Measurement of Product Architecture:
A Case of the Bicycle Industry

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Abstract:

We argue how to measure product architecture by applying the measurement framework proposed by Fixson (2005 2008) to assess the architecture of bicycles. Our results reveal that (1) function component allocation indicates integral architecture (2) interfaces are highly standardized, and (3) integrating these results, bicycle architecture is modular. We also found that while Fixson's framework (2005 2008) is helpful and useful, analysis of the interdependency between components is lacking. Based on our research, we suggest that function should equal component allocation (referred to as function component allocation) to determine product architecture, and, more importantly, component interactions should be described to illustrate the entire product architecture.

Keywords: product architecture, function-component allocation, modular, bicycle

Introduction

Business management and innovation management scholars became more interested in product architecture following the improvements to Information Technology (IT) since 1990 The focus of this technological innovation has changed from automobiles and electronics to PCs and software. The impact of product architecture on industry structure and firm competition has been thoroughly researched (Baldwin and Clark 2000: Langlois and Robertson 1992; Fine 1998; Sturgeon 2002) For example, Henderson and Clark (1990) demonstrated that the failure of industry incumbents is caused not only by radical product innovation, but also by minor improvements in technological products, which is known as architectural innovation.

Although the relationship between product architecture and firm competition has attracted interest, little is known about how to assess product architecture. Campagnolo and

Camuffo (2009) discussed how accurately assessing product architecture has some difficulties. First, product architecture changes over time. Second, product architecture may vary with the unit of analysis. Despite these difficulties, it is important to examine the assessment methods to advance the investigation of product architecture.

In this paper, we argue how to measure product architecture by applying the measurement framework proposed by Fixson (2005 2008) to assess the architecture of bicycles. We found that while Fixson's framework (2005 2008) is helpful and useful, analysis of the interdependency between components is lacking. Based on our research, we suggest that function should equal component allocation (referred to as function component allocation) to determine product architecture, and, more importantly, component interactions should be described to illustrate the entire product architecture.

The reminder of the paper is organized as follows. In the next section, we discuss the prior research about product architecture. Product architecture research includes product level analysis, industry level analysis, and organizational level analysis, and we focus on the product level analysis literature. In the third section, we describe in detail the measurement framework proposed by Fixson (2005 2008) In the fourth section, we assess the architecture of bicycles using three steps based on the Fixson's framework. In the fifth section, we discuss the usefulness and limitations of Fixson's framework (2005 2008)

Literature review: Product architecture

Ulrich (1995) defined product architecture as the scheme by which the function of a product is allocated to its physical components. Product architecture is divided into two types: modular architecture and integral architecture. Modular architecture includes one-to-one mapping from the functional elements in a function structure to the physical components of the product, and specifies de-coupled interfaces between components (Ulrich 1995 p. 422) For example, a typical type of modular architecture is a PC, in which architecture does not interfere with each component.

Components of modular architecture are highly standardized, and final products are made with ease by assembling components (Fujimoto 2001) Even an amateur with some extent knowledge is able to build a PC by assembling components, such as the display, CPU, hard disk drive, and keyboard. Thus, the production process of a modular architecture tends to be labor-intensive, and simply assembling the product does not confer competitive advantage. Instead, competitive advantage can be gained by manufacturing modular architecture products in countries with low-cost and huge labor forces.

Integral architecture includes a complex (non one-to-one) mapping from functional elements to physical components and/or coupled interfaces between components (Ulrich 1995 p. 422) For example, a typical integral architecture product is an automobile. The function of an automobile includes driving stability, ride quality, and fuel consumption. Components such as the engine, suspension, and body affect driving stability. Improving driving stability is accomplished by changing concurrently all components that affect this function. Contrary to modular architecture, integral architecture products are not manufactured by assembling components. In order to work, the design of integral architecture products must integrate function and components. Thus, competitive advantage can be gained by manufacturing integral architecture products through concurrent engineering.

2.1 Measurement method in Fixson (2005 2008)

Fixson (2005) built a systematic measurement method for product architecture and, elaborating upon the discussion of Ulrich (1995) proposed three steps for analysis: 1) function equals component allocation schemes 2) interface characteristics, and 3) pulling it all together.

