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Technovation 25 (2005) 771–782
technovation
www.elsevier.com/locate/technovation

Interface strategies in modular product innovation

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Abstract

Modular architectural approach has been an important perspective in product innovation research. In this study, we have tried to build a basic theory for understanding interface strategies in modular product innovation through a literature review that covers a number of concepts including product architecture, functional modules, internal and external interfaces, product platforms and families. Based on a product's internal and external dimensions and openness of interface, we construct a strategic matrix of interface possibilities in modular product innovation. We also discuss the technological and organizational requirements for each strategy.

Based on case studies of Taiwan's machine tool industry, we examine the practical application of interface strategies. This study finds that existing external interface standards impose limits on product innovation and the innovative efforts tend to focus on internal interfaces and modules, while an open supply network contributes to the high openness between different products in Taiwan's machine tool industry. In addition, we also discuss the architectural essence of Taiwan's machine tool industry, with an expectation that such a discussion may provide the impetus for structural changes in product innovation and supplier networks in the industry.

Keywords: Modular product; Product innovation; Interface strategy; Product architecture; Machine tool industry

1. Introduction

Accelerating product innovation speed is a key issue in seeking rapid response to market demands. Modular product architecture has the characteristics of low cost and high product variety with an increase in advancement of the innovative processes. Accompanied with the tendency to change from vertical integration to OEM and ODM, supplier's networks dominate important parts in the innovation processes than ever.

Product architecture normally dominates the innovative processes and production system structures (Ettlie et al., 1984; Clark, 1989; Sanchez and Mahoney, 1996). This domination shows the importance of understanding innovative system structure and the essence of products. Research categorizes innovation typologies into incremental and radical from the viewpoint of technology discontinuousness, and into modular and architectural innovation from levels of product changes (Tushman and Anderson, 1986; Ulrich, 1995; Sanchez, 1996; Veryzer, 1998). Garcia and Calantone (2002) have divided the innovation into three categories: all new, incremental, and radical. The incremental innovation dominates most innovative practices while modular product architecture is widely implemented in this kind of new product development.

The product architecture approach (Henderson and Clark, 1990; Ulrich, 1995; Stone et al., 2000) is not only suitable to understanding the essence of modular product structure, but also to grasping the factors affecting innovative processes for both researchers and practitioners. We understand a product as a technical system which is composed of subsystems and interfaces, and regard a product as having two major levels including system and subsystem while the subsystem is named usually as function module in the modular product.

This study focuses on interface strategies in modular product innovation. To clarify how interface properties affect the innovative strategy, we will study the essences of interfaces in product architecture and identify the strategic meaning of interfaces in innovative decision.

We will summarize architecture definition in modular products by a literature review in order to find out the meaning of interface strategy in new product development. After that, we will study the technical system's composition of products and the characteristics of interface to identify the dimensional properties that affect the innovative practices and decision-making procedures. Depending on

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doi:10.1016/j.technovation.2004.01.013

the strategic meaning of properties we will build an analysis unit and propose a theoretical matrix of interface strategy in modular product innovation. Finally, we will examine this matrix with case studies of Taiwan's machine tool industry, and demonstrate the managerial meaning, and some further research topics.

2. Literature review

2.1. Typologies of product innovation

In this study, we define product innovation as: the planning and realization processes that create or rebuild a new technological system and provide the necessary functions to satisfy the needs of customers The final goal is to provide a solution that can be utilized or accepted by customers.

When looking at product change we see that product innovation can be identified as incremental or radical (e.g. Abernathy and Utterback, 1978; Nelson and Winter, 1982; Ettlie et al., 1984; Meyer and Utterback, 1993; Uttreback, 1994), and patterns of innovation relate highly to organizational structure and environment. From the viewpoint of product architecture, modular products have particularly innovative models including the modular and architectural (Henderson and Clark, 1990; Ulrich, 1995). Since the architecture approach is implemented widely in practice, it is a very important perspective for innovative research.

2.2. Product architecture

Product architecture is the interactive pattern of functional modules in a product system. Architecture is the scheme by which the function of a product is allocated to its physical components. Decomposing a product design into functional components and specifying the interfaces that define the functional relationships between those components creates the product architecture.

The product architecture acts as the guideline in subsequent design processes (Ulrich, 1995; Sanchez and Mahoney, 1996). The properties of architecture are a technical system that represents the interactive relationships between components (Fujimoto et al., 2001). This relationship is the basic design concept of deconstruction and mapping.

Ulrich (1995) suggested a three stage approach to lead processes from product concept to physical product. First, define function structure: the arrangement of functional elements and their interconnections, then decide the mapping from functional elements to physical components, and finally, specify the interfaces among interacting physical components. From this we conclude that a product is composed of two major elements from the architectural perspective: physical components and interfaces.

A component is defined as a physically distinct portion of the product that embodies a core design concept and performs a well-defined function (Clark, 1985; Henderson and Clark, 1990; Ulrich, 1995). The component is named usually as a functional module in a modular product. Interfaces provide the interacting relationship between components. A functional structure describes the relationship between the components and the interfaces, which allows the product to operate effectively.

