The Power of Product Architecture Innovation: Modularity, Integrality, and Competition

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Abstract

Modular product architectures have recently received a surge of attention due to their advantages for product variety, mass customization, and standardization. It has been suggested that many products and systems migrate over time to higher levels of modularity. To explore the linkages between product architecture and competition in an industry, we study an unusual case of decreasing product modularity that is linked to substantial changes in industry composition. We identify conditions favorable for the start of the product architecture change process, and specify detailed mechanisms through which the de-modularization resulted in a near-monopoly position of the attacking firm. We argue that the product architecture simultaneously represents a firm's decision variable and shapes the firm's competitive environment, and the relative weight between them is determined by contextual circumstances.

Keywords

Product Architecture, Modularity, Integrality, Compatibility, Meta-stable equilibrium

1 INTRODUCTION

Two literature streams have approached the study of the effects of product architecture from two different directions. The literature in operations management exhibits a substantial body of work that has studied the impact of modular product structures on process efficiencies. Complexity reduction, scale effects, and risk pooling are examples of the mechanisms through which modularity can help to improve the performance of operations, be they product development, manufacturing, or logistics (van Hoek and Weken 1998; Salvador, Forza and Rungtusanatham 2002; Mihm, Loch and Huchzermeier 2003). Many of these studies take on a firm-level perspective and assume the degree of product modularity as a decision variable of the individual firm. On the other hand, the literature in technology management has explored the intricate interconnections between technological innovations and competition. Firms are subjected to industry era changes, suffer from cognitive limitations to detect architectural innovations coming from outside, or potentially invest in ultimately unsuccessful technology candidates (Anderson and Tushman 1990; Henderson and Clark 1990; Utterback 1994). One aspect that recently has generated particular interest in this field is the role that the overall structure of a product plays for the competitive positions of the firms involved in an industry (Baldwin & Clark, 2000). With the exception of the latter study of the computer industry, the majority of these studies takes on an industry-level perspective and studies firms defending themselves to outside attacks via technological innovations. In this paper, we argue that the product architecture connects the above fields as it is linked to both operational efficiency and strategic effectiveness. Given that product architecture decisions are made during new product development, we believe that understanding these connections can contribute to developing a new product development strategy, and thus contributing to bridging a gap in the operations management literature (Krishnan and Loch 2005).

Product architectures have been categorized into two archetypes: integral and modular (Ulrich 1995; Baldwin and Clark 2000; Schilling 2000). The classic illustration for a modular product is the personal computer, other examples include software, some recent textbooks, and sectional sofas. But product architectures are not static; they can change over time. It has been suggested that product architectures often evolve towards higher levels of modularity. Some empirical evidence exists in support of this path of product architecture change (Baldwin and Clark 2000; MacCormack, Rusnak and Baldwin 2004; Shibata, Yano and Kodama 2005).

Two theoretical frameworks lend support to the development in this direction. Both suggest that product features often associated with modularity, e.g., mix-and-match compatibility, increase with industry maturation and time. The first framework, the life cycle framework for industries and products, emphasizes the stabilizing effect that occurs through a selection of a dominant design as an industry evolves (Abernathy and Utterback 1978; Utterback 1994). In the model's first phase, the fluid phase, numerous technological options compete with each other. At this time, neither the problem that the products are trying to solve nor the way in which they will do so is yet exactly defined. The following transitional phase witnesses a shakeout of ideas – and firms associated with these ideas – until in the specific phase a dominant design emerges and only few competitors remain. The dominant design emergence shifts the emphasis from product innovation to process innovation and, more relevant here, allows additional product differentiating features, such as variety and compatibility with complementary products and components, to gain a relatively larger role. This increase in utility through compatibility is also the idea that underlies the second framework: network externalities. This framework suggests that a utility a user derives from her product does not only depend on the individual product itself but also on the number of other users in the network (e.g., phone) or the availability of complementary products (e.g., software for a computer).

Given this widespread support for the idea of increasing modularization, what could explain a development towards increasing integrality? To explore this question we investigate the linkages between product architecture and competition in an unusual situation of decreasing product modularity, and use our findings to extend the frameworks discussed above. In our study of the bicycle drivetrain component industry we observe an increase in product integrality and this change in product architecture is associated with substantial changes in industry composition, i.e., the product de-modularization resulted in a near-monopoly position for the attacking firm. Using this interesting case we address the following three research questions in this paper: First, how do product architectures change over time, i.e., how can we understand the direction of change? Second, why do product architectures change at all? Who starts the change process and what role do environmental conditions play? Third, what are the consequences of these product architecture changes once they are initiated? In other words, what are the mechanisms through which product architecture changes might propagate through an industry and what is their impact on competition?

In the next section, we review the literature on product architecture changes and their known causes. In section 3 we present the detailed data of our industry and product architecture studies. In section 4 we analyze in detail the beginning, the progress, and the consequences of the product architecture changes in this industry, and use the findings to extend the above named theoretical frameworks. Section 5 concludes.

2 PRODUCT ARCHITECTURE CHANGE

Before studying product architecture changes one has to define what he considers as a product architecture. Thus, we begin by reviewing methods of their description and then discuss theoretical arguments for and empirical findings of trends of product architecture change.

2.1 What is a Product Architecture?

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. Various approaches have been chosen to overcome this difficulty. Some scholars use indirect measures, i.e., the degree of product modularity is measured indirectly by asking managers to assess 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 (cf. (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 (cf. (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. Building on Ulrich’s work, a multidimensional product architecture assessment method has been suggested to move closer to the goal of making these relative differences measurable (Fixson

2005). The method relaxes Ulrich's definition of product architecture in three important ways: (a) it allows the two dimensions *function-component allocation* and *interfaces* to vary independently from each other, (b) it defines *interfaces* as composed of three separate characteristics, and (c) it assesses the degree of modularity per function, instead of creating an average modularity assessment for the entire product. For the study of product architecture changes of bicycle drivetrains we will employ this assessment methodology.

2.2 Are there Patterns of Product Architecture Change?

From a theoretical perspective, the evolution of product architecture has been described as originating somewhere near the integral extreme and moving over time to the more modular end of the spectrum. One line of research that supports this view is the industry life cycle perspective (Abernathy and Utterback 1978; Utterback 1994). This perspective identifies the emergence of a dominant design in the industry evolution as the event that defines the fundamental aspects of the product in question. Prior to the emergence of a dominant design various product concepts compete with each other until the emergence of a dominant design signals the coalescence of the competition around a set of implicitly agreed upon parameters. The dominant design is not necessarily the technologically most sophisticated solution, but typically represents a solution that satisfies most customers. As such, this process is the result of ongoing product development by firms and testing by consumers (Clark 1985), and can be described as a process of socio-cognitive sense making (Rosa, Porac, Runser-Spanjol and Saxon 1999). Once the dominant design has emerged and a substantial subset of design solutions and parameter choices is no longer challenged, the focus of competition shifts away from peak performance towards product features such as variety or interconnectivity, i.e., compatibility. These latter competitive foci tend to favor modular product architectures.

A second theoretical perspective that supports the idea that product architectures tend to evolve towards higher degrees of modularity is the one that expanded our understanding of competition between products with the notion of network externalities. Products and services that increase in value for the user as more users are accrued and as additional applications become available, exhibit this effect. Communication technologies (telephone, fax, etc.) fall in the former category (additional users), software products and video games into the latter (additional applications). Work on network externalities has lead to the identification of product compatibility as a key explanation for network effects, and the installed base as a critical competitive advantage for firms competing in these industries (David 1985; Katz and Shapiro 1986; Rosenbloom and Cusumano 1987; Economides 1996).

Some empirical evidence exists that indeed documents the direction of product architecture evolution from integral to modular. For example, computers have been identified as initially having had a rather integral structure that later evolved towards significantly higher degrees of modularity (Baldwin and Clark 2000). Similarly, internet browser software (MacCormack et al. 2004), numerical controllers (Shibata et al. 2005), and college textbooks (Schilling 2000) have been found to migrate towards higher levels of modularity, and only temporarily, if at all, to revert back to more integral structures in the 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.

Another view on product architecture evolution has been formulated by Fine (1998). His double-helix model suggests that product architectures really oscillate over time between modular and integral forms, and neither form is permanent. In his model, product architecture and industry structures change in a co-evolutionary pattern.