2.2 Function-component allocation schemes[1]

An objective index is needed to accurately measure product architecture. For the first step, we introduce a function and component allocation scheme. To ensure repeatable results, we clarified three items: (a) what a function is (b) what a component is, and (c) how an allocation scheme is established.

First, function means the technical functions and attributes as would be used for marketing (Fixson 1995 p. 352) For example, the function of an automobile is driving stability, ride quality, and fuel consumption. These functions are directly comparable among automotive companies and we can compare the driving stability, ride quality, and fuel consumption between Toyota and Honda's cars. The hierarchy level on which a product's functions are selected is a matter for analysis. All products have a nested system, which can be divided into sub-components. A modest hierarchy level should be chosen for product architecture analysis. For example, when assessing the product architecture of a hair dryer, researchers can set the function" to dry hair" at the highest level. However, this is not worth assessing because all components have this function. On the contrary, if researchers set a function too narrowly, only some or one component will have the function and be the driver of the component.

Second, component means an assembled product that has a hierarchical system. It is im-

portant to determine the product hierarchy level that corresponds to the level of functions as determined earlier. For example, a bicycle tire is a component, and even a nut that composes the wheel is a component. Additionally, assembled lower level components build higher level components.

Third, in order to proceed to function component allocation analysis, there are three steps. The first step is to construct a matrix with the product's functions in the first column and its components in the first row, and determine which component contributes to which function. A simple way to describe if a component relates to a function is to use a 1 if it does and a 0 if it does not. The second step is to calculate two indices for each function. The first index is the number of components that jointly provide a function. The second index is the degree to which a set of components contributes to another function. The third step is to map each function onto the function component allocation map using these two indices. The horizontal axis depicts Index 1 (the number of components participating in a function) and the vertical axis depicts Index 2 (the total number of functions that the components under consideration provide) The maps are divided into four quadrants. When the number of function component allocations are low, located in the left lower quadrant, the product is close to having a modular architecture. When Index 1 and Index 2 are high, located in the right upper quadrant, the product has an integral architecture. When each index is in the left upper quadrant, the product has an integral consolidated architecture, and in the right lower quadrant, the product has an integral fragmented architecture.

2.3 Characteristics of an interface

The assessment of an interface describes three indices: interface strength, interface irreversibility, and interface standardization. Interface strength means technological characteristics (transfer of mechanical forces, materials, signals) and includes a measure of intensity. There are four indices to assess interface strength: (1) a special interaction identifies the need for adjacency or orientation between two elements (2) an energy interaction identifies the need for energy transfer between two elements (3) an information interaction identifies the need for information or signal exchange between two elements, and (4) a material interaction identifies the need for materials exchange between two elements. Interaction strength is evaluated on a five-point scale, from 2 to 2 A score of 2 means the most strong interaction, and a score of 2 means the weakest interaction. The matrix in Table 3 shows that the upper left corner contains the number of spatial-type interactions and shows the number of energy type interactions, the lower left corner shows the number of information-type interactions, and the lower right corner shows the number of material-type

interactions.

The second interface characteristic is interface reversibility. This characteristic is measured by two indices. First, the difficulty to physically disconnect the interface is considered. This index is measured by the degree of tool requirement and time to disconnect. For example, some components can be separated by hand, while others require a wrench or a weld. The second index measures the position of the interface in the whole product architecture. If a component's interface is deeply buried in the product architecture, the interface reversibility is high.

The third interface characteristic is the degree of interface standardization. If a component can be replaced by other components, the interface is highly standardized. For example, considering the interface between a lamp and light bulb, if the same lamp can be used with different light bulbs, the interface is standardized. A component that connects to all interfaces, such as a Lego, has a highly standardized interface.

Measurement of product architecture

In this section, we measure the product architecture of a bicycle. To measure this we apply Fixson's framework as introduced previously. Here, we assess product architecture using three steps. The first step is to assess the function component allocation. This step considers how functions are allocated to physical components and whether interfaces are coupled. The second step is to assess interface characteristics. This step considers two indices in the component interface: interface reversibility and the degree of standardization. Finally, the third step is the measurement of product architecture. This step integrates the information from step one and two, and judges whether bicycle architecture resembles integral architecture or modular architecture.