In this paper, we define the product architecture as a technical system that allows the constituents of a product to interact and correlate with each other. Product architecture is the decomposing and integrating of technical subsystems to perform product functions. From the architectural perception, corresponding to the technical system of functional structure, the properties with which components interact and correlate is the interface.

Organizations that develop products often organize developing and producing processes into structures that closely reflect the architectures of the products they develop (Henderson and Clark, 1990). Fully specifying the component interfaces in a modular product architecture requires a well-developed understanding of the basic technologies used in each component and, especially, of the way in which components interact in a product architecture (Sanchez, 1996). For this reason, the architectural approach and the interface perspective are important and suitable to study in innovative strategic issues.

2.3. Modular product and integral product

A modular architecture occurs when existing multiple physical substructures have a one-to-one correspondence with a subset of a product's functional model. With respect to integral product, modular products are machines, assemblies or components that accomplish an overall function through combination of distinct building blocks or modules (Stone et al., 2000). Meyer and Utterback (1993) reported that, by means of changing the component modules in a modular product, firms can introduce new products into the market or do product upgrading with limited effort, shorter lead times, and lower costs. Other researchers provide the evidence of modular architecture contributing to acceleration of innovation (e.g. Henderson and Clark, 1990; Meyer and Utterback, 1993; Pine, 1993; Ulrich, 1995; Sanchez, 1996; Shock and Hartrum, 1998; O'Grady, 1999; Dahmus et al., 2001).

In contrast to modular products, the simple mapping of function and component does not exist in integral product. Multi-functions can be achieved with single component or multi-components, but it is hard to identify a simple relationship between functional and physical structure in integral products. Staffs and organization producing integral product must interact much more frequently and more closely to optimize the performance of their products (Ulrich, 1995; Fujimoto et al., 2001).

The superiority of modular products is the modularization focus on particular functional units to standardize and contribute to the ease of disassembly and reassembly, in order to construct different products or systems. This ease creates more variation and flexibility of the final products (Baldwin and Clark, 1997). This clarifies that standardization is a key concept in modularization.

In product technical systems, interface plays the key role in integrating, compatibility, and is the basis of new products or function extension. Sanchez (1996) reported that the modular product is a special model to create flexible product architecture by means of standard interfaces. This explains not only the importance of standard interface to modularization, but also the switching of focuses from module exchange to compatibility of interface and architecture.

2.4. The meaning of interface strategy research

Internal interfaces in a product play a critical role in the product planning and realizing processes. A product can be fully functional when it is composed of modules that are connected by internal interfaces. Interfaces accommodate connection, transformation, and interaction functions. By setting standard interfaces, product can achieve replaceable, upgradeable, and functionally variable abilities by means of variant functional subsystems which allow it to construct different products.

A single product is usually one part of an upper level technical system. Products with complementary properties are increasingly important in the real world. As the complexity of the product system increases, single firms find it hard to provide all the necessary assets, thus the openness of interfaces dominates systemic compatibilities.

Complementary assets are the products or subsystems that can fit and interact with specific product to achieve functions not available initially. They can be part of a product available from inside or outside the firm, or can be other products or subsystems that interact with the product by external interfaces.

Compatibility depends on the previously committed system architecture and interface standards under an industrial disintegrating environment (Mahajan and Muller, 1991; Matutes and Regibeau, 1992; Bucklin and Sengupta, 1993; Dhebar, 1995; Sengupta, 1998). For an individual product acting as a part of an upper level technical system, the external interfaces accomplish connection, transforming, and interaction functions similar to the internal interfaces in a product. Compatibility and complementarity, which represent the positioning of products in upper level architecture and the positioning of components in product architecture, are critical issues for product success in the planning stage.

One of the key issues in compatibility and complementarity is the commitment of interface rules in connecting subsystems (Kano, 2000). It represents the constructing and dominating power of internal and external interface standards that contributes firm's competence in new product development. Globalization promotes the necessity of disintegration and cooperation to create huge technical system and suggests that single firms are unsuitable to work alone. By first committing system architecture and defining interface, each company can focus on what it does best in the subsystem. Examples can be found in the telecommunication system, the air transportation system and the construction of computer networks.

3. Theory of interface strategies

When we consider the development of product platforms and product families, standard interfaces are previously defined issues and rules as usual. Thus, the decision of interface's rules can be easily overlooked and the strategic role of interfaces can be covered. The importance of internal and external interfaces is clear from the previous discussion. In the theoretical development period, we discuss the characteristic of interface by analyzing the properties of internal and external interface and the effect of openness in discovering the strategic meaning of different open levels in internal and external interfaces.

3.1. Definition and characteristics of product interface

We take a product as a technical system existing for specific purposes where interfaces provide the properties for subsystems to interact and correlate. Interfaces possess the interacting functions such as connecting, transferring, transforming, and controlling. Physical interface specifications define the interacting protocol between components, and the geometric matching of existing physical connections. The particular interfaces of elements construct informative structures that define the necessary output of the developing processes (Sanchez, 1996).

