions, product architecture and industry structure, we construct proxies to measure the change over time of the underlying construct. 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 allows interesting insights into the powerful effects that product architecture choices can have on competitive outcomes.

An interesting direction to extend this research is to investigate product architecture changes and their consequences in larger, more complex supply networks. Earlier we pointed out that many studies do not distinguish clearly between vertical, horizontal, or sequential industry structures. In this study we have focused deliberately on a rather horizontal industry structure of limited size to isolate product architecture effects caused by integration 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, Raynor and Verlinden 2001), and some empirical studies indicate that a firm boundary shift, caused by a product architecture change, might occur in one direction within a dyadic relationship, but not at all or in the reverse direction in the dyad below (Fixson, Ro and Liker 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.

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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**
Road	5	12	27	18	215	134	143	134	147	179	346
MTB	N/A	N/A	N/A	N/A	N/A	43	48	59	94	134	369
Hybrids	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	58
Others	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	30
Total	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 annoucements and aggregated them for each year.

Table 2: Measuring function-component allocation (Shimano at t_{-1}=1980)

Product Architecture Shimano: t-1=1980

		Components						Index 1	Index 2
		1	2	3	4	5	6		
	Functions	Brake levers	Shifter	Derailleur	Free-wheel	Chain	Hub	Component count	total functions involved with these components
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

		t_{-1} = 1980		
	Functions	Power Transm.	Gear Shifting	Brake Actuation
PA Dimension 1	Function-Component Allocation Scheme			
	Index 1	3	2	1
	Index 2	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: Longitudinal data on changes of product architecture and industry structure

				t_{-1} = 1980			t_0 = 1985			t_1 = 1988			t_2 = 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
Product Architecture	Industry Leader	PA Dimension 1	Function-Component Allocation Scheme												
			Index 1	3	2	1	3	4	1	3	4	1	3	5	1
			Index 2	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
			Standardization	3,3	3,3	N/A	8,8	8,8	N/A	6,6	6,6	N/A	4,4	4,4	N/A
	Rest of Industry	PA Dimension 1	Function-Component Allocation Scheme												
			Index 1	3	2	1	3	2	1	3	4	1	3	4	1
			Index 2	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	5,5	5,5	N/A	7,7	7,7	N/A	8,8	8,8	N/A
Industry Structure	Within Segment Concentration [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 Segment Concentration [Integration Index]	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%		
			N/A	5.6% *			3.0%			4.1%			1.7%		
		MTB	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_{-1} = 1980			t_0 = 1985			t_1 = 1988			t_2 = 1990		