3.1 Step1: Function equals component allocation

Here we describe the functions and components of bicycle architecture. To assess the product architecture correctly, it is important to select a moderate hierarchy in components and functions. We decided to categorize the functions and components by consulting a specialist in the bicycle industry and referring to descriptions in bicycle books.

The function of bicycles is divided into three areas: comfortablity, safety, and speed (Tsuchihashi 2014) Comfortability is an aggregate function of riding quality and maneuverability of a bicycle. This function includes how vibration from the ground while riding is reduced and the degree to which riders can steer quickly. Safety is the function of how

riders are able to drive safely. This function includes decent braking capability and speed reduction. Speed is the function of how riders can accelerate quickly and shift gears to a weaker power for driving on a sloped road. Components of bicycles are divided into six parts[1]: frame, handle, gear-crank, tire, saddle, and brake. The gear-crank includes the crank, peddle, chain, and freewheel. The tire includes the hub, spoke, rim, tire, and tire bulbs.

Figure 1 shows which components affect these functions. This figure illustrates the interaction of function and component allocation. In addition, Table 1 shows a quantitative illustration of the content in Figure 1 As indicated in Table 1 the five components (frame, handle, gear, tire, and saddle) affect the function of comfortability. For example, the quality of materials significantly influences comfortability. A bicycle made with an iron frame can absorb shock from the ground, but iron has a weight disadvantage. While a bicycle made with an aluminum frame weighs less than an iron frame, the riding quality is harder, which means it has a weaker capacity to absorb shock. Moreover, an aluminum frame does not rust and it can last a long time. The shape of a frame also affects comfortability. Although a bicycle frame has historically been a diamond shape, designers of bicycles changed the shape of the frame to help woman with long skirts. Second, bicycle handles affect maneuvering as the handle is used to change the direction of the tire and drive the bicycle. Third, gears interact with comfortability. A bicycle rider can ride up or down a hill by shifting the derailleur, the gear change mechanism, according to the slope of a hill. Forth, concerning the tire, a wider tire has a more comfortable ride. Meanwhile, a tire with higher air pressure has a less comfortable ride because of the vibrations from ground. Fifth, the saddle affects comfortablility. A firm riding saddle is not comfortable for longer riding periods. Additionally, if the shape of the saddle does not fit the rider, friction between the saddle and rider's leg can be painful.

Based on the discussion above, Index 1 is rated on a scale of five because that is the num-

Table 1 Measuring Function-Component Allocation

Components

Functions		1 Frame	2 Handle	3 Gear	4 Tire	5 Saddle	6 Brake	index 1	index 2
1	Comfortablity	1	1	1	1	1		5	3
2	Safety	1			1		1	3	3
3	Speed	1		1	1			3	3
	Functions count	3	1	2	3	1	1		

Classification of bicycle components are made using bicycle statistics from Japan (Japan Bicycle Promotion Institute)
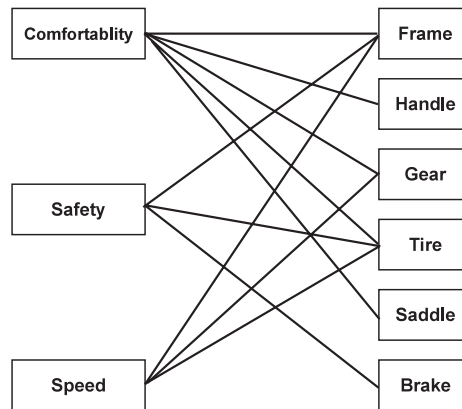
Figure 1 Function-Component Allocation

ber components that affect the function of comfortability. Each component also affects safety and speed, which is why Index 2 is rated on a scale of three.