2.3 Triggers of Product Architecture Change

A variety of factors has been identified as potential cause for product architectures to change. Again, most of these factors have been researched in association with increasing modularity. The factors can be grouped into two categories – exogenous and endogenous – with respect to the extent to which they are under a firm's control. Exogenous factors triggering product architecture changes can originate from changes in both the market domain and the technology domain (Schilling 2000). A significant change in the market domain, for example, is the increase of customer heterogeneity. It has been suggested that the need for greater product variety is answered best with modular product architectures since they allow creating a wide product variety while still maintaining near-mass production efficiency, an approach often labeled as mass-customization (Pine 1993; Meyer and Lehnerd 1997; Ramdas 2003). Similarly, changes in the technology domain can create forces that cause product architectures to change. For example, the introduction of the quartz movement in wrist watches triggered a fundamental shift of the watches' product architecture (Jacobides and Winter 2005). More generally, the appearance of new materials, new components, or new processes can cause this effect. What is 'new' can even be more subtle than tangible materials or components; new knowledge gained about a technology, for instance, can cause a product architecture to shift (Henderson and Clark 1990; Schilling 2000; Macher and Mowery 2004).

Changes in product architecture can also be caused endogenously. In most cases, it is the product designer, or a team of product designers, that defines the product architecture of a new product or decides to change the product architecture of an existing product (Alexander 1964). For example, in their account of the development of the early computer industry Baldwin and Clark (2000) identify a relatively small group of engineers at IBM that was ultimately responsible for the modular design of the computer's product architecture. Similarly, MacCormack et al. (2004) describe the conscious decision of the program architects to modularize the internet browser software Mozilla. Characteristic for these accounts of endogenous product architecture change is the existence of a deliberately acting central decision maker with respect to the product architecture; this architect typically exerts architectural control (Schilling 2000).

For some products a product architecture change is also possible as the aggregate outcome of numerous individually myopic decisions. In the mortgage banking industry the product – and the process to create it – separated over time into several distinct pieces, i.e., modules. No individual decision had the ultimate modularization in mind, yet it happened in aggregation (Jacobides 2005).

3 DATA AND MEASUREMENTS

To better understand *why* product architecture change begins *when* it begins and *what* the consequences of the change are for industry participants, demands a better understanding of the product architectures change process itself. 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 develop longitudinal data sets of both product architecture and market of our target 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 for several reasons. First, and most importantly, the product architecture exhibited during the 1980s a significant change in the direction of our interest: from modular to integral. Choosing a case that represents an anomaly has been identified as 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 (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 allows to better control for industry-level factors on competition (Dalziel 2005; Jacobides 2005).

To construct the historical accounts of the bicycle drivetrain industry and product architecture we collected both quantitative and qualitative data. For the purpose of triangulation of our data we used a variety of data sources. We collected archival data from magazines, data bases, books, news articles, and academic journals. In particular, we scanned a decade of all issues of the magazine *Bicycling*, which was the leading trade journal in the U.S. during the 1980s. In addition, starting in 1984, *Bicycling* published the *Super Spec Database (SSD)*, an annual listing of all new bicycle models introduced, including the information on who supplied each component. Four additional sources were particularly helpful in understanding bicycle drivetrain technology and the technical changes that occurred in bicycle drivetrain components 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 interviews and e-mail exchanges. We checked data with company representatives, industry observers, and technical journalists and editors of bicycling-related magazines, and we learned details on component compatibility through face-to-face interviews with bicycle mechanics with years of experience in the bicycle repair business.

3.2 The Bicycle Drivetrain Component Industry 1980-1990

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 and specialty bicycle categories around 1990. 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).[1] Consequently, we focus our analysis on the bicycle component firms that supply drivetrain components for these two categories of bicycles.

Insert Table 1 about here

Every bicycle consists of a frame, a drivetrain, and other components such as wheels, tires, and handle bars. As a major part of the bicycle, the drivetrain is at the center of our analysis. A bicycle drivetrain comprises shifter, derailleur, freewheel, chain, and hub. For control purposes we include brake levers. Initially, each of these six components represented its own market segment. The history of the bicycle drivetrain and its associated industry throughout the 1980s is characterized by two phases. The first lasted from 1980 to 1984, the second from 1985 to 1990.

3.2.1 Phase1: 1980–1984

In the early 1980s the standard bicycle drivetrain was what could be called perfectly modular. During this phase inter-firm component compatibility was very high, and most bicycles were sold with a mix of component sets. Similarly, the structure of the industry was fairly heterogeneous and competitive within each segment as well as across the segments. In 1984, 60 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 (see Appendix for details; 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; from 12% to 20% for Shimano, and from 5% to 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.

The MTB market was small in this first phase. 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

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[1] The percentages refer to the SSD database which covers all bicycles over a price point of $150. In other words,

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).

3.2.2 Phase 2: 1985 – 1990

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 cogs 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 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. Shimano introduced this new set first in its top RB line Dura-Ace. A second effect of the new design was that Dura-Ace components with S.I.S. were no longer interchangeable, i.e., compatible, with components manufactured by different firms or even with Shimano's own other components. Shimano introduced S.I.S. 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.

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our data do not consider extremely inexpensive bicycles.

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.

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 dominating 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 1989, Shimano took the 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. 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 and 1991, respectively. 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).

Following the change in product architecture, the competitive situation on the industry level also dramatically changed in the second half of the 1980s. While in 1984, for the RB drivetrain industry the Herfindahl indices ranged from 1,680 to 2,690 for the six different segments, this range shifted over the course of six years to 4,130 to 4,270, indicating a significant increase of industry concentration within all segments.[2] This increase was even more pronounced in the MTB drivetrain industry, where the Herfindahl indices increased from a range of 1,210–4,550 in 1985 across the six segments to a range of 6,320–6,790 in 1990 (Figure 1). The industry concentration increased not only within segments, but also across segments. In 1984, only 5% of the new RBs introduced came with all drivetrain components provided by a single supplier (labeled as ‘Type 1’), and 60% of the new models had their six drivetrain components supplied by four, five, or six different firms. In contrast, by 1990, 92% of all RBs offered in the U.S. came with all six drivetrain components supplied by a single firm. Similarly, the share of MTBs who featured all six drivetrain components from one supplier grew from 7% in 1985 to 94% in 1990, and no MTB had its six drivetrain components supplied by four or more different firms at the end of the decade (Figure 2). This increase in industry concentration coincides with the

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[2] The Herfindahl index is a measure of concentration. It 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 is the Herfindahl index.

emerging dominance of one 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 Figure 1 about here

Insert Figure 2 about here

3.3 The Bicycle Drivetrain Product Architecture 1980-1990

To study the underlying changes of the product architecture over time requires to address two major difficulties. The first difficulty concerns the multi-dimensional nature of modularity, and the second attends to the possibility of heterogeneity of degrees of modularity across firms within an industry at a given point in 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). "Products can be made increasingly modular both by expanding the range of compatible components (increasing the range of possible product configurations) and by uncoupling integrated functions within components (making the product more modular at a finer level)." (Schilling 2000:318) To account for these two major dimensions – *function-component allocation* and *interfaces* – we employ a product architecture assessment methodology (Fixson 2005) that measures them along separate dimensions. As mentioned earlier the method 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 characteristics: *interface type*, *interface reversibility*, and *interface standardization.* The interface type describes the interface's technical nature (transfer of mechanical forces, materials, signals, etc.) and includes a measure of intensity. The interface reversibility describes the effort required to disassemble the interface, an aspect important if the product is expected to vary over its own lifetime. The third characteristic, interface standardization, we use as synonymous to compatible, i.e., it 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. Third, the method assesses the degree of modularity per function individually, instead of creating an average modularity assessment for the entire product. The underlying rationale is that products can be modular with respect to some functions but much more integral with respect to other functions.

Next we apply this methodology to the bicycle drivetrain component set that includes shifter, derailleur, freewheel, chain, and hub, plus break levers. 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. If a component contributes to a function, then the corresponding cell is marked with a '1.' Using 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 in 1980. The two indices span a plane with a perfectly modular, i.e., one-to-one, function-component allocation in the lower left hand corner. Every function can be located in this plane (see left hand side of Figure 5).