This study focuses on the system and subsystem level of product as shown in Fig. 1. Modules are technical

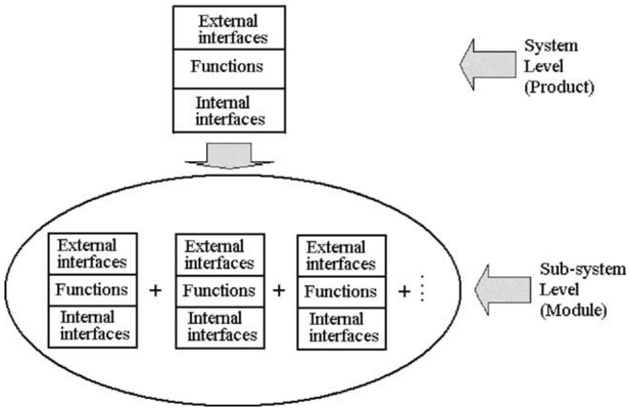

Fig. 1. Two-level product hierarchy.

subsystems that embody some specific functions while interfaces provide the interrelations between modules. Products provide full functions by means of functional modules correlated and connected by interfaces. Interfaces have disintegrating and integrating characteristics in a product system. They disintegrate, divide and transform from the top down, while they perform the interacting, connecting and integrating functions from the bottom up.

3.2. Interface in product platform and product family

A product family is a group of differentiated products, which satisfy segmented market needs with a common product platform. In practice, a product family usually includes products which have finite variant functions (Meyer and Utterback, 1993; Sanderson and Uzumeri, 1995). The concept of product family is a group of products sharing some common elements.

Platform strategy is the using of common subsystems in multi-products to construct product platforms. In this way, firms can develop product families in shorter development time and thus gain economic benefits (Muffatto, 1999). The group of common elements usually considered as the product platform, include common functional subsystems and interfaces (Meyer and Lopez, 1995; Meyer and Lehnerd, 1997). Dahmus et al. (2001) provided an approach for generating architecture which creates product families that share interchangeable modules. Both product platforms and families are the application result of a firm's core competence (Meyer and Utterback, 1993).

The common interfaces contribute commonality and compatibility in sequential platform subsystems. Specifying requirements for component interfaces before component development begins enables the processes for developing components to become decoupled. In other word, processes for developing components, like the modular component designs themselves, are no longer highly interdependent or 'tightly coupled'. They encourage greater innovation at the component level, and allow access to an enlarged network of component development resources (Sanchez, 1999).

Sundgren (1999) reported that interface management contributes to shortening the time to market of new product platform innovations and provides short-term and extensive effects. This implies that the effect of interfaces will vary in different product innovations; therefore it is hard to demonstrate long-term effects and strategic meaning of interface decisions for a single product. Thus, we will now focus on product family to discuss the meaning of interface.

3.3. Internal and external interfaces

When we access the effects of interface decision, we have to survey the internal interfaces with respect to the technical system in product level and the external interfaces relating to technical system in the upper level. The upper system level includes the product and the complementary assets. There is much research about interfaces in innovation in software and communication industry (e.g. Meyer and Lopez, 1995; Shock and Hartrum, 1998; Pangalos, 1999; Kano, 2000) but there is a lack of adequate attention to the managerial meaning in product innovation. We begin from the architecture perspective to summarize the role and characteristics of interfaces in order to propose strategic meaning and practical implications.

Interfaces are the base of both integrating and disintegrating of product architecture. Internal interfaces coordinate functional elements to perform full product functions, while external interfaces connect external products (e.g. complementary products) or users and affect the upper level technical systemic performance (e.g. Meyer and Lopez, 1995) and play the key role in system standard including complementary assets.

As described above, a firm has to consider both internal and external interfaces at the same time when evaluating interface strategy to construct competence of the product and the firm. We propose that the study on product innovation cover product system architecture and upper level system architecture simultaneously.

3.4. Openness of interface

From the strategic perspective, openness is an important essence of interface We find out that openness has highly strategic meaning in innovative research with the analytical dimensions of internal and external property. Meyer and Utterback (1993) provided the concept of a product platform and a product family that is the evidence of changing from close-property to open-property by means of applying common components to various products. Fujimoto et al. (1998) reported that the openness is the extensive level for which the technical knowledge of product is accepted and implemented by social systems. The increase of complementary and compatible products promotes network externality to higher total openness in many ways (Katz and Shapiro, 1985). Open strategy can provide the advantage of risk sharing, system enlargement, and lower the cost of network members.

We infer that the standardization tendency and the effects of standards diffusion from product innovators to other users represent the open level. Since openness represents the sharing of system information, commonly accepted standards are the significant symbol of openness and normally named as a dominant design (Abernathy and Utterback, 1978; Anderson and Tushman, 1990; Uttreback, 1994). The standard associations act as the standard makers of product systems and interfaces in industries (Fombrun and Astley, 1982; Gabel, 1987; Kano, 2000). The standards indicate sharing of specific information and knowledge; they also create the rules governing members. Standards play a major role in making the tacit and localized knowledge on which new products and manufacturing processes are based.

