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A comparative analysis between LCD panel and flat glass in the TFT-LCD industry from process architecture-based view

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Keywords: process architecture, process industry, global competitiveness, LCD panel, flat glass

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INTRODUCTION

This paper aims to clarify the cause-and-effect relationships between global competitiveness and process architecture in the Japanese “process industry” from an architecture-based approach. Moreover, we identify the source of competitiveness. Concretely, we attempt to conduct exploratory research to compare the LCD panel and flat glass in the TFT-LCD (Thin Film Transistor Liquid Crystal Display) industry.

The global competitiveness of the Japanese automobile industry has been regarded as high, while that of the Japanese PC industry has been considered low. This is because an automobile has an integral architecture whereas a PC has a modular architecture. Moreover, Japanese manufacturers have organizational capabilities with integration from an architecture-based approach (Fujimoto, Aoshima, Takeishi, 2001). However, this type of research has focused on assembled products such as those in the automobile and electronics industries (i.e., Clark & Fujimoto, 1991; Baldwin & Clark, 2000; Ogawa, Shintaku, Yoshimoto, 2006) and rarely focused on materials or equipments in the “process industry” despite the fact that there have been many strong suppliers in Japan.

A few exceptional empirical research studies have been conducted on the process industry. Fujimoto & Oshika (2006) tested the hypothesis that the product with integral architecture had higher sustainable competitiveness than that with modular architecture. They implemented a questionnaire survey concerning 254 products in Japan (81 products in the process industry and 173 products in the assembly industry) and developed an architecture index. Further, they analyzed the cause-and-effect relationship between the architecture index, labor intensity index, and global competitiveness scores such as export ratios, and overseas sales ratios by regression analysis. In addition, they clarified that if the architecture index score was higher (more integral), then the global competitiveness score was significantly higher in both the assembly and process industries. However, the content validity of the architecture index was uncertain since the questionnaire data included the respondents’ subjective bias.

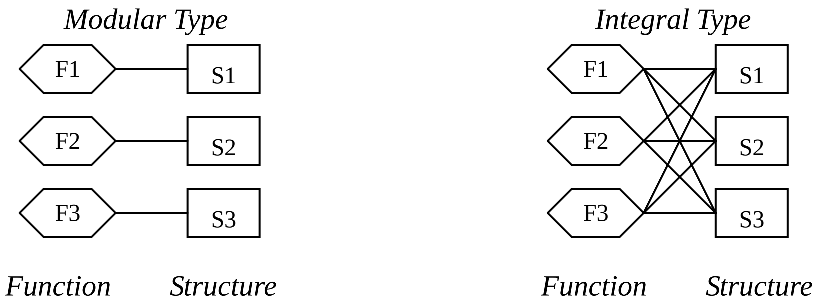
However, the empirical research of Fujimoto, et al. identified the trade pattern of steel products in Korea, China, and Japan (Fujimoto, 2008; Fujimoto, et al, 2006). For example, although Japan had imported the steel for the inner panel of automobiles from Korea, it had exported a considerable amount of steel for the outer panel of automobiles to Korea and China. This is because the steel for the inner panel tended to have a modular process architecture, whereas the steel for the outer panel tended to have an integral process architecture that only Japanese manufacturers could produce with their organizational capabilities of integration in the steelmaking process. Process architecture (not product architecture) is considered to be more important in the process industry than in the assembly industry (Fujimoto, 2003; Fujimoto & Kuwashima, 2002). Fujimoto, et al. (2006) discussed the abovementioned process architecture of two types of steel for automobiles.

However, very little empirical research has been conducted on other process industries. Hence, this paper focuses on the process industry and attempts to conduct exploratory research to compare LCD panel and flat glass in the TFT-LCD industry. It proposes to clarify the cause-and-effect relationships between global competitiveness and process architecture in these industries. Are they highly globally competitive? What kind of architecture do LCD and flat glass in the TFT-LCD industry have? Thus, we try to identify the source of competitiveness.