Insert Table 2 about here

To measure the interface characteristics *type* and *reversibility* we construct a matrix that lists all components in its first column and its first row. Above the diagonal we describe the interface type by assessing each interface on a scale from -2 to +2 for each category mechanical, material, energy, and signal (Pimmler and Eppinger 1994). Below the diagonal, we assess the degree of interface reversibility by separately assessing 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 in 1980. 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. 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.[3] To increase comparability across the three interface measures we aggregate the standardization assessment per function. Figure 4 shows the interface standardization assessment for Shimano in 1980. Finally, to allow quick visual comparison we collapse the assessments for each of the three interface characteristics on a low-medium-high scale (see right hand side of Figure 5).[4]

Insert Figure 3 about here

Insert Figure 4 about here

Insert Figure 5 about here

The second particularity that needs to be addressed in the measurement of product architecture change over time is to account for possible unevenness 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

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[3] 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*.

[4] The values of 'low' and 'high' for the interface characteristic *type* can be interpreted as intensity or functional strength of the interface.

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 the name of the firm that actively began to change its product architecture “Shimano,” and the second simply with “Rest-of-Industry.” To study product architecture change and its effects over time we measure product architecture at four points in our observation time frame (t_{-1}=1980, t_0=1985, t_1=1988, and t_2=1990).

Figure 6 presents graphically our product architecture measurement results and the changes over time. In 1980 (t_{-1}) all three functions exhibited a relatively high degree of modularity with respect to the function-component allocation (closeness to the origin in the x-y plane), and the interface characteristics *type, reversibility,* and *standardization* were all relatively high (depicted high on the z-axis). These assessments were even across the industry. In 1985 (t_0), performance improvements arose from Shimano’s systemic innovation that cannot be assigned to any single component. As a consequence, the function-component allocation for the functions ‘power transmission’ and in particular ‘gear shifting’ became more integral, i.e., less modular (see (a) in Figure 6). Simultaneously, the level of interface standardization for these two functions dropped significantly as a consequence of the lost interchangeability (b), while the degree of interface type and reversibility exhibited no change. The reduced compatibility of Shimano’s S.I.S. systems with the overall market also led to a drop in interface standardization for the rest of the industry (c). From 1985 (t_0) to 1988 (t_1) Shimano’s product architecture remained unchanged. Nevertheless, because Shimano gained market share and introduced new lines of S.I.S., the degree of its interface standardization increased slightly (e). Meanwhile, the rest of the industry had introduced their own, increasingly integral, architectures by 1988 (d). In addition, the drop in market share led to a lower level of interface standardization for them (f). In 1990 (t_2) Shimano again increased the integrality of its product architecture by making the hub part of the integral design. Consequently, the modularity of the function ‘gear shifting’ fell further (g). However, increasing market share led to an increase in interface standardization (h). Through the same mechanism, the interface standardization for the rest of the industry further decreased (i).

Insert Figure 6 about here

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4 ANALYSIS: EXPLAINING THE POWER OF PRODUCT ARCHITECTURE INNOVATION

Building on both qualitative and quantitative data of our longitudinal study we now turn to addressing the questions concerning direction, origin, and consequences of product architecture change. We believe these insights are applicable beyond this particular industry.

4.1 How do Product Architectures change?

This question is concerned with the direction of product architecture change and the path the change process takes. Concerning the direction of change most empirical studies find product architectures changing in one direction – towards higher degrees of modularity. A few scholars have included the option of product architecture change in the reverse direction – towards higher degrees of integrality – in their models, either as an oscillation process between modular and integral structures (Fine 1998) or as a migration towards an equilibrium that is determined by external forces (Schilling 2000). Depending on the set of forces this migration can be towards or away from higher levels of modularity. Thus, while we are not the first to suggest the possibility of a product architecture change towards integrality, our empirical data describing this process documents this process in real life.

Concerning the path of change our fine grained product architecture measurement allows us to see a more detailed picture of the change process than what the simple dichotomy between modularity and integrality appears to suggest. First, the detailed product architecture measurement demonstrates that product architectures can change along a number of dimensions – jointly or individually. For example, while Shimano's product architecture innovations made the function-component allocations for the functions 'power transmission' and 'gear shifting' more integral, it left the function-component allocation of the function 'actuating brakes' unchanged in its modular state (Figure 6). Similarly, of the three interface characteristics, the innovations affected only the dimension *interface standardization.* The possibilities of combining changes along these multiple dimensions suggest that product architectures not only oscillate or migrate along a one-dimensional axis with the endpoints modular and integral, but can morph into various sub-forms in a multi-dimensional space. In the next two sections we show that the impact on the competition originates from the changes along individual product architecture dimensions. Second, our data show temporal heterogeneity of the product architecture change across firms. This demonstrates that the dominant design concept is helpful once it is emerged, its emergence, however, requires accounting for the unevenness of product architecture change in an industry. This unevenness contains some of the explanation for the change process, and – to some extent – for the forces that drive changes between phases of the industry life cycle. The extent to which the product architecture is a firm's decision variable, or context, depends on this temporal heterogeneity.

4.2 Why do Product Architectures change?

The literature on product architecture change provides two categories of explanations. The first category views the product architecture as a firm's decision variable with little influence from outside forces. This view implies either an industry in its very early life cycle stage, or a product that is only to a very limited extent subject to compatibility request. The second category emphasizes the opposite effect; here the focus is on external forces that drive the product architecture change. For example, Schilling's (2000) model assumes that a 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. Of those eleven propositions only the first three can be construed as being to some degree under a firm's control. 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 the case of the bicycle drivetrain component industry only propositions 1 and 2 are relevant; the variables of all other propositions exhibited no change at all or no change in the predicted direction. The analysis of the effect of the component specificity of the bicycle drivetrain components on product modularity finds exactly the outcome that proposition 1 would predict, i.e., that the degree to which functionality is achieved through component specificity at t_0 will be negatively related to increasing interfirm modularity at t_1. To improve the shifting performance Shimano developed a more integral product architecture. Shimano's index shifting (S.I.S.) technology integrated four components (shifter, derailleur, freewheel, and chain) into a set of tightly coupled components. As a consequence of the increased component specificity, the interfirm product modularity decreased. Notice that the measure *interfirm product modularity* presents some heterogeneity between industry leader and industry average and that there is a time difference between Shimano's introduction of the new integral architecture (at t_0) and the one of the rest of the industry (at t_1). Similarly, proposition 2 predicts that the more difficult it is for customers to asses the quality and interactions of components, the less likely it will be to observe interfirm product modularity later. Our analysis of the bicycle drivetrain component case confirms this prediction. The increased integrality of the new product architecture made it more difficult to assess quality and interactions of individual components and the degree of modularity decreased.[5]

While Schilling's model would correctly predict the overall migration direction of the dominant design of the bicycle drivetrain, it does not explain *why* the process started in the first place. In our view, the findings from the bicycle drivetrain industry point to a larger issue of

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[5] As the later attempts of the major competitors illustrate, it was not even clear to them what exactly caused the higher performance of Shimano's shifting systems. Thus, it is safe to assume that Shimano's customers, i.e. bicycle assembly firms (and bicycle end users) also found it difficult to assess what role exactly each component played in Shimano's indexed shifting systems.

what appears to be an underappreciation of the role of a firm's own actions. For example, the majority of the forces in Schilling's model are exogenous to the firm – suppliers, customers, and competitors. Even so, the model allows two avenues through which firms can actively influence the balance of forces. First, if a firm possesses market power or architectural control it "might be able to push the market to an otherwise unlikely equilibrium." (Schilling 2000:329) This is typically the case either very early in the industry life cycle or when a firm already possesses a critical asset. IBM's re-design of the computer architecture in the 1960s (Baldwin and Clark 2000) is an example of the former, Microsoft's control over the operating system market an example of the latter. However, neither case describes Shimano's position in the bicycle drivetrain industry *before* the firm attacked: It was a relatively mature industry and Shimano did not command extraordinary market power. The second possibility in Schilling's model for a firm to influence the balance of forces that hold a system in equilibrium is to affect the system's degree of synergistic specificity. Schilling suggests that scientific advancement can change the synergistic specificity of a system (Schilling 2000:316). This would indicate that knowledge advancement itself can change the degree to which a system is modular. While this leaves the question unanswered when the process works towards modularity and when away from it, it does open the door for a firm to endogenously affect the product architecture prevalent in its market. In our case 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.[6] 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.[7]

Concerning industry incumbents, the literature on innovation has focused on explaining the reasons why incumbents fail in some circumstances (Henderson and Clark 1990; Christensen 1997) or why they succeed in others (Tripsas 1997; Hill and Rothaermel 2003) faced with a technological innovation. In either case, the impetus for change is coming from outside of the firm. Similarly, industry life cycle shifts are typically described as external to the individual firm. In contrast, the case of the bicycle drivetrain industry shows that under certain circumstance a firm inside the industry can rock the applecart. Both timing and supporting activities of Shimano suggest that the equilibrium that holds the interfirm product modularity forces in balance is not simply the sum of its forces. Rather, the equilibrium is sensitive to the *specific combination* of external and internal forces as well as the degree to which mechanisms

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[6] 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.