Table 1
Open tendency of interfaces

	High	Medium	Low
Existing level of standards	No standard	Enterprise-wide quasi-industrial standards	Industrial standards
Product models adopting the interfaces	Single product	Multi-products within a firm	Multi-products cross-firms
Production and usage knowledge	Within specific system require expertise training	Familiar by finite social networks (supply networks and user networks)	Widely spread and learned by firms and social networks

The indexes of interface openness include standardization tendency and commonality of interface knowledge about production and usage. Interface standardization tendency can be surveyed from the existing levels of interface standards and the extension of interfaces fitted to individual products as shown in Table 1.

Existing levels of standard can be distinguished into none, firm-wide, quasi-industrial standard and industrial standard. The openness tendency is highest when the public industrial standards exist. The openness is also distinguished in adoption of single product, commonly adopted in multiple products. The open tendency is highest when the interface is used in cross-firms products.

Commonality of knowledge about production and usage of interfaces can also be identified in Table 1. This factor depends on the richness of enterprise's available resources and the positioning strategy of products and firms. The consumer's adoption of an interface is important in forming a social system and affects the success of new products and new interfaces (Dhebar, 1995; Ziamou, 2002).

From the viewpoint of social systems, we propose that the openness of internal interfaces in product architecture usually tends to be close and limited within the scope of firm. The reason is the users are less sensitive to internal interfaces and the firms are willing to achieve advantage of differentiation with close and unique internal interfaces. The external interfaces tend to be more open and usually beyond the enterprise's boundary to meet the requirement of complementarities.

3.5. Interface strategic matrix

Interface strategies in product innovation can be considered to have two levels. The first one is the decision of internal and external interface arrangements that related to the positioning strategies of a product in upper technical systems. The decision of internalizing or externalizing particular interfaces belongs to the strategic level of product architecture. Taking personal computer as example, the monitor is embedded in a notebook computer and the connecting interface of monitor and other computer components is an internal interface. A desktop computer's monitor connects the main box with an external interface.

The second level is the open decision of interfaces which relates to compatibilities and complementarities with other products and social networks. It is the basis of the economic scale effect for an interface fitting into different product systems or subsystems. Commonality and standardization can help to elevate the learning effect and network effect to that interface, and enhance the stability and economy for the interface and the entire architecture (Garud and Kumaraswamy, 1995).

The different open tendency of internal and external interfaces creates the product interface strategies. It belongs to the positioning strategy which constructs the product differentiating competence for firms and hints at the dependence on internal and external resources.

With this two-level analysis, we propose a strategic matrix of interfaces shown in Fig. 2. The horizontal dimension captures the impact of openness on upper level technical systems and social networks, while the vertical captures its impact on individual product architecture and platform. Openness of the internal interface represents the compatibility and exchangeability between components and products. Openness of the external interface represents the compatibility and exchangeability between single product and upper level product systems. We suggest that these dimensions can define more precisely the positioning, compatibility and possibility of expansion of a product, and thus it is an interface strategic matrix with a theoretical and practical context.

3.6. Typologies of interface strategies in product innovation

When the openness of internal interfaces is low and the external interface is also low, it is an entire interface innovative strategy. The innovations focus on both the internal and external interfaces. When the external openness is high under low openness of internal interfaces, it is

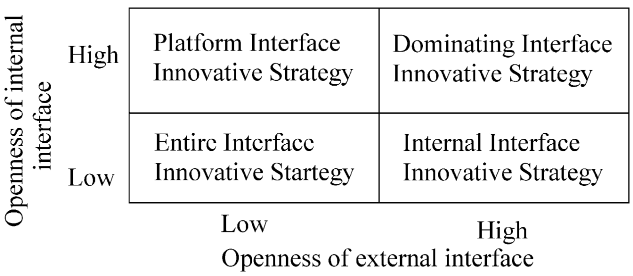

Fig. 2. Interface strategic matrix.

an internal interface innovative strategy following the regulations of open interface standards.

When the tendency of internal interfaces is open but the openness of external interface is low, it is a platform interface innovative strategy. The innovations focus on the external internal interfaces to seek the possibilities of platform construction, therefore, it is a platform interface innovation strategy. When the openness of external and internal interface is both high; it is a dominating interface innovative strategy suing the dominating position and the decisive power in interface standards.

When outside supplied subsystems are available but cannot be fitted into product interface; strategic thinking and the decision will differ. One of the solutions is to modify the existing interface, give up the existing architecture and interfaces to achieve an advantage in outside resource utilization. This tends to be an internal interface innovative strategy. One issue to be considered is the impact on existing product systems. Another solution is adding a transforming interface (Farrel and Saloner, 1992) to keep the existing interface and transform it into a compatible interface to match with an outside supplied subsystem. Since this method achieves the commonality of an existing interface, it is a platform interface innovative strategy.

Garud and Kumaraswamy (1995) reported that existing functional modules or interfaces have their system limit and must be overcome by the upgrading or evolving of the interface. It is possible to induce new interface and/or module innovations. Interface innovation and module innovation take turns or happen simultaneously, thus, the openness of interface will vary relatively. For this reason, the interface decisions in product innovative processes not only have strategic meaning, but also have the corresponding environmental requirements. We will discuss this issue in Section 4.