ARCHITECTURE-BASED APPROACH

Process industry, based on design theory in the manufacturing industry, is defined as “the industry whose design activities are mainly occupied by process design” (Fujimoto, 2003). It includes upstream of semiconductor or LCD, steel, flat glass, chemical, brewery industries. For example, a structure that achieves a target function cannot necessarily be described as explicit knowledge in the steel industry. Thus, a product design tends to be omitted or simplified because designing the product is unfeasible. As a result, functional design is directly translated into process design.

The question that arises, then, is what type of architecture do the products in the process industry have? Product architecture is defined as “the arrangement of functional elements,” “the mapping from functional elements to physical components,” and “the specification of the interfaces among interacting physical components” (Ulrich, 1995). This concept is related to the following two aspects. One is “the relationships between the function and structure of a system,” and the other is “to the extent to simplify or standardize the interfaces between elements of a system” (Fujimoto, et al., 2001). For example, if the relationships between the function and structure of a system resemble one-to-one relationships, then product architecture is of the modular type; however, if they are complicated, then product architecture is of the integral type (see Fig.1).



Modular Type

Integral Type

Figure. 1 The basic type of product architecture

Source: Fujimoto (2003), Fujimoto & Kuwashima (2003) revised.

Fujimoto (2003) and Fujimoto & Kuwashima (2002) extended the architecture concept to the production process, or process architecture, in the process industry because it seemed to be more important to “process design.”

According to their research, “process” entails a system that is made up of a series of production equipment, tools, workers, process of working, and operations for commercialization. Production process functions by transforming raw materials to produce a product with a specified structure. Further, a series of processes are formulated and a method to connect the process flow and layout is designed. This is what constitutes process design.

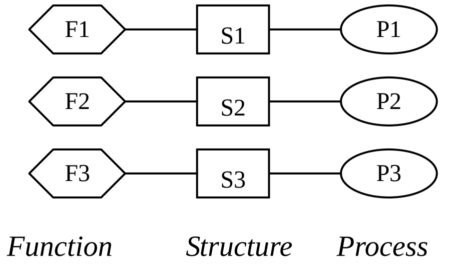
Moreover, process architecture is defined in a similar manner as product architecture. However, its definition includes the following two aspects. The first is “the relationships between the structure and process of a system,” and the other, “the relationships between function and structure of a system.”

Furthermore, process architecture is classified into the following two types—modular type and integral type. The former resembles one-to-one relationships such as the relationships among the function, structure, and process of a system (Modular Type 1), while the latter is similar to the relationships between the function and process of a system (Modular Type 2; see Fig. 2, upper-side).

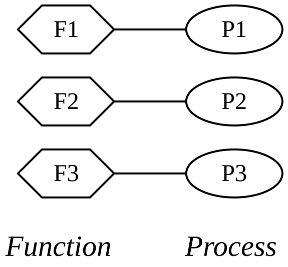
The integral type is constituted by complex relationships such as those between the function and structure of a system (Integral Type 1), the structure and process of a system (Integral Type 2), the function, structure, and process of a system (Integral Type 3), and the function and process of a system (Integral Type 4).

Other types of architecture are the open type or closed type (Fine, 1998; Baldwin & Clark, 2000). The former is of the modular type and is defined as “a system whose interfaces among elements are standardized at the industry level.” Therefore, it enables the design of a functional product by combining several elements (modules) across firms. The latter is defined as “a system whose interfaces among elements are standardized within a certain firm.” Therefore, it is only possible to combine several elements within a certain firm to efficiently develop a functional product (Fujimoto, et al., 2001).