[7] 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.

such as network effects are present. Although they were much weaker than in digital communication technologies, lowering the network related switching costs helped the focal firm to get the product architecture out of the shallow dip that had kept its equilibrium somewhat stable. In others words, just as inertia and resistance can prevent immediate system adaptation, firms can create a momentum that gets the system out of its meta-stable equilibrium.

4.3 What are the Consequences of Product Architecture Change?

The second question that the equilibrium models leave unanswered in case of the bicycle drivetrain industry is *why* the product architecture change led to such a drastic change in the industry landscape and *how* the change actually proceeded. The detailed case analysis reveals two aspects that provide additional explanation: the understanding of the *dual role of product architecture* as a firm's decision variable and context, and the different mechanisms triggered by *individual* product architecture characteristics. Schilling's model focuses on the dominant design in an industry, a good proxy in stable and slow moving situations. As Shimano's example illustrates, however, under certain circumstances a firm can change its own product architecture, and thus create forces to which its competitors must react. In the bicycle drivetrain case these forces worked through three different mechanisms, and the mechanism affected different types of competitors very differently (Figure 7).

Insert Figure 7 about here

The first mechanism forced the competitors who offered all of the six drivetrain components, i.e., systems firms, into a system competition on higher performance levels, whereas the second mechanism drastically reduced the available market size of complementary components to which component competitors could attach their products. These mechanisms were caused by changes in two different dimensions of the product architecture: a more complex function-component allocation and reduced interface standardization. The third mechanism then made this form of competition difficult for the firms still standing because the origin of performance differentials was much harder to detect.[8]

The index shifting technology that Shimano introduced in 1985 relied on a precisely and constantly provided chain gap. The chain gap design is affected by a number of design variables, distributed across several components. As a consequence, Shimano forced its competitors into a systemic competition (mechanism 1). Although the two major contenders, SunTour and Campagnolo, introduced their own integrated designs in 1986 and 1987, respectively, the erosion of their market shares continued almost to their extinction. What explains this effect? We argue that an integral function-component allocation requires not only deep system understanding for the initial inventor, but it also is – for the very same reason – difficult to imitate (mechanism 3) (Rivkin 2000; Ethiraj and Levinthal 2004). Although by 1990 the designs that all three firms produced were remarkably similar, the time it took SunTour and Campagnolo to close the quality gap, Shimano used to corner almost the entire market (cf. market share data in the appendix).

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[8] 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

The second product architecture change, which is entirely separate from the first, is the reduction of the product architecture dimension *interface standardization*. The reduced inter-firm compatibility between the components of the new system and individual components manufactured by other component firms essentially cut off a significant fraction of the market of products that the component firms used to rely on as complementary goods (mechanism 2). The incompatibility of Shimano's S.I.S. components reduced the accessible network size for these component competitors and left them three options: form alliances or joint ventures to create an organization capable of developing an entire drive train, be acquired by a systems firm, or simply leave the industry. Some firms, for example Sachs and Huret, chose the first option and introduced their own integrated system ARIS in 1987. However, the competition on the systems level was formidable and ARIS never garnered more than 1% market share in the road bicycle market. Some component firms managed to get acquired, but the majority of the firms exited the industry. The combined market shares of component firms slipped in each component segment in both road and mountain bicycle markets to less than 8%.

What these process details help explain is the drastic nature of the change in industry composition due to the product architecture change. Equilibrium models describe the degree of interfirm modularity as determined by a balance of mostly external forces. This suggests that if one of these forces changes in its size, the system migrates to a new equilibrium where the forces are again in balance. While the model allows for system inertia and firms resisting outside forces, it assumes outcome equifinality. In contrast, our data suggest that some forces, once unleashed, can create a momentum on their own, e.g., the specific type of network effect, and

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strategies. The data we collected allows us to reject this hypothesis. All through the decade all three firms offered component sets across the price spectrum, albeit with Campagnolo leaning slightly to the high-price segments.

continue to push the industry beyond what the initial differential in forces would have predicted. In other words, the system exhibits inertia not only in its stable state.

The recent focus in the literature on complex adaptive systems seems to suggest that adaptation to a performance landscape, and the search process that can do this best, is at the heart of the decision problem. While we do not challenge the evolutionary nature of competition per se, we believe that cases like the one described in this paper open the door to allow a larger role for agency in the debate (Gavetti and Levinthal 2004). Competitive actions on the firm level matter (Ferrier, Smith and Grimm 1999). Particularly intriguing is the dual role of the product architecture as simultaneously a decision variable for the firm and as context for the rivals. Its shift from being one to being the other has been described in the industry life cycle literature as uni-directional (Abernathy and Utterback 1978). In other words, in the early phase of an industry when a firm still has substantial decision freedom, the product architecture choice is relatively unconstrained. Later in the industry life cycle, however, after the emergence of a dominant design, many product architecture decisions become limited by compatibility requirements of other products and technologies.

We suggest that the process of industry life cycle can be reversed. In fact, our case may be an incarnation of what has been called industry de-maturity. Abernathy et al. (1983) suggested this possibility but provided radical technological change, most likely from outside the industry, as the likely cause. We extend the range of possible causes for industry de-maturation by including a re-definition of product architecture, coming from inside the industry. Thus, viewing the product architecture as both a firm’s decision variable and industry context establishes an important link between the typically firm-level engineering and operations view and the typically industry-level innovation and competition perspective.

5 CONCLUSION

The contributions of this paper are twofold. First, we show how product architecture change began and proceeded in the bicycle drivetrain component industry between 1980 and 1990, and dramatically altered its composition. With detailed product architecture assessments over time and across firms we identify the mechanisms that explain the change process and the final outcome. Second, the theoretical contribution links the product architecture change to the industry life cycle literature via dominant design reversal. We develop the dual role of product architecture as both decision variable and context, and identify specific characteristics of situations that trigger change and create the internal momentum of change processes. Overall, we suggest to increase the role of agency in modularity models and to link engineering and operations decisions to firm strategy.

5.1 Implications for Future Research

One direction for future research is to replicate the study in different settings to test the external validity of the findings. In addition, we see two conceptual extensions that appear particularly promising. First, we recognized that the bicycle drivetrain component industry exhibits weaker network effects than most of the digital communication industries. An interesting direction for further research would be to explore the different degrees of network effects caused by different types of compatibility. Second, our study is restricted to one, relatively well-defined, industry only. However, product architecture effects are most likely felt throughout entire supply chains. For example, studies show that a firm boundary shift, enabled 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 structural industry changes are not homogenous along the supply chain. Future research should address these complex relationships.

5.2 Implications for Managers

The findings suggest potential points of managerial intervention on at least three levels. First, 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, Verlinden and Westerman 2002). If true, this would mean that a way to turn one's own sector from a modular into a rather integral one is extremely valuable. Our study shows an example of how this can be done with help of product architecture design decisions. Second, the study allows us to explore the positions of the ultimately unsuccessful competitors. Analyzing both their positions and their defense confirms that it can be very valuable to have a knowledge base stretching beyond the narrow current production portfolio (Brusoni, Prencipe and Pavitt 2001). Finally, thinking about how to create and maintain a strategically sufficient knowledge base requires to take a long-term perspective. As the examples of SunTour and Campagnolo demonstrate, it can take substantial amounts of time to build up the knowledge required to compete – time that competitors seldom grant.