* = Data from 1984

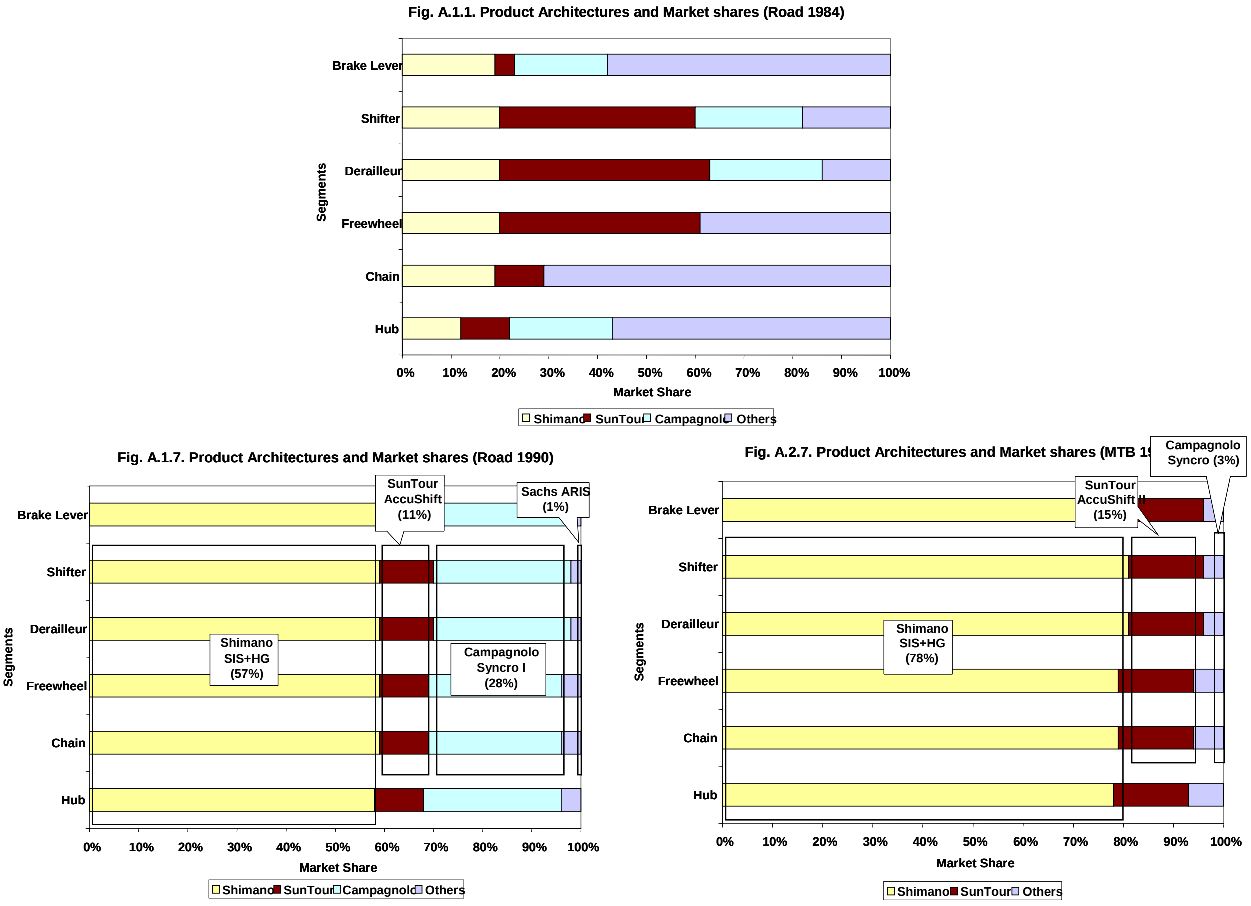


Fig. A.1.1. Product Architectures and Market shares (Road 1984)