4. Discussions

4.1. Openness and standardization of interface

The purpose of a building standard is to create a common commitment to system architecture. Not making precise definitions of standards will help to keep flexibility and freedom of development (Garud and Kumaraswamy, 1995). The commonality between product, technology and organization create a basis for long-term evolution. Modular architecture enhances the product's developmental speed by adopting standard interfaces and accelerates the innovative speed to reach the systemic performance limit. On the other hand, in order to overcome the performance limits and seek the advanced innovative chance, it is likely to break through the standard interfaces or commonly adopted architectures (Fujimoto, 1998). Therefore, interface standardization can help to speed system improvement and perform the upper limits of improving efforts at the same time, thus the interface decision is a key issue in product innovation.

Standardization of interface not only affects the product itself, but also affects the innovative organization and the supply systems. Suppliers with different capabilities need a different organizational interactive models (Langlois and Robertson, 1992; Araujo et al., 1999; Hsuan, 1999). Innovators can benefit from the industrial-wide interface standards in the product extension and the commonality of production system and the supply networks to lower the entire cost to members in the network. With lower openness of specific interface can help firms to embrace the differential advantage and delay the technical diffusion to keep competence. When the openness exceeds the firm's domain, technical diffusion effects will enlarge outside resources to benefit all followers and enhance competition. The conflict between higher and lower open tendency is always a sophisticated managerial issues.

4.2. Evolution of interface openness

Innovative speed is affected directly by outside resources on which firms can depend (Clark, 1989). Pioneer products usually lack usable modules and interfaces and thus, interface openness tends to be low. The modules and interfaces serving specific applications are supplied by basic levels of the supply system (Chen and Liu, 2002). If there are available resources, direct application is possible and the openness tends to be higher. Learning effects and production scale economy benefit the extension from existing product to other product to encourage the adoption of open strategy.

The regulation force of rigid external interface requirements constrains the innovative activities of firms. Enterprise tends to utilize highly close internal interfaces to build defensive barriers to compete, although it is possible that available resources do not exist yet. These phenomena happen regularly under all new technical system booms or extreme changes.

We propose that the openness of internal interfaces tend to be low and it is usually hard to across the enterprise's boundary while the external interface benefit from integrating with complementary products, the open tendency is usually high. In this situation, keeping open external interfaces and focusing on module innovation is a reasonable strategy. This represents the interface standards embody some kind of constraints and correlate with social systemic momentum including the producers and the users.

4.3. Four strategies and correlative environment

4.3.1. Pioneer product—entire interface innovative strategy with close internal and external interfaces

In the infant period, the product concept is not clearly defined and understood by producers and users. This means that the functions of a product do not have a commonly followed standard. The decision of interfaces depends on the innovator's thinking and not on social networks. Before the external interface standards are accepted, the open tendency of external interfaces is often low.

New internal interfaces with low openness will appear to coordinate the interaction of modules to achieve best performance. Under this situation, it is possible to release the limit of adopting existing interfaces for all new products to seek the interface innovation although some existing interfaces may be acceded.

The pioneer products have higher internal interface innovative opportunities than external interfaces since the enterprise's autonomy. The innovative organization tends to encourage the advanced innovative ideas over the existing regulations. The new external interface can be secured by market testing and the new interfaces accompanied by new released functions can fertilize the adoption of consumers and induce product's success (Ziamou, 2002). Once a new external interface accepted by users, there is the opportunity to act as the dominating standard in market and foreclose other new interfaces. Therefore, dominating the external interface innovation is also an important part of entire interface innovative strategy.

4.3.2. Product family—platform interface innovative strategy with open internal and close external interfaces

This strategy keeps low openness for the external interfaces and standardizes the internal interfaces to implement multi-products in the firms. The regular case is the process of developing platform to construct product family. Implementing the standardized interfaces into succeeding products can induce firm-wide open effects and can be categorized into the platform interface innovation.

This strategy can leverage in-firm knowledge to accelerate the module innovation with lower cost and effort. But the innovative organization usually has the tendency not to adopt the common system (Garud and Kumaraswamy, 1995) even the replicated implements can help a firm get long-term benefits. Hence, specific organizational formulations and incentive systems are necessary to encourage the internal cooperation.

4.3.3. Mature product—dominating interface innovative strategy with open internal and external interfaces

The product-creating firms increasingly function as an open system to build and leverage knowledge with the network resources in dynamic product markets (Sanchez, 1996). The correspondent environments will vary when the external and internal interfaces are gradually accepted as the industry-wide standards.

Dominating interface innovative strategy includes two models. The first model is the performance-optimizing strategy that dominates module innovation by using available outside resources to construct new products and to compete in market with low cost. The possible difficulty here is the performance limits of existing interfaces. These limits may result in further interface innovations breaking through these limits. There are possibilities of switching to the entire interface innovation.