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7 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		

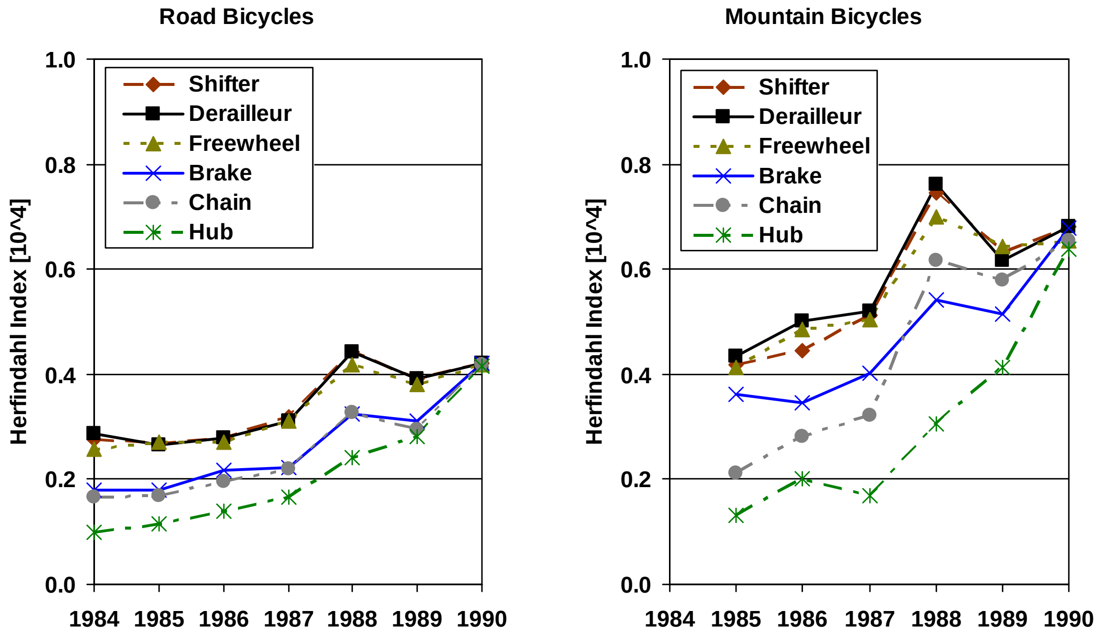


Figure 1: Industry concentration within segments

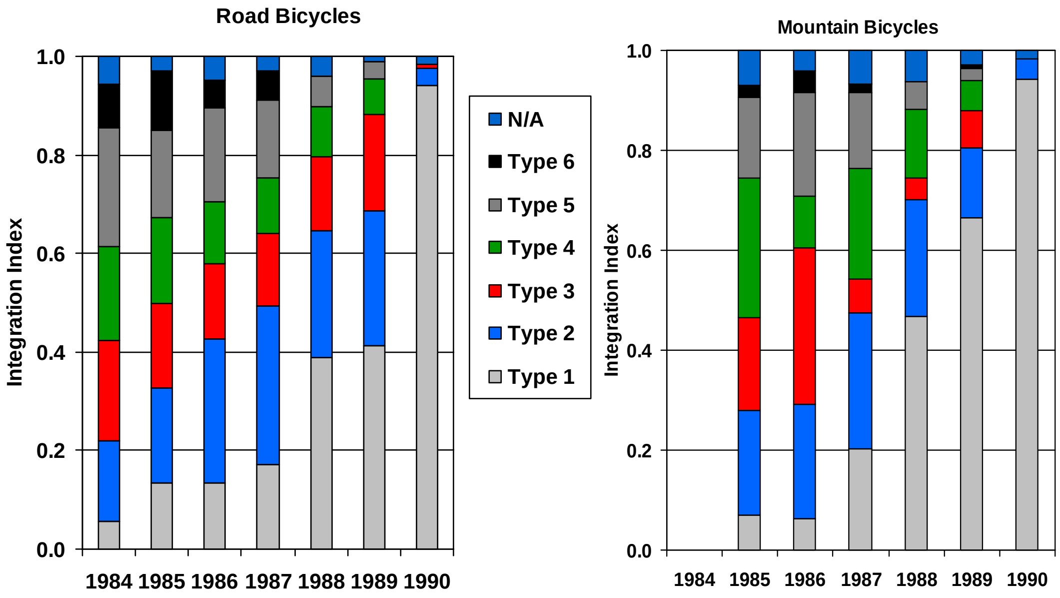
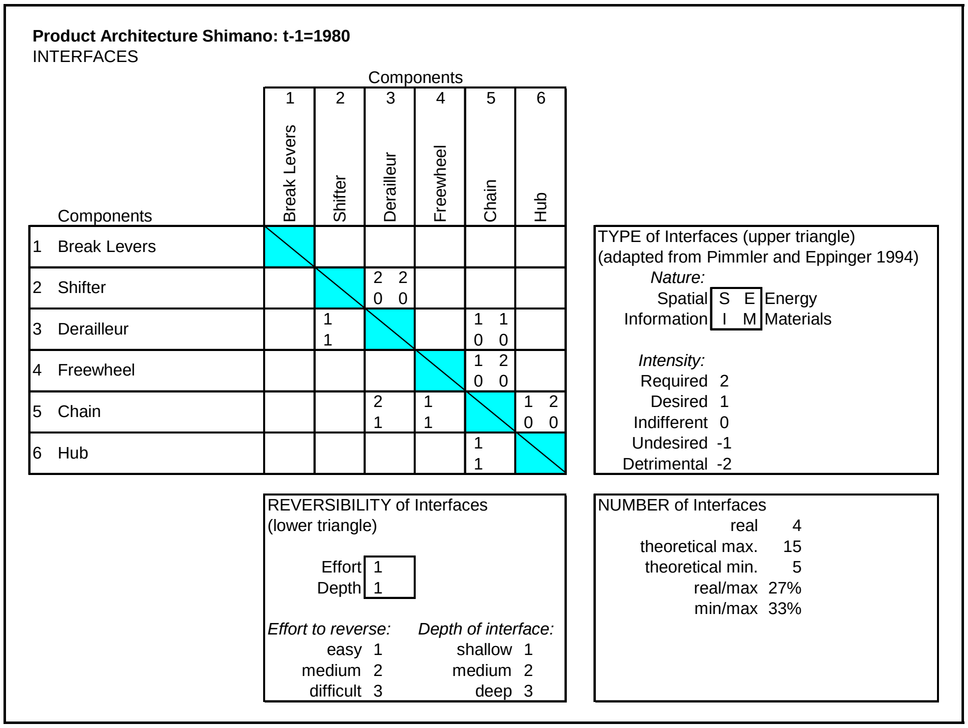


Figure 2: Industry concentration across segments



Product Architecture Shimano: t-1=1980

INTERFACES

Components

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	
5 Chain			2 1	1 1		1 2 0 0
6 Hub					1 1	

TYPE 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

REVERSIBILITY 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%

Figure 3: Measuring interface type and interface reversibility (Shimano at t_{-1}=1980)

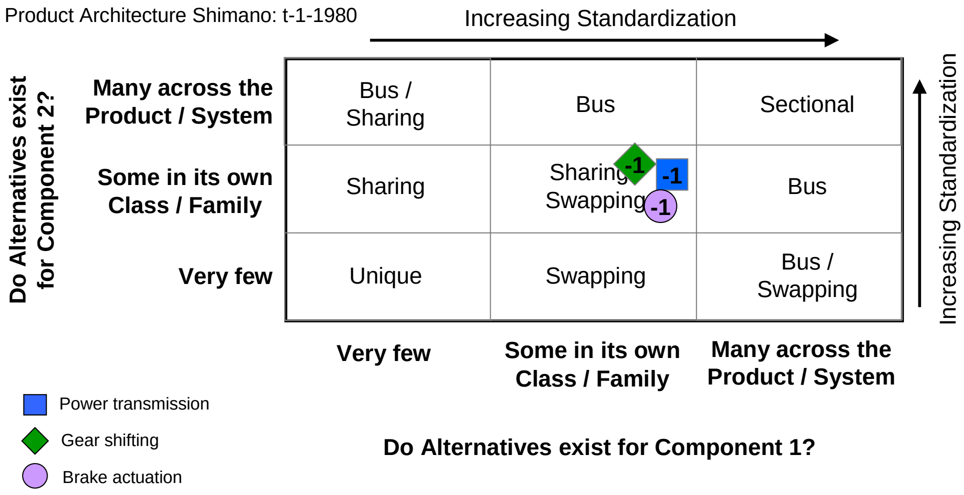


Figure 4: Measuring interface standardization (Shimano at t_{-1}=1980)