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

Fig. A.2.7. Product Architectures and Market shares (MTB 1

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

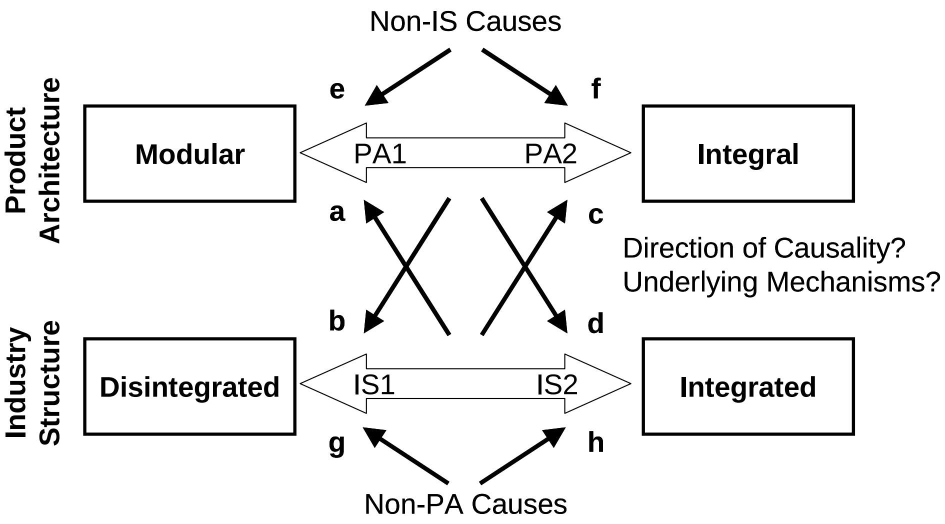
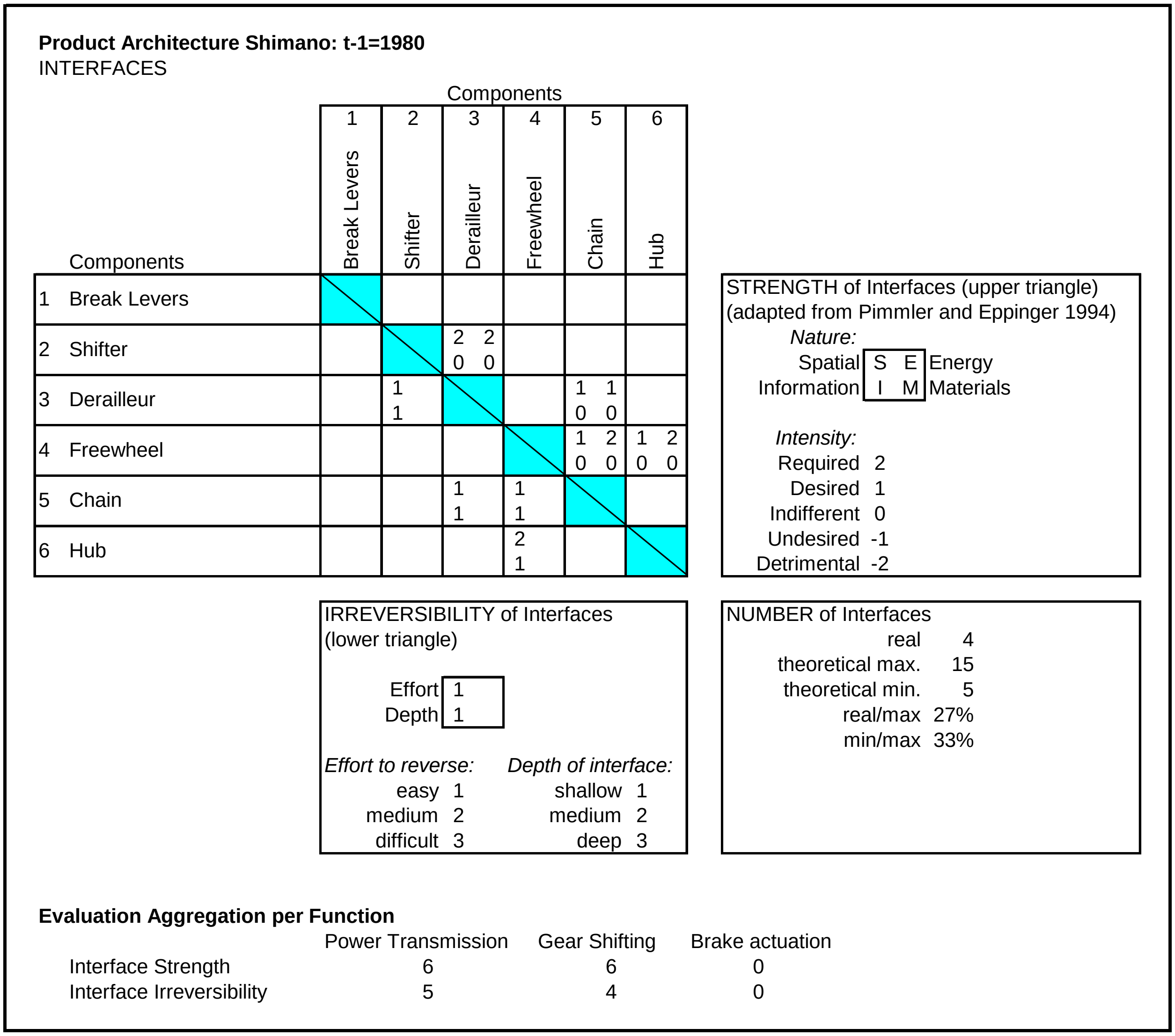


Figure 2: Research framework



Product Architecture Shimano: t-1=1980

INTERFACES

Components	1 Break Levers	2 Shifter	3 Derailleur	4 Freewheel	5 Chain	6 Hub
1 Break Levers						
2 Shifter			2 2 0 0			
3 Derailleur		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	Energy
Information	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_{-1}=1980)