The other one is the dominating strategy of externalizing the internal subsystems into new products that embrace specific functions of the original product. Transforming internal interface into external interface necessitates building and dominating the internal standards and then externalizing them as the industrial standards. To get the leading position and dominate the standards is important in this strategy and it highly relies on the strategic decision and the environment of firms.

Since both strategies have a strongly dominating tendency, we summary these as the dominating interface innovative strategy.

4.3.4. Growing product—internal interface innovative strategy with close internal and open external interfaces

When the external openness is increasing more quickly than internal interfaces, the general agreement about a product and the complementary assets will contribute to the dominant design, though creating and introducing the new external interface is a hard and time-consuming work in booming product.

Internal interface innovative strategy is preferred as a means of following the external interface standards. In order to enhance the internal interface performance and keep close to seek the best performance of a product, the internal interface innovative is the key issue. The commonality and standardization of interfaces are not so important but rather the module innovation is the focus point typical in this period. The issues of forming production system and social networks should be the focus of management to accelerate the adoption of the products.

4.4. Dynamic evolution of interface strategy

From the viewpoint of its lifecycle, a product will go through several stages. In the infant stage, the product concepts including product functions and architecture are not well defined and understood by producers and users; decisions concerning the interface openness depend on the available resources and the innovator's perspective. The internal and external interfaces usually tend to be less open in pioneer products.

As the dominant design emerged, the product architecture gradually stabilizes and the openness of external interfaces gradually becomes greater as time goes by (Anderson and Tushman, 1990). At the same time, differential products from different firms with finite functional variations will stock the market. Except for the particular components and relevant interfaces, the internal interfaces in product platform are more and more open by implementing to multi-products. The entire tendency is open for internal and external interfaces at this time. And the result is the internal standardizations across enterprise's boundary to push the standardizing of product architecture and thus contributes to the disintegration of industry.

The standard interfaces begin to become unsettle because the needs of product variation and begin to exceed the performance limit in a mature product. Introducing new interfaces and modules to test the market response usually become the focus in this stage. The possible results are the emerging of new interfaces or the detriment of existing architecture to form new products.

Therefore, different interface strategies are suitable at different stages of a product. Along with the positioning strategies and the available resources of individual firms, the product interface strategies can be implemented in specific situations.

5. Case studies in Taiwan's machine tool industry

5.1. Purpose and method

We examine the interface strategy theory by studying the new product development practices in Taiwan's Machine tool industry. We focus on three main builders who mainly produce the Lathe and Machining Center. Their products make up almost one-third of Taiwan's annual production quantity and Taiwan was the number 6 machine tool exporter in the world in 2002. We follow the new product development records for more than 10 years and interview the R&D staff to identify the innovative activities and the related environmental conditions in firms.

Our case study has three stages: first we collect data from the product catalogues and menus, the product development project records and interviews with R&D staff; after that we identify the main internal and external interfaces in products. Finally, we survey and score the open tendency with the indexes developed in this study. The open tendency is identified from higher to lower and grade from 5 to 1 as: (A) follow the existing industrial standards; (B) follow the quasi-industrial standards of multi-firms; (C) the interface is commonly applied in firm-wide products; (D) is implemented only in specific product but with plenty production resources; and (E) is implemented in specific product with finite resources.

5.2. Analysis of main product series

Since these products are not all new and the product architectures have been stable for decades, we suggest that the external interfaces are stable and open while the internal interfaces are open but a little less open than the externals as discussed in previous sections. The interface development tends to reveal the externally standardized and internally differentiated situations.

A-company produces VL1 to VL3 series Lathe in sequence for last decade, each series is composed of 3–5 product families and every family is composed of more than 2 products. The ME model is a pioneer product in VL2 series for particular functions. B and C companies have FM1 to FM4 and YM1 to YM3 Machining Center series that each series is composed of 2–5 product families. FM4 Horizontal Machining Center series is a predecessor of FM3 and is a pioneer product in local market. YM3 is the Horizontal Machining Center, too. The others in Table 3 are Vertical Machining Centers.

The scores of interface openness are listed in Tables 2 and 3. Some particular external interfaces listed in the tables have two scores because more than one type of interfaces are implemented in a product series.

5.3. Evidence from case study

5.3.1. Full views

We reveal some phenomena in our case study.

1. All the products are not entirely new in the world and the dominant design exists which is apparent from the stable product architecture.
2. Every product family includes more than two individual products, the structure of manufacturing and developing networks are highly similar.
3. Every product family is constructed by a platform that is composed of the main structural modules and the internal interfaces; these interfaces are similar in geometry and differ in dimensions.
4. The external interfaces ordinarily follow the industrial standards.