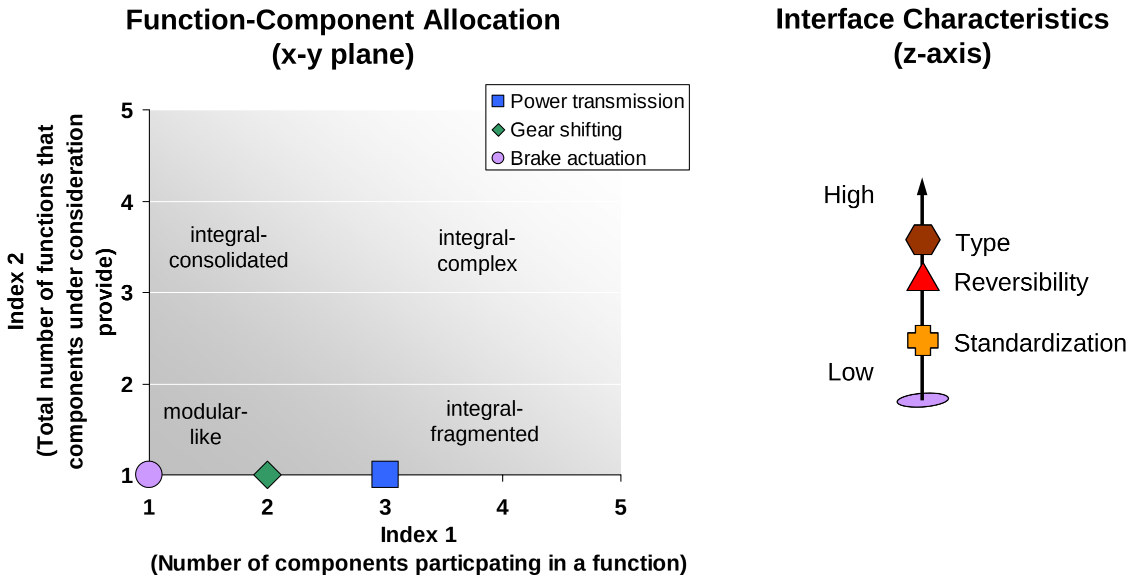


Figure 5: Elements of a pictorial product architecture description

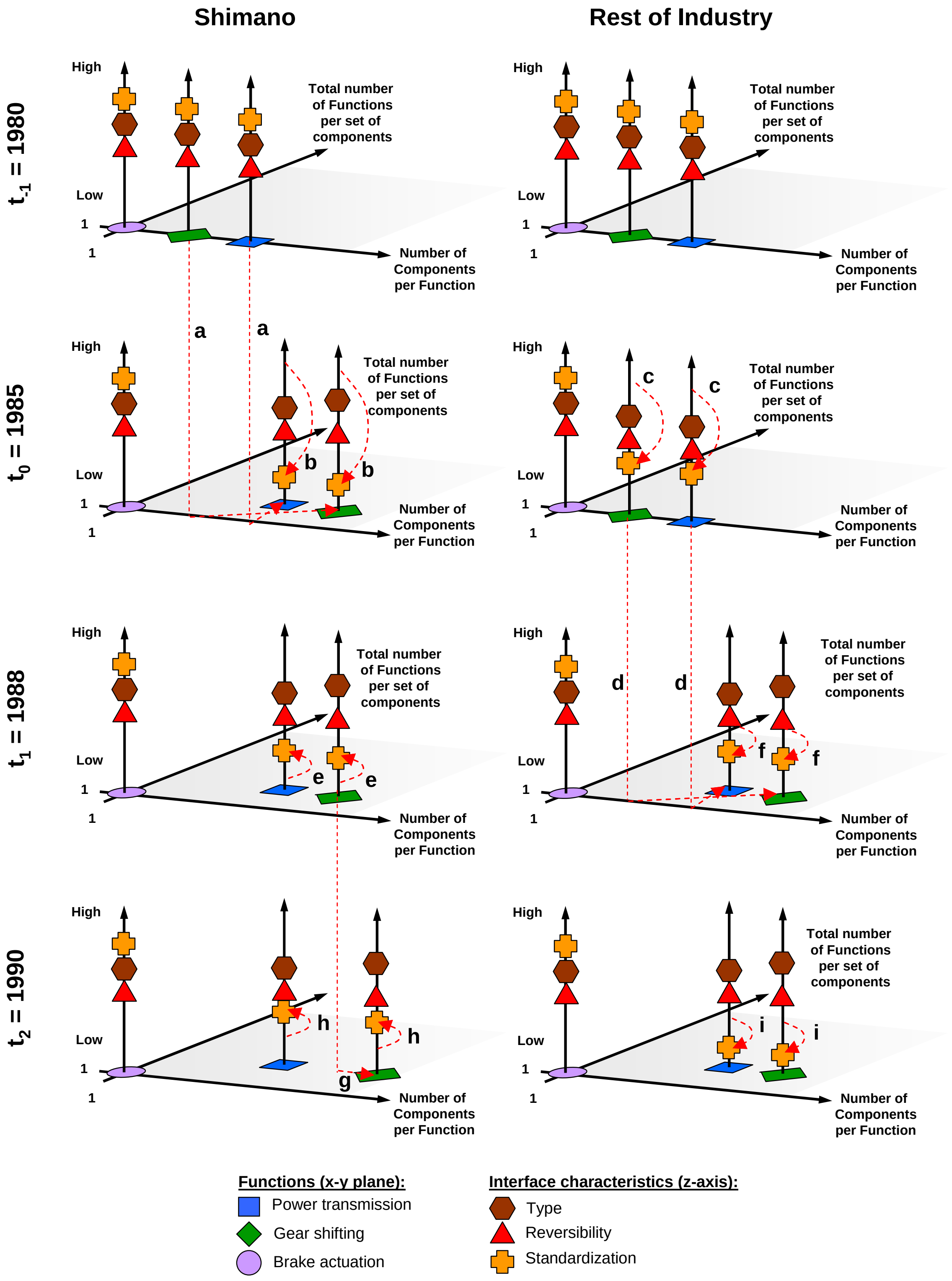


Figure 6: Product architectures assessments across time and across firms

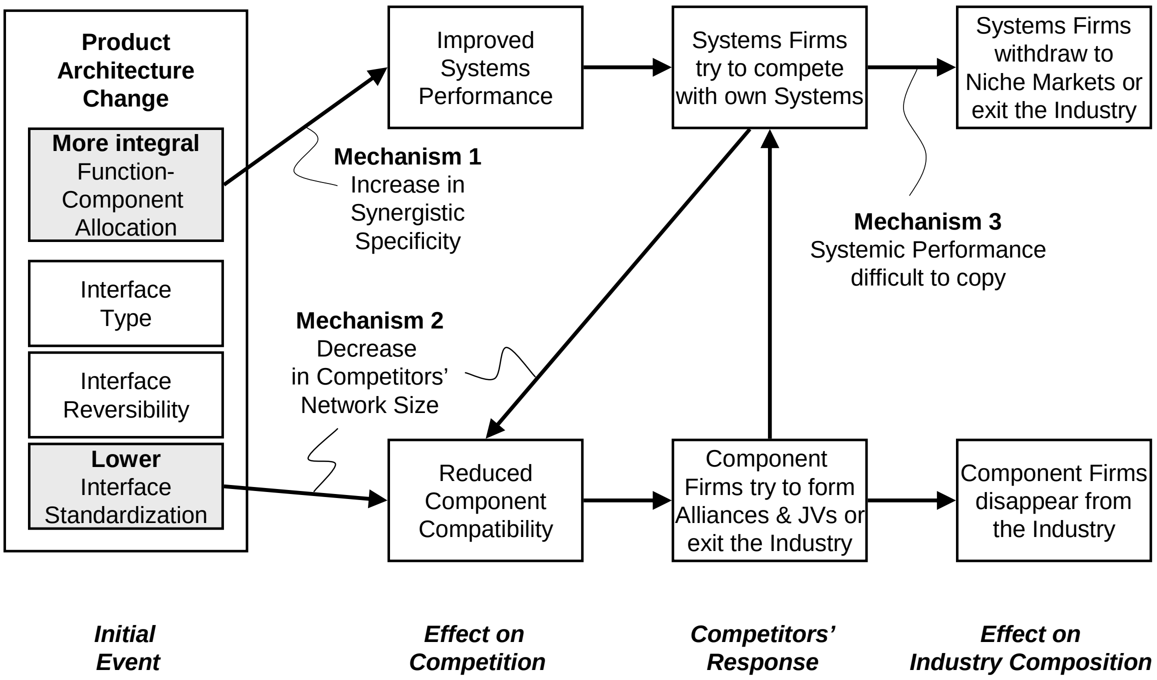


Figure 7: Three mechanisms through with product architecture change affects competition

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)