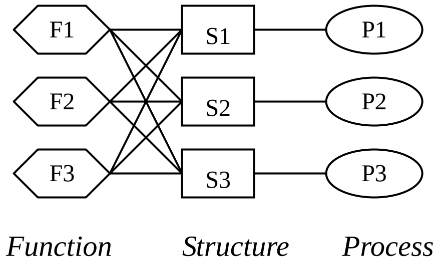
Modular Type 1



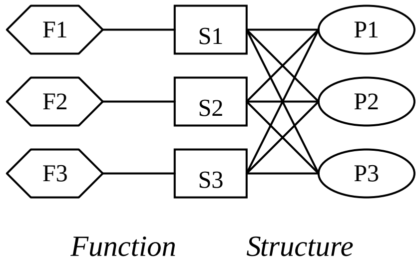
Modular Type 2



Integral Type 1



Integral Type 2



Process

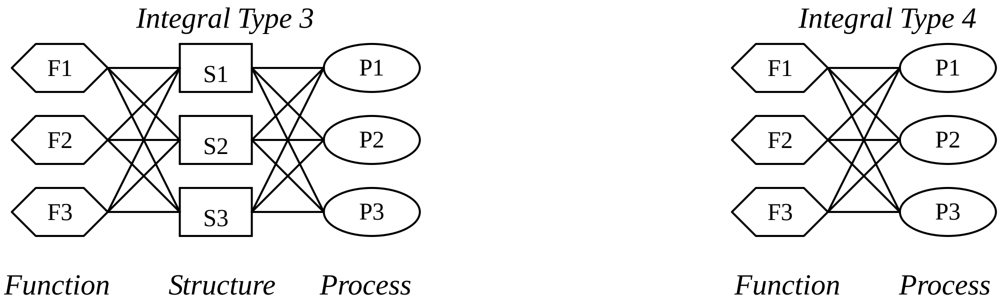


Figure. 2 The basic type of process architecture

Source: Fujimoto (2003), Fujimoto & Kuwashima (2003) revised.

Architecture is a relative concept. For example, if the process elements of a system increase or the connections between functional elements and process elements increase, then process architecture becomes more complex and more integral; However, the opposite is also true. Moreover, architecture is also a dynamic concept. Hence, architecture is shifted from being integral to modular or vice versa (Fine, 1998; Chesbrough & Kusunoki, 2001). Furthermore, if architecture is modular and open, the speed of the transfer of technology from developed countries to developing countries is more rapid (Ogawa, et al., 2005; Shintaku, et al., 2006b).

Thus, the questions that arise are as follows. What type of process architecture in the Japanese process industry achieved high global competitiveness? What was the source of competitiveness? In order to answer these questions, we conduct a comparative analysis between LCD and flat glass in the TFT-LCD industry.

CASE STUDIES: LCD PANEL AND FLAT GLASS IN THE TFT-LCD INDUSTRY

In this section, we analyze the global competitiveness of LCD panel and flat glass in the TFT-LCD industry. The flat glass is one of the main components of LCD panel, and the LCD panel is one of the main components of the LCD TV. The analysis of the LCD panel is partially based on Shintaku, et al. (2007; 2008) and that of the flat glass is partially based on Tomita & Ogami (2008).

The case of the LCD panel

First, we analyze the case of LCD panel. Fig. 3 proffers the global market shares for TFT-LCD panel production by country. Although Japan first developed and commercialized the TFT-LCD panel in the early 1990s, Korea and Taiwan quickly caught up with the process and surpassed Japan in the early 2000s (Shintaku, 2008; Shintaku, et al, 2006a). Why did Japan lose its competitiveness so rapidly in the TFT-LCD panel industry?