Table 2
Openness of product interface—Lathe

	Interface	VL1 series	VL2 series	VL3 series	ME model	Memo
Internal interfaces	1	C	C	C	C	
	2	C	C	C	C	
	3	C	C	C	E	
	4	C	C	C	C	
	5	C	C	C	–	ME model take place interface 5 with 6 and 7
	6	–	–	–	C	
	7	–	–	–	E	
	Openness	3	3	3	2.3	Average
External interfaces	8	A	A	A	A	
	9	B/C	B/C	B/C	E	
	10	B	B	B	B	
	11	C	C	C	–	ME model take place interface 11 with 12
	12	–	–	–	A	
	Openness	3.9	3.9	3.9	3.25	Average

Table 3
Openness of product interface—Machining Center

	Interface	FM1 series	FM2 series	FM3 series	FM4 series	YM1 series	YM2 series	YM3 series	Memo
Internal interfaces	1	B/C	C	B/C	E	B/C	C	B	
	2	B/C	C	B/C	C	C	C	C	
	3	C	C	B/C	E	C	C	C	
	4	B	C	B/C	E	B	C	B	
	5	B	C	D	D	B	C	B	
	6	C	C	C	C	C	C	C	
	Openness	3.4	3	3	1.8	3.4	3	3.5	Average
External interfaces	7	A	A	B	B	A	A	B	
	8	A	A	A	A	A	A	A	
	9	B	B	B	B	B	B	B	
	Openness	4.6	4.6	4.3	4.3	4.6	4.6	4.3	Average

For the open tendency of interfaces, we discover that:

1. The openness is low for the internal interfaces. Most of them are commonly implemented in multi-product in the firms, and lack industrial or quasi-industrial standards. But some products implement outsourced components such as the linear guide way in Machining Center and this contributes to higher open tendency.
2. Most external interfaces outreach the enterprise boundary in order to adopt the industrial standards and the tendency is very open. Since the complementary assets are supplied from outside non-monopoly suppliers; the external interface's open level will be higher in the future and will eventually form the formal industrial standards.
3. Common architecture is the basis of a product family; only finite interface dimensions vary in different individual products. This contributes to the commonality of manufacturing and the use of knowledge in networks.

5.3.2. Characteristics and tendency of interface strategies

All the products of three companies reveal the open trend that indicates that the stableness and openness is increasing when the dominant design and the mature supply network take shape. From the fact that outsourced quasi-standard components are gradually being adopted in new product development, we suggest that the openness will be greater in the future.

If we look only at the index of existing standard level, the difference between product internal and external interfaces is clear and this also evidence the proposition that the external openness is higher than internal interfaces. However, the internal interface is more open oriented when we discuss in more detail the producing processes and the supply systems.

When enterprises do not adopt purchased quasi-standard interface components, they usually design the interfaces with highly similar in geometric and manufacturing processes and most of these interfaces are provided by suppliers. For example, the boxway interfaces are similar in geometry but vary in dimension for different products and different firms. But the manufacturing processes and the equipment are the same. The plenty resources outside the firms contribute to greater open level of interfaces. This indicates that the second index for openness that the commonality of interface's producing and using knowledge is suitable to survey the openness.

We also identify the different interface tendencies in pioneer products. ME model Lathe is an example with particular functions in VL2 product series. Part of this product belongs to highly close modules that are embedded in the close interfaces to perform particular functions. Even the complementary products are not available from suppliers and no standards can be studied. This company develops the specific interface and the complementary assets by itself. Thus, the interfaces embody high close properties in the early stage of product's lifecycle.

A similar situation occurs in the motion interfaces of separated boxway in FM4 series Machining Centers. This interface needs large machining equipment and only one supplier is available in Taiwan at this time. The evidence suggests the second proposition, that the internal interface's openness is low particularly in pioneering products since the commonality knowledge in production and usage is low.

The construction cycle of every product series is highly similar in industry, evidence that the common product architecture and common interface concepts in modular product have been widely implemented in Taiwan's Machine tool industry. Every enterprise develops multiple functional modules with different performance to construct a product family and construct the platform by shared main structural modules. For example, there are three spindle modules in one product family of A-company and some of them are shared even in other families. Since we focus on interface in this study, we will not discuss modules in more detail here.

5.3.3. Evidence on interface theory

Platform interface strategy has been evidenced by the facts that the main structural modules and regulated interfaces construct the common product platform in all product series. Alternative modules with common internal interfaces have been widely used in product family development.

The internal interface innovative strategy is well fitted in the growing stage of lifecycle from the fact that every firm dedicates to develop the variant internal interfaces and modules to build a product differentiated from those of other companies under similar architecture and highly standardized external interface circumstances.

The dominating interface standard strategy is only partially evident. The tool magazine of Machining Center was an internal module in the beginning, but the expert suppliers later emerged in this industry. They supply the similar modules to multi-firms with intermediate interface, in order to fit with different products, but they keep both the magazine's interfaces and the customer's product interface unchanged.

Some machine tool builders have given up the magazine design entirely, and this is the evidence that externalizing the initially internal modules and interfaces of the mature product is part of the dominating interface innovative strategy. This happened in FM1–FM2–YM1–YM2 series, although the interface standard is dominated by the suppliers rather than by the machine tool builders.

The entire interface innovative strategy has only been partially verified, too. Only some pioneer products follow some external standards and do some external interface innovation. Reasons may be the technical follower role of Taiwan in this industry and the new product architectures have not yet emerged which can compete with the existing ones. Firms lack the power to dominate the standards or to innovate in the external interfaces. The difficulty of adopting the dominating strategy can be uncovered.