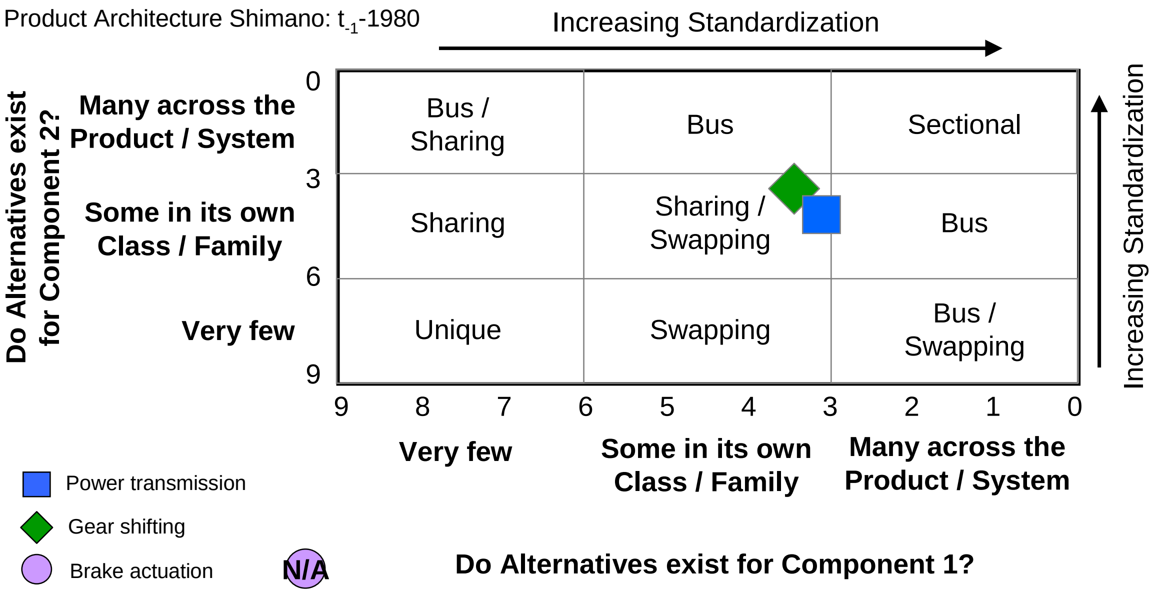


Figure 4: Measuring interface standardization (Shimano at t_{-1}=1980)

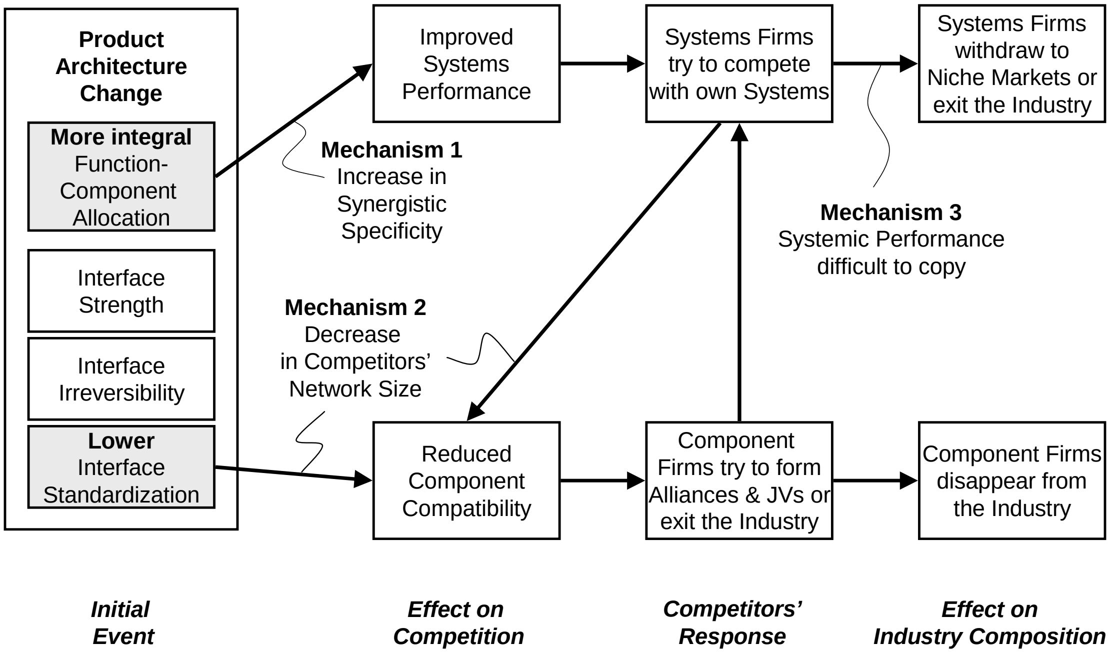


Figure 5: Three mechanisms through with product architecture changes affected competition