Next, the components that affect the safety function are the frame, tire, and brake. First, if a frame is not robust it can crack from deterioration or impact. Second, a tire is most important to safety as it is the only part that comes in contact with the ground, and braking power is gained by the friction between the tire and ground. Third, when a rider grabs a brake handle to stop, pulling the brake lever generates friction between the rim and brake shoe, causing the spinning of the wheel to stop. In this example, Index 1 has a rating of 3 because three components affect safety. These components contribute to comfortability and speed, and Index 2 has a rating of three.

Finally, the components that affect the speed function are the frame, gear, and tire. If a much lighter material, such as carbon, is used for the bicycle frame, a rider is able to ride much faster than if a heavier material, such as iron, was used. Although a carbon frame is lighter than iron or aluminum, carbon is more expensive than other materials. The gear and derailleur control speed. A smaller gear ratio has a higher rotating speed and the rider has less power. Meanwhile, a bigger gear ratio has a faster rotating speed and the rider has more power. In this scenario, a rider can go longer distance from pedaling one rotation. Shifting gear ratios contribute to speed and efficiency when riding on a sloped road. From the above discussion, Index 1 is rated as a three because three components contribute to speed.

Figure 2 illustrates the result of the function　component allocation. The horizontal axis represents Index 1　and the vertical axis represents Index 2　All three functions are located in the upper right quadrant, which exhibits an integral-complex style since several components are also involved in providing other functions.
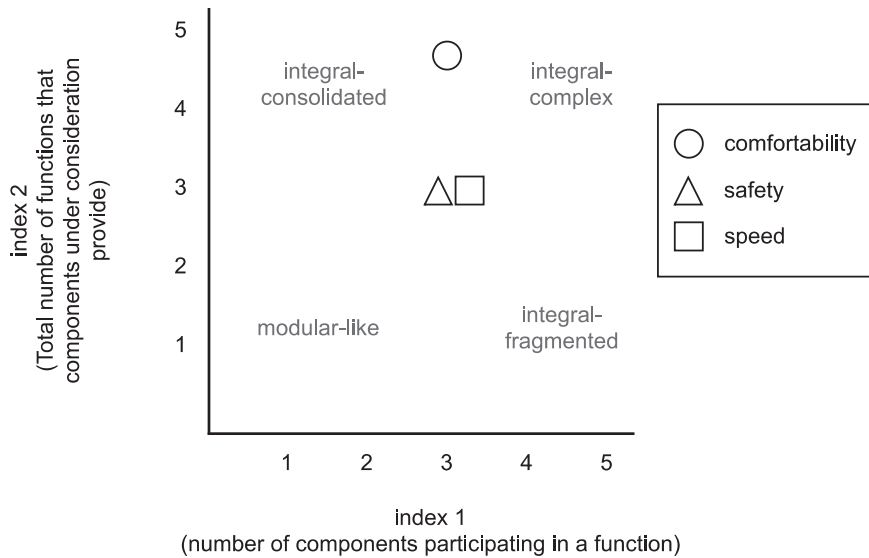
Figure 2 Function-Component Allocation Map

3.2 Step 2 Interface characteristics

In this section, we assess the characteristics of the interfaces between components. This assessment is conducted using three steps: （1）assessment of the interface strength （2） assessment of the difficulty of interface reversibility, and （3）assessment of the degree of interface standardization.

First, we consider how many interfaces a bicycle has. There are six component groups in bicycle architecture, and theoretically the maximum number of interfaces is 15 and the minimum is five² Calculating the number of interfaces in a bicycle, we obtain eight interfaces. These eight interfaces include: （1）frame handle （2）frame gear （3）frame tire （4）frame brake （5）frame saddle （6）handle brake （7）gear tire （8）tire brake

Next, Figure 3 illustrates the characteristics of the bicycle components interfaces. Above the diagonal we describe the interface strength by assessing each interface on a scale from 2 to 2 for each of the following four categories: spatial, material, energy, and informational. For example, considering the interface between the frame and handle, the score of spatial is 2 energy is 2 information is 0 and material is 0 The spatial relationship is very strong due to the perfect connection between the handle and frame. The energy interface is also very strong because the frame and handle move concurrently when a rider maneuvers the handle to change direction. In contrast, there is no relationship between the

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If the number of components is n, then the number of interfaces is at least $n-1$ and at most $(n(n-a))/2$

information and material interfaces. As another example, considering the interface between the frame and brake, the score of spatial is 1 energy is 0 information is 0 and material is 0 Although the brake wire is set along the frame, it is not tightly connected, which explains why the score of spatial is 1 The energy, information, and energy score is 0 because there is no power transmission.