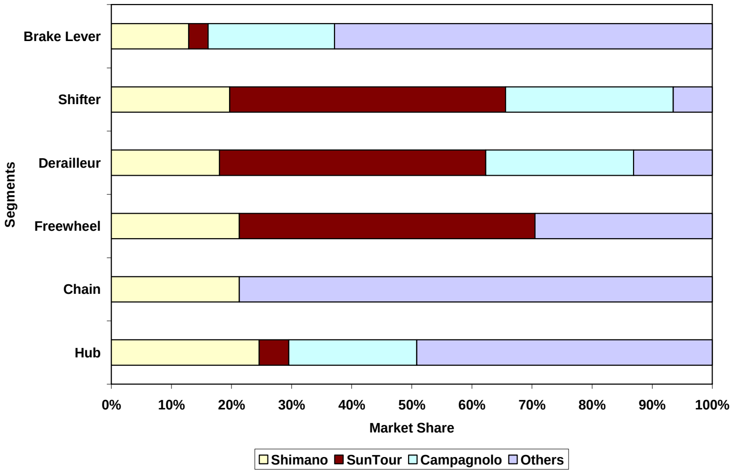


Fig. A.1.1. Product Architectures and Market shares (Road 1984)

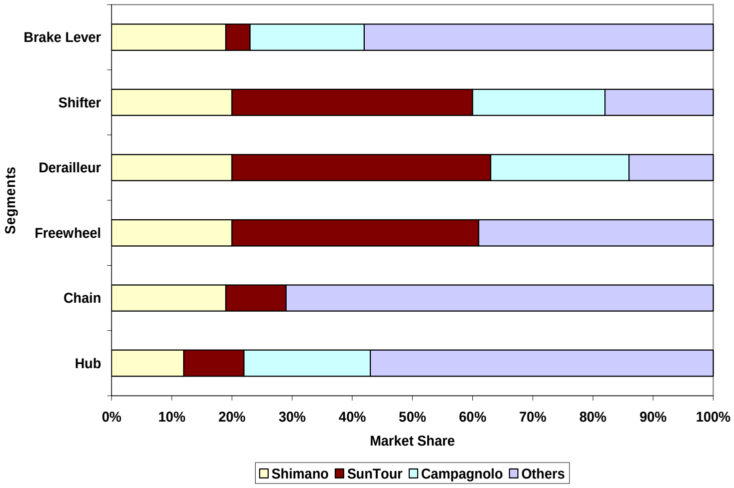


Fig. A.1.2. Product Architectures and Market shares (Road 1985)

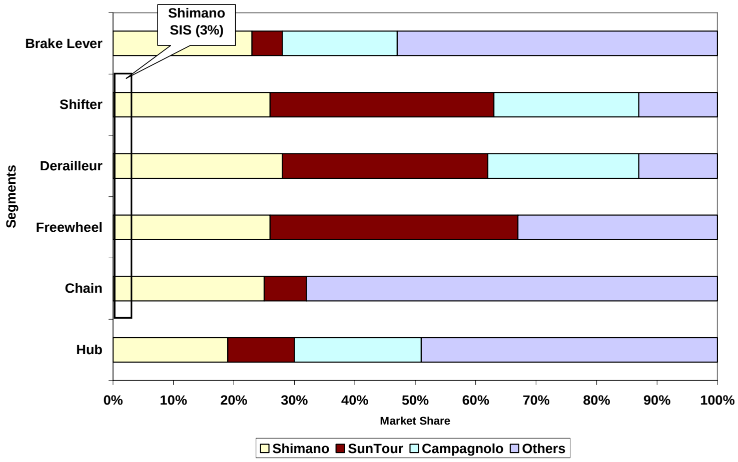


Fig. A.2.2. Product Architectures and Market shares (MTB 1985)

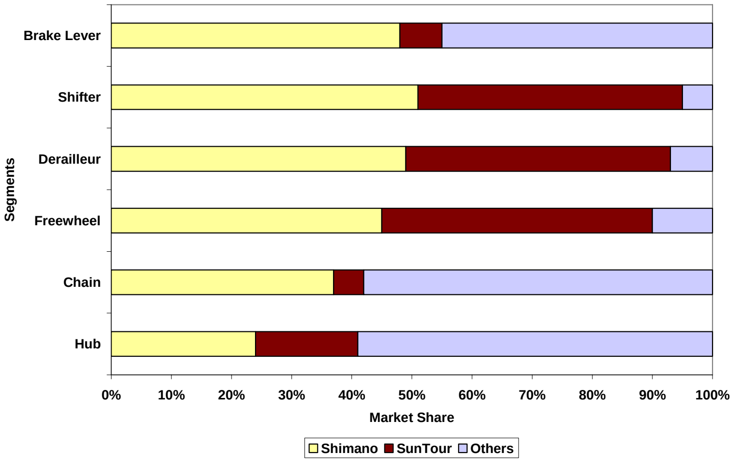


Fig. A.1.3. Product Architectures and Market shares (Road 1986)

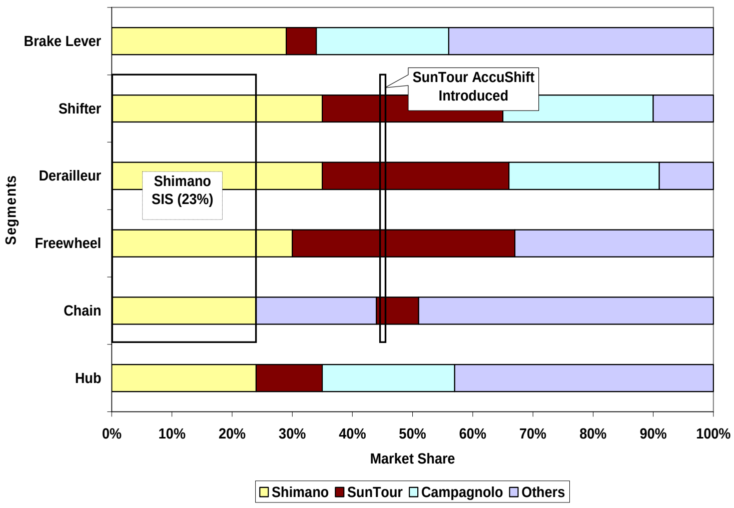


Fig. A.2.3. Product Architectures and Market shares (MTB 1986)

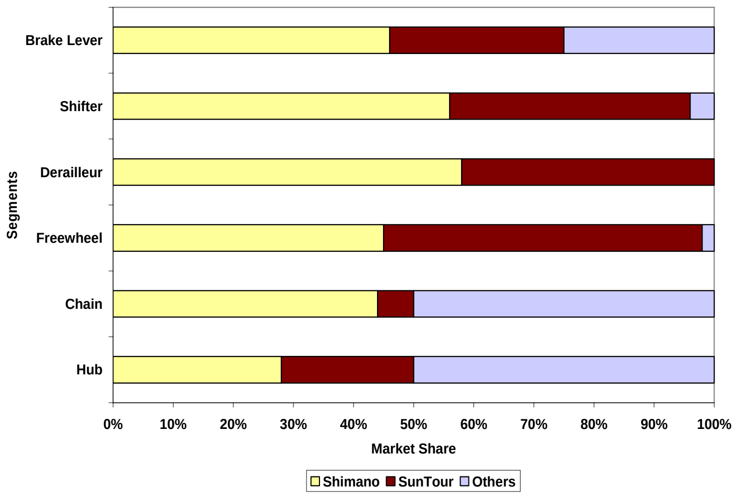


Fig. A.1.4. Product Architectures and Market shares (Road 1987)

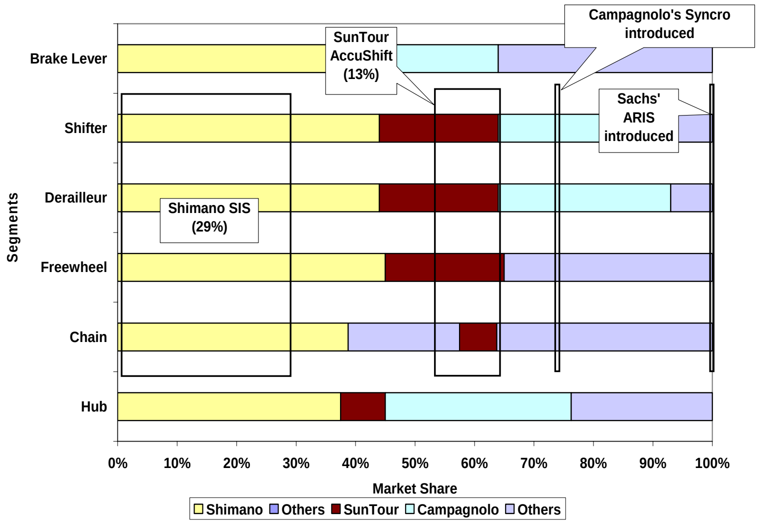


Fig. A.2.4. Product Architectures and Market shares (MTB 1987)