APPENDIX

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

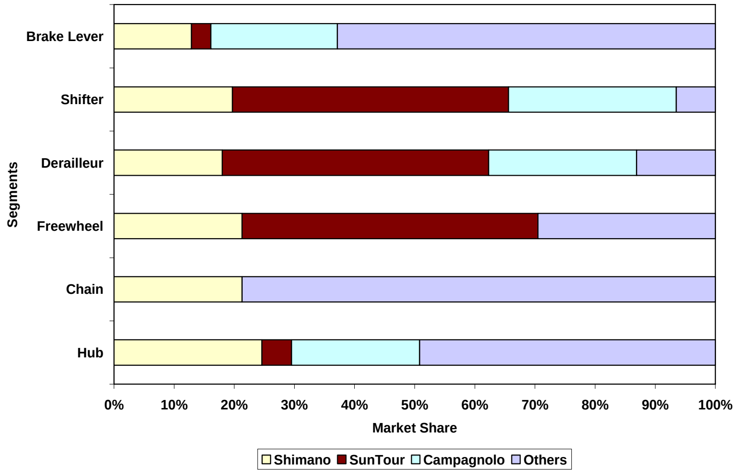


Fig. A.1.1. Product Architectures and Market shares (Road 1984)

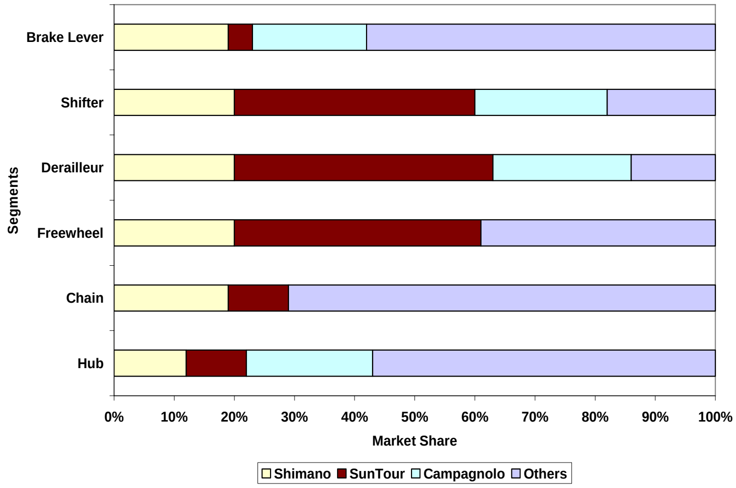


Fig. A.1.2. Product Architectures and Market shares (Road 1985)

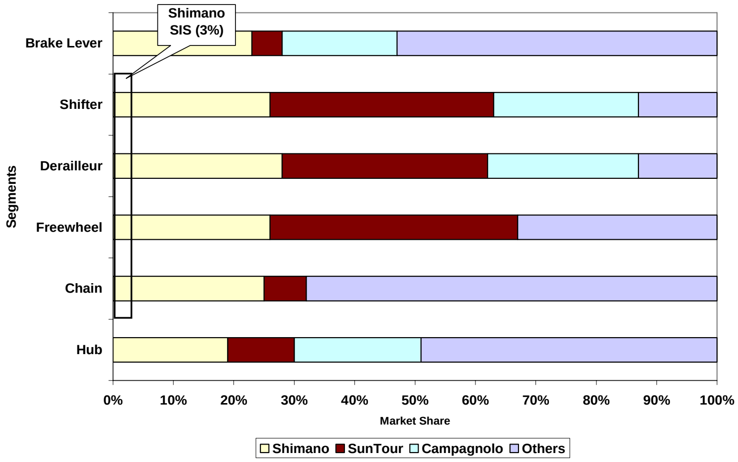


Fig. A.2.2. Product Architectures and Market shares (MTB 1985)