	Frame		Handle		Gear		Tire		Saddle		Brake	
Frame			2	2	2	2	2	2	2	2	1	0
			0	0	0	0	0	0	0	0	0	0
Handle	1										2	2
	1										0	0
Gear	2						2	2				
	2						0	0				
Tire	1				2						1	2
	1				1						0	0
Saddle	1											
	1											
Brake	1		1				1					
	1		1				1					

Strength of Interfaces (upper triangle)

| | | Spatial | S | E | Energy |
| | | Information | I | M | Materials |

Intensity
Required	2
Dsired	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
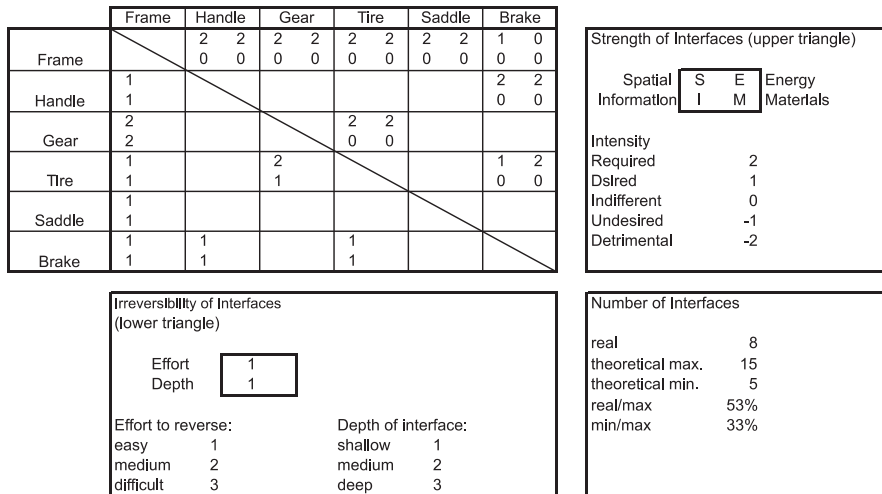| real | 8 |
theoretical max.	15
theoretical min.	5
real/max	53%
min/max	33%

Figure 3 Interfaces: Characteristics Strength and Irreversibility

Below the diagonal in Figure 3 we assess the degree of interface irreversibility by separately estimating the effort required to disconnect the interface. The upper left quadrant represents the level difficulty of reversibility and the lower left represents the depth of the interface. For example, for the degree of irreversibility between the frame and gear, the score of difficulty of reversibility is two, and the depth of interface is two. This is because the bottom bracket, the main component of the building gear, is embedded in the frame and doing so requires special tools and skills. In contrast, the score of difficulty of reversibility and the depth of interface between the frame and saddle is 1 It is very easy to attach and detach the saddle to the frame by only rotating a nut on the top of the frame, without tools or skill.