Due to the limits of human resources and other constraints, developing all products in a series completely take several years. In the developing period, building platform to derive new product family and developing new products in a family proceeded Box and Cox. The innovative model is the mixing of platform interface and internal interface innovations. Making internal interface innovation at first for the pioneer product and then setting this as the firm's standards to implement into the design of a product family is the normal process. At the same time the firms implement similar architecture to develop the new pioneer product in new family to construct the product series. This pattern is widely evidenced in this industry in Taiwan. This contributes to the evolution of interface openness in Fig. 3.

Long-term stable product architecture is a symbol of mature product. Every firm seeks performance optimization in different products by developing the modules with variant functional performance under regulated internal interfaces. Combined with the platform and the internal interface innovative strategies implemented in different stages, the evolving phenomena of interface strategies is shown in product lifecycle.

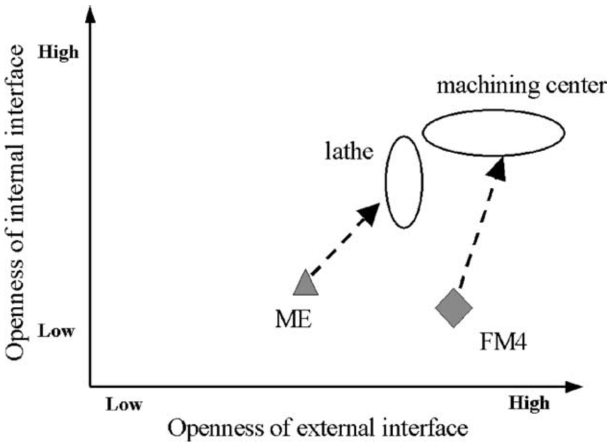

Fig. 3. Evolution of interface openness.

6. Conclusions and further researches

6.1. Conclusions

We define a product as a technical system satisfying specific needs. The product architecture is the mapping of the components with the product functions. Playing the key role of connecting and interacting between components, the interface standardization is a decisive issue in new product development.

We study the properties of interfaces including internal and external dimensions and the open essence to propose the interface strategic matrix and discuss the environmental conditions of strategies. The main conclusions are:

1. The internal and external interface decisions affect the product strategies in the product architecture level, and relate to the composition of subsystems. It can be categorized into the positioning strategies of subsystem in a product and the positioning strategies of a product in the upper technical system.
2. Open-property of the interface can be measured with two indices, that is the levels which the interface standards exist and the knowledge commonality of producing and using the interface.
3. The interface strategies constructed by different open levels in internal and external interfaces can enhance the product variation and enterprise's competence. Openness relates to the fitness of a product with the technical system, and is affected by the dependence on the internal and external resources. It is indeed the managerial thinking in the enterprise strategic level.
4. The interface strategies revolute dynamically with the changing environment and time. Available resources and the positioning of firm will affect the interface strategies in specific stages for firms. As the product matures, the open level will increase for both the internal and the external interfaces while the external interfaces will usually be more open than the internal ones.

5. The entire interface innovation and the dominating interface strategies are the strategic actions to break through the limits of resources. Since it is too hard to be implemented by the firms, we suggest that the possibility of success is quite low and thus will seldom happen. But when it happens, who dominates the standards will assume the leading edges in industry.

6.2. Meanings for machine tool industry

The Machining Center and the Lathe are not all new products and it hints the high open level situation in both internal and external interfaces. Since internal interfaces are not so sensitive to users of machine tools, the machine tool builders have more opportunities to do interface innovation. Accompanied by the role of technical follower in this industry, Taiwan's machine tool builders tend to take the strategy of following external interface standards and strive for internal interface variation and focus on module innovations. However, thanks to a highly expert non-monopoly supply network which is composed of plenty process service providers and parts suppliers, variant products with similar modules are build rapidly in distinguished cost and performance.

In order to avoid price war in this market, dominating system level architecture and interface standards to execute dominating interface strategy is important action. Focusing on internal interface and module innovation to form the product platform innovation can compensate for the disadvantage of lacking dominating powers on external interface standards. Once radical technical change happened, or the product architecture reformed, there will be opportunities for implementing the entire interface innovation strategy to promote long-term competence.

6.3. Meaning to product innovation and further researches

Research reports that the innovative organizational structure is highly similar to the product architecture. In order to grasp the benefits from outsourcing and product differentiation, adopting suitable open levels in product and organization relationships should not be neglected any more. This supports the importance of interface research.

This study makes academic contributions in many ways: the relevance of internal and external interface properties to the product innovation is shown to complement the product innovation studies; the indexes of open tendency to measure the interface open level are provided; the interface strategy matrix is proposed to supplement the product planning and realizing strategies; and the importance of the interface decisions are highlighted to construct the complete product innovation strategies.

This study discovers the theoretical and practical meaning of interface strategies in product innovation from the perspective of architecture. Due to time restrictions, there are many issues, which cannot be discussed in this paper, but would be good subjects for future research. For example: the effects of product's interface strategy on supply network; organizational interface strategy related to product strategy; decision model of in-firm interface strategy and dynamic evolutionary trajectory of interface strategies.

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