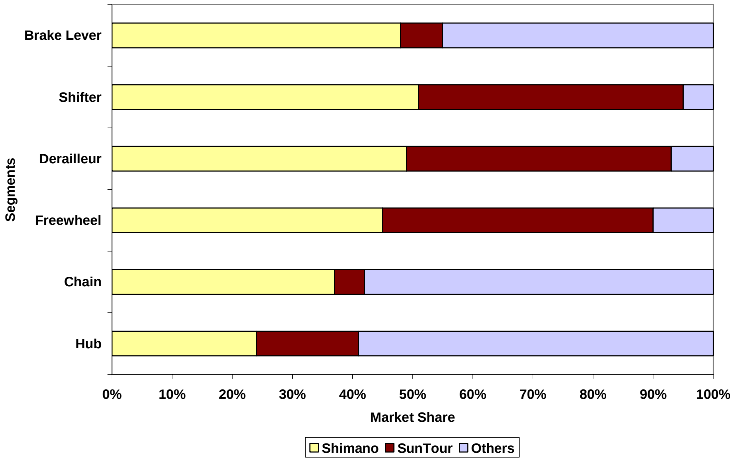


Fig. A.1.3. Product Architectures and Market shares (Road 1986)

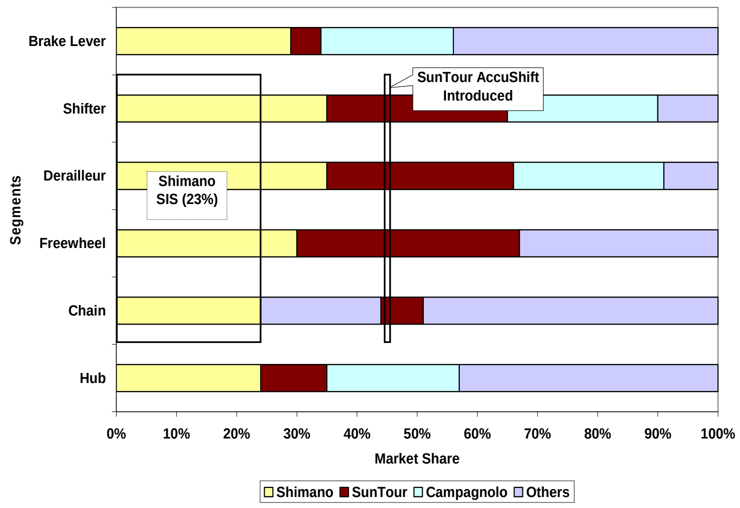


Fig. A.2.3. Product Architectures and Market shares (MTB 1986)

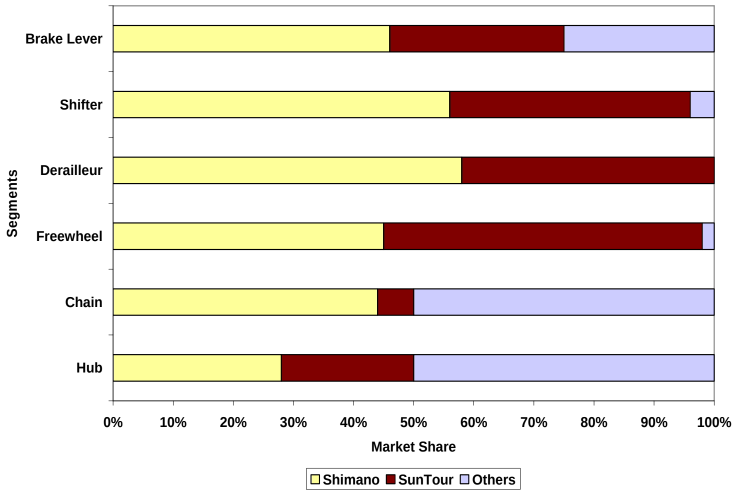


Fig. A.1.4. Product Architectures and Market shares (Road 1987)

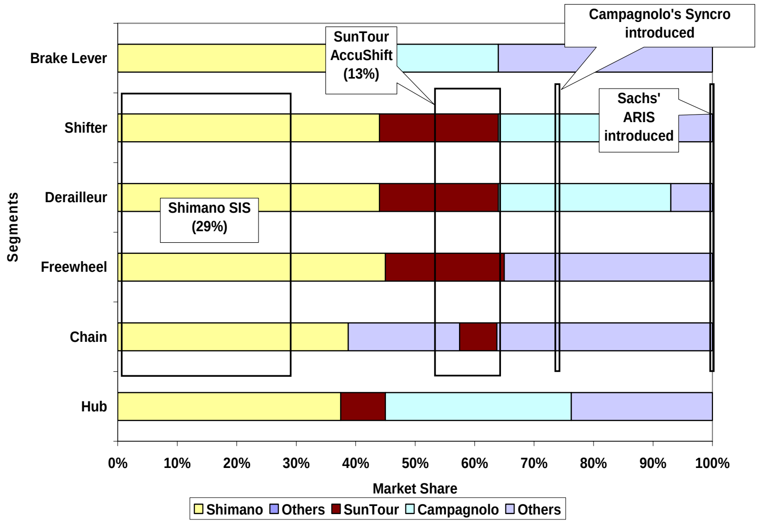


Fig. A.2.4. Product Architectures and Market shares (MTB 1987)