Finally, Figure 4 illustrates the degree of interface standardization. One extreme, the lower left corner, represents interfaces where there are very few alternatives in the industry. The other extreme, the upper right corner, represents interfaces where there are many alternatives. The eight interfaces of bicycles are located in the upper right cell, meaning that all interfaces are highly standardized.
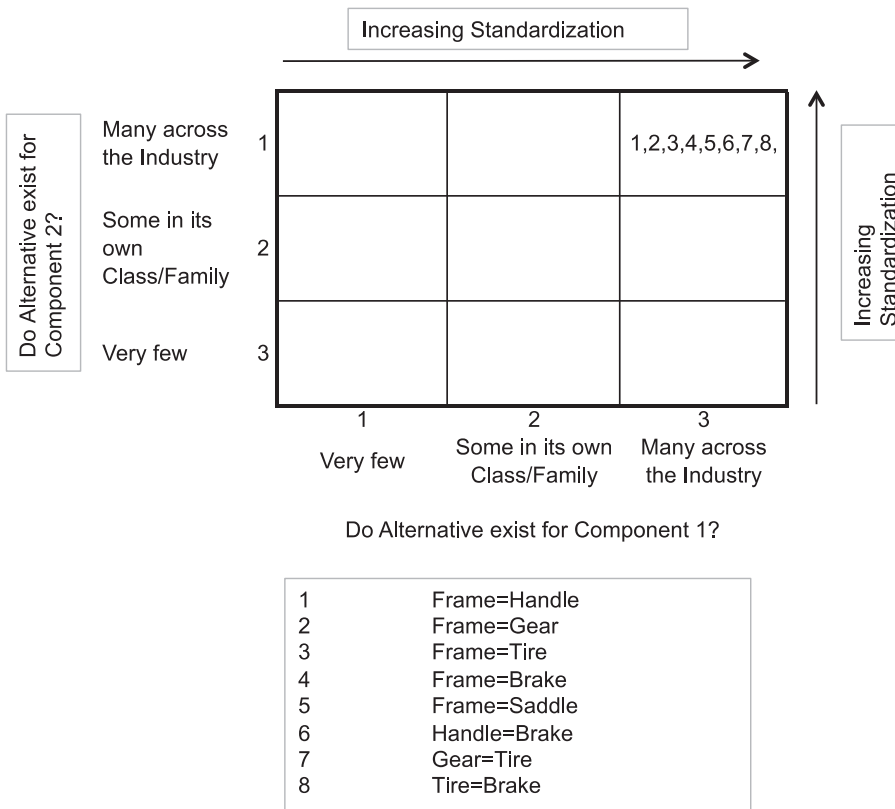
Figure 4 Measuring interfaces standardization

3.3 **Step 3: Integration framework and assess product architecture**

Table 2 shows the complete product architecture assessment results. Dimension 1, with a score close to 1, indicates modular architecture. In contrast, a score close to 6 indicates integral architecture. For a bicycle's architecture, Index 1 is 5, 3, and 3 for comfortability, safety, and speed respectively, and Index 2 is 3, 3, and 3 respectively. These scores are at the middle of the high and low scores, thus indicating that the bicycle product architecture is between modular and integral.

Table 2 Summary of product assessment

			Comfortablity	Safety	Speed
Step1	Function-component Allocation	index1	5	3	3
		index2	3	3	3
Step2	Interface Characteristics	Strength	28	20	24
		Irreversibility	19	14	17
		Standardizatior	3.3	3.3	3.3

Next, interface characteristics include three indices. First, the scores of the strength of interface are 28 20 24 for comfortability, safety, and speed respectively. Theoretically, the highest scores can be 56 48 and 56 for integral architecture, and the lowest scores can be 7 6 and 7 for modular architecture. Our research scores of 28 20 and 24 indicate a near integral architecture. Second, the scores of irreversibility are 19 14 and 17 Theoretically, the highest scores can be 32 24 and 28 and the lowest scores can be 16 12 and 14 Similarly, the lowest score indicates a modular architecture, and the highest score indicates an integral architecture. Our research scores of 19 14 and 17 which are close to the lowest score, indicatea modular architecture. Third, the scores of the degree of standardization are 3.3 3.3 and 3.3 If the score is close to three, the interface tends to have modular architecture. If the score is close to one, the interface tends to have integral architecture. Our research scores indicate perfectly modular architecture.

To summarize these results, Step 1 indicates that a bicycle has a minimal integral architecture, and Step 2 indicates a modular architecture. Integrating these results shows that a bicycle has close to a modular architecture.

Discussion

We conducted an assessment of bicycle architecture based on the work of Fixson (2005 2008) We now discuss the Fixson's framework for analyzing product architecture. We then compare the previous studies that assessed bicycle architecture.