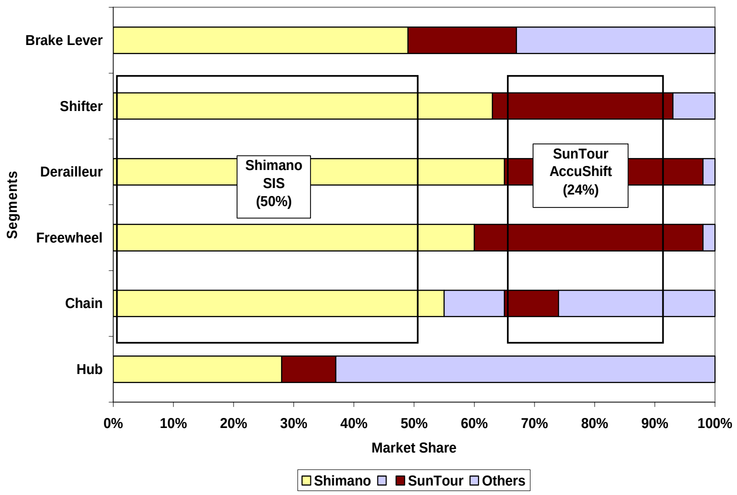


Fig. A.1.5. Product Architectures and Market shares (Road 1988)

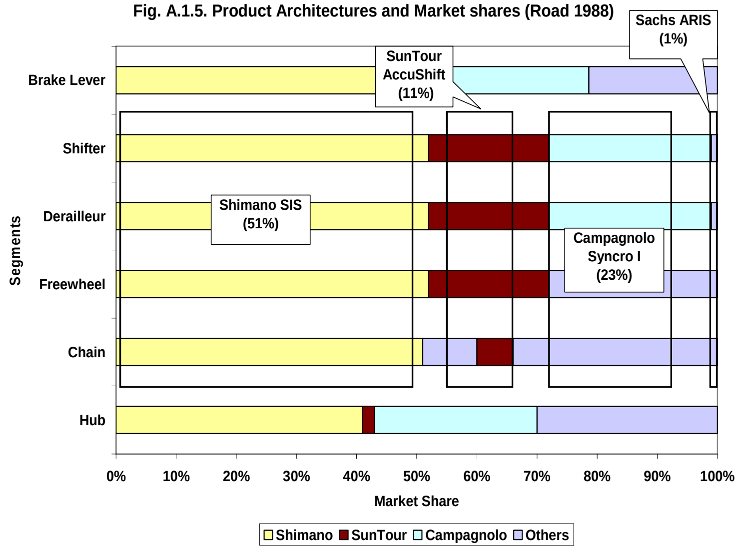


Fig. A.2.5. Product Architectures and Market shares (MTB 1988)

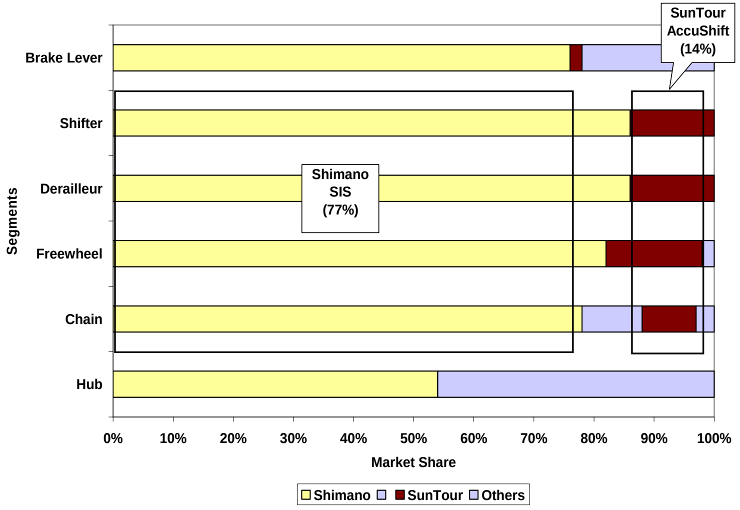


Fig. A.1.6. Product Architectures and Market shares (Road 1989)

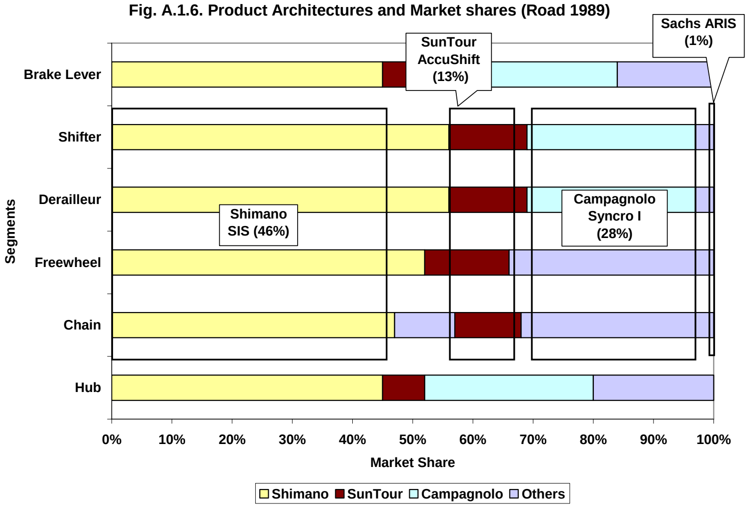


Fig. A.2.6. Product Architectures and Market shares (MTB 1989)

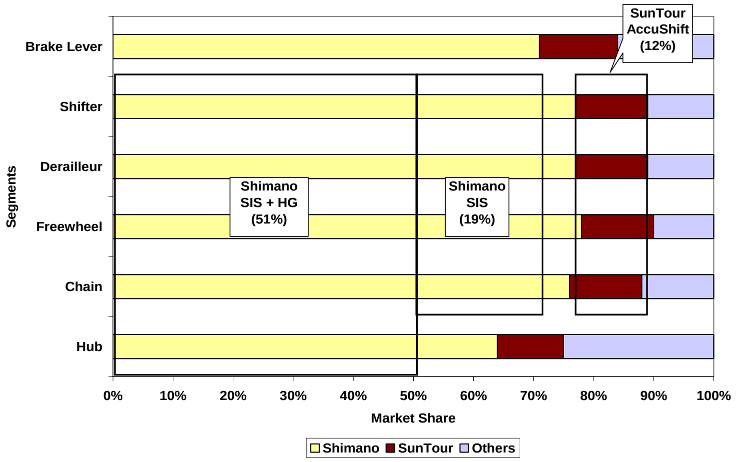


Fig. A.1.7. Product Architectures and Market shares (Road 1990)

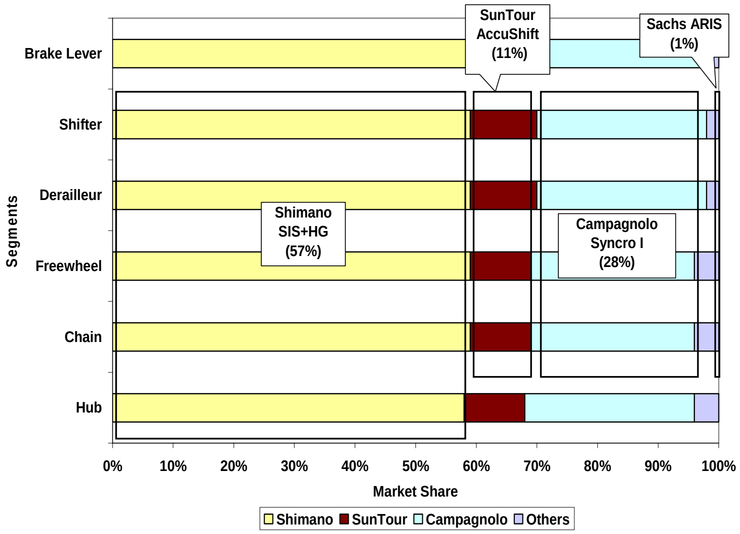


Fig. A.2.7. Product Architectures and Market shares (MTB 1990)