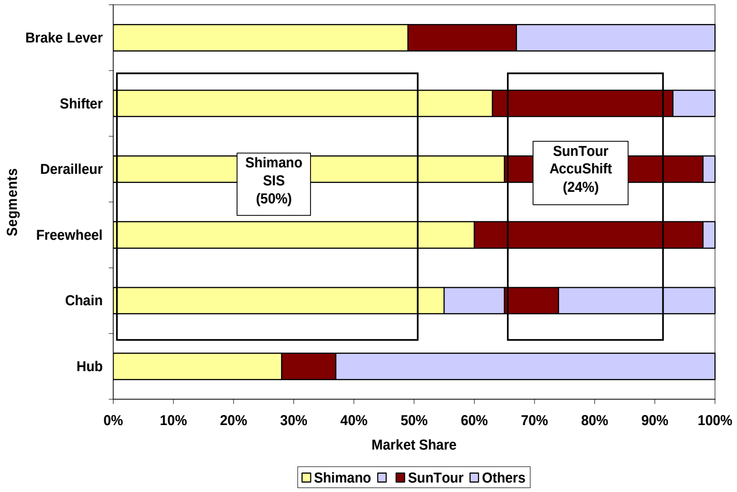


Fig. A.1.5. Product Architectures and Market shares (Road 1988)

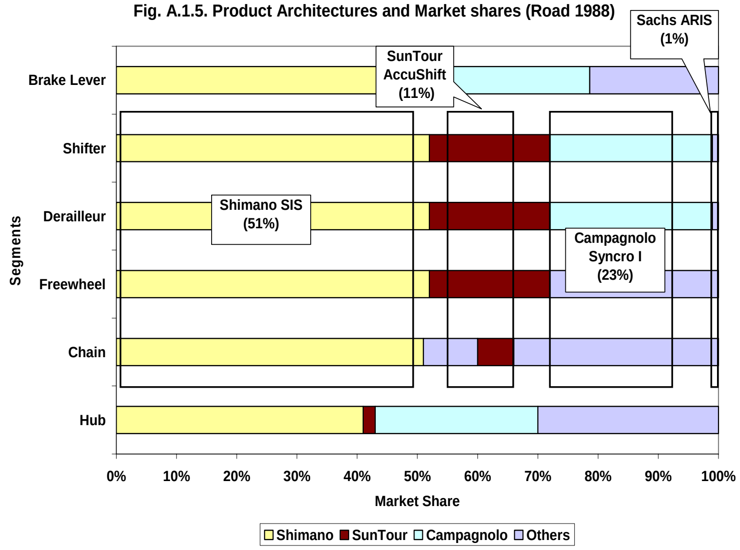


Fig. A.2.5. Product Architectures and Market shares (MTB 1988)

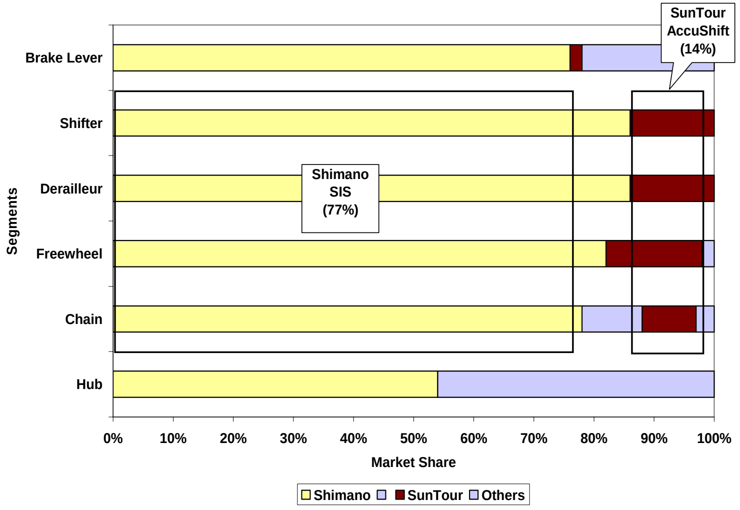


Fig. A.1.6. Product Architectures and Market shares (Road 1989)