4.1 Evaluation of the framework of product architecture

Fixson (2005 2008) refined the concept of product architecture proposed by Ulrich (1995) Fixson defined modular architecture as a one-to-one mapping from the functional elements in the function structure to the physical components of the product, and specified de-coupled interfaces between components. Here we first discuss Step 1 (function component allocation) and then Step 2 (interface characteristics) Thus, the most important contribution of Fixson (2005 2008) was the development of a quantitative and repeatable analysis framework for product architecture. Prior to Fixson (2005 2008) researchers evaluated product architecture based on their intuitive judgment. By using the framework of Fixson, we were able to assess product architecture more systematically.

While this framework is useful, there are some problems. The most significant problem is that this framework does not consider the interaction between components. Our analysis shows that to correctly assess the product architecture, the degree of coordination between

components to improve a function must also be assessed. Figure 5 illustrates the only one function　component allocation, affecting the comfortability function abstracted from Figure 1　The point to emphasize is that there are not only lines between function and components, but also curved lines connecting components. For example, when improving comfortability, whether only the frame was changed or all components were changed concurrently is important. The strength of interdependence between components is critical to discern modular or integral architecture. Considering bicycle architecture, comfortability is realized by only changing the frame and it is not necessary to coordinate the other components concurrently.
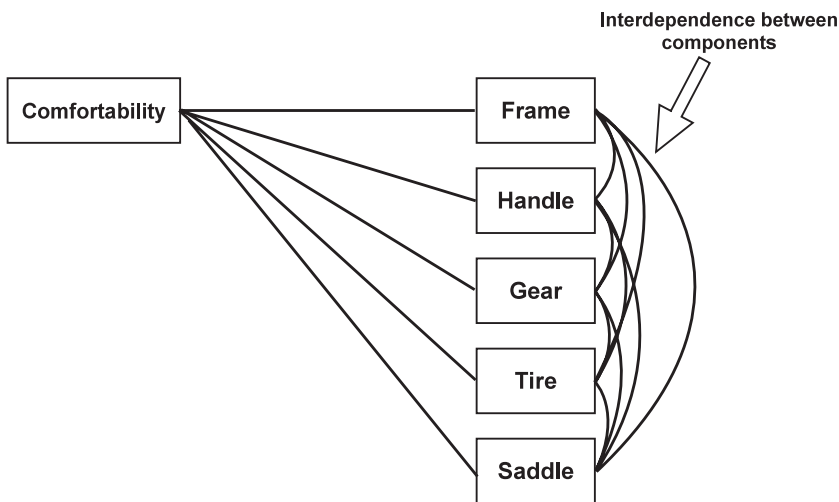
Figure 5 Interdependence between components affecting functions

As the above discussion indicates, whether function　component allocation is a one-to-one relationship is not critical for assessing product architecture. Indeed, although one-to-one or non one-to-one mapping is important theoretically, determining the type of product architecture is interdependent between components. Even if the function　component allocation of a product shows non one-to-one mapping, when each component does not affect other components, such as in a bicycle's architecture, changing components independently can improve function. Therefore, the interdependence between components that affects a function is critical for product architecture.

4.2　Analysis of bicycle architecture

Much prior research states that bicycle architecture is modular without analyzing it in detail (Fujimoto　2001; Galvin and Morkel　1999)　This research described a bicycle as modular based on its standardization of interface. As bicycle components are highly stan-

dardized, most components are used in other components interchangeably[3] However, as our results indicate, the assessment of product architecture should include not only interface characteristics but also function   component allocation. Our results show that bicycles have a slightly integral architecture in function   component allocation. Thus, judging the type of architecture without analyzing a product's function   component allocation may yield inaccurate rough results.

Conclusion

In this paper, we analyzed bicycle architecture based on the work of Fixson (2005 2008) Our results reveal that（1）function   component allocation indicates integral architecture（2）interfaces are highly standardized, and（3）integrating these results, bicycle architecture is modular.

There are two issues for future research. First, when applying this analysis framework to other products, future research will need to modify the measurement methods. There are many complex products that have more layers of hierarchy than a bicycle. For a complex product, choosing a moderate hierarchy and building the assessment indices is an important issue.

Second, future research should elaborate the framework for analyzing interdependence between components. We proposed that interdependence between components affects product architecture. When the coordination of components improves a function, the difficulty of coordination should be assessed objectively. Future research of these issues can expand the research of product architecture.

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