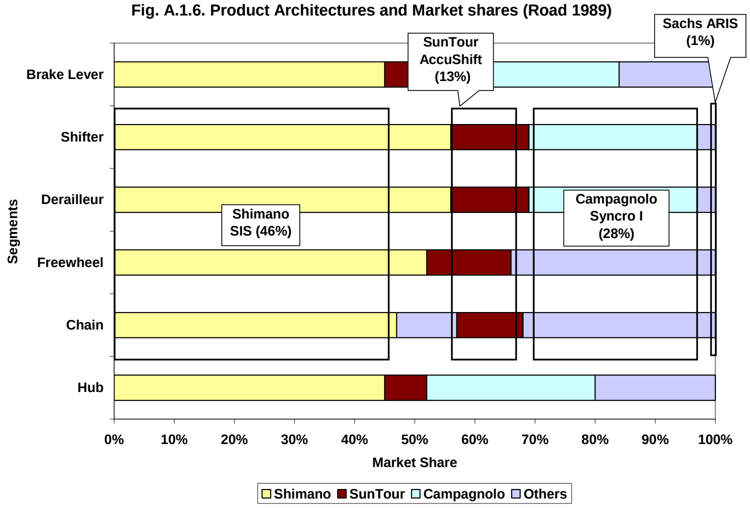


Fig. A.2.6. Product Architectures and Market shares (MTB 1989)

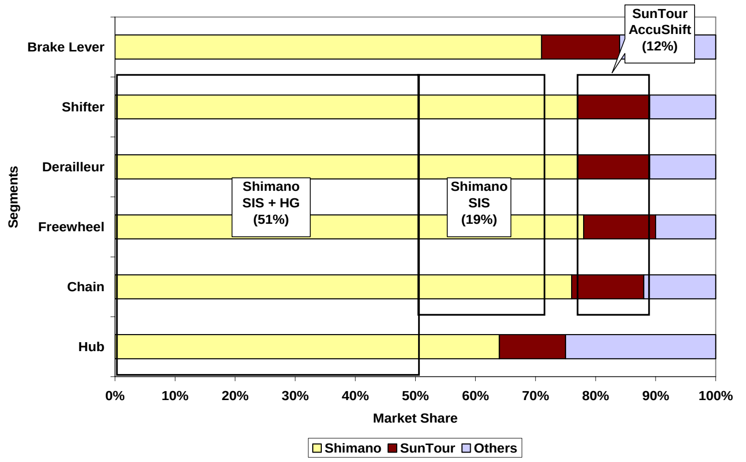


Fig. A.1.7. Product Architectures and Market shares (Road 1990)

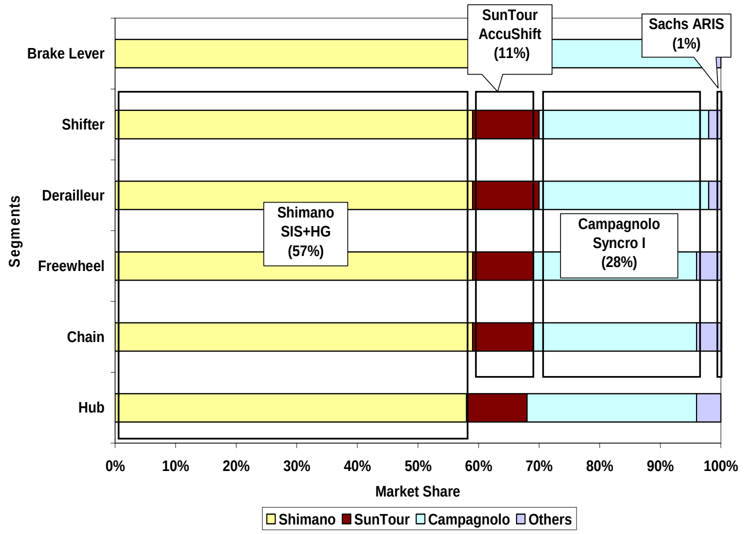


Fig. A.2.7. Product Architectures and Market shares (MTB 1990)