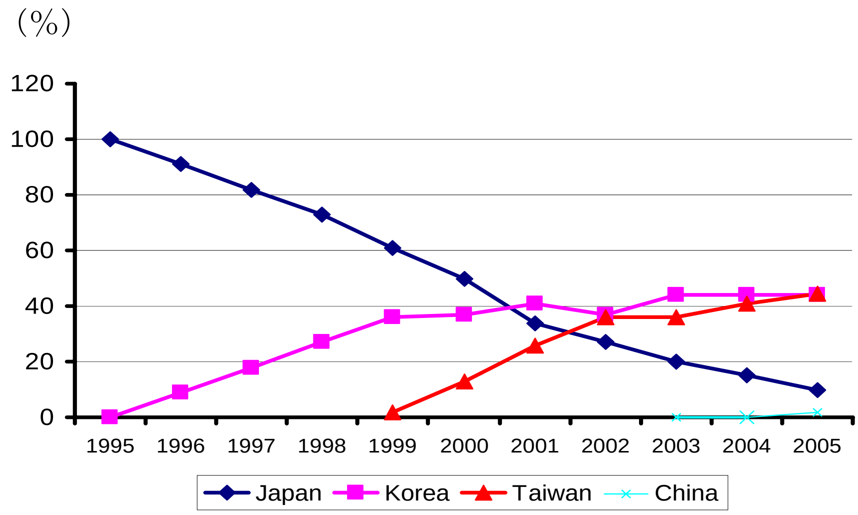


Figure. 3 Global market shares for LCD panel production by country

Source ：Shintaku, et al. (2007), Original Source ：SERI (1999)，Display Research (2002, 2006)

This phenomenon cannot be fully explained by product architecture analysis. Since the product architecture of the TFT-LCD panel appears to be integral, the main function of the panel is its “display quality,” which comprises resolution, luminance, contrast ratio, color reproductivity, response speed, viewing angle, and so on (SEMI Color TFT-LCD Committee, 2005; Suzuki, 2005). Furthermore, the panel consists of several main components, including an array substrate, a color filter, an alignment layer, a liquid crystal, a polarizer, a driving circuit, and a backlight unit. The relationships between the function and structure of this product system have a high interdependency and are complex like those observed in the integral type shown in Fig. 1 (see Fig. 4).

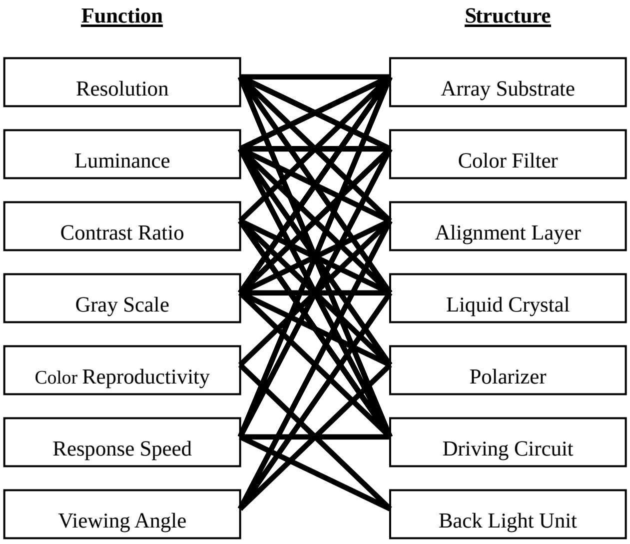


Figure.4 Product architecture of TFT-LCD panel

For example, in order to achieve high luminance, some structural parameters, such as the array substrate, color filter, alignment layer, liquid crystal, and polarizer, must be fine-tuned and optimized. Other functions, too, need to be performed. This type of architecture makes it difficult for developing countries to quickly reproduce the TFT-LCD panel.

Although Japan had transferred its technology to Korea and Taiwan by means of a strategic alliance after the late 1990s (Shintaku, et al., 2006a), Korea and Taiwan had smoothly set up a lot of plants of generation five mother glass size, in spite of the fact that Japan had not invested in any similar plants. As a result, these countries reversed the global market share of the TFT-LCD panel.

Subsequently, we attempt to clarify the logic behind such a phenomenon from a process architecture-based approach. The process flow of the TFT-LCD panel entails the following four main processes: the array process, the color filter process, the cell process, and the module assembly process. The array process is one wherein a considerable number of thin film transistors and circuit/pixel patterns are formed on a glass substrate like those in a semiconductor. This process involves several subprocesses such as cleaning, deposition, coating, exposure, developing, etching, and ashing. These processes are repeated several times in sequence to form the TFT array.

The color filter process is one wherein multicolored layers such as black, red, green, blue matrices are formed to correspond with the TFT array. This process is similar to the series of array subprocesses. Suppliers mainly produce the color filter and LCD panel manufacturers buy it from them. However, recently, major panel manufacturers have been manufacturing color filters themselves for cost reduction.

The cell process is the one used in assembling the LCD panel. This process consists of several subprocesses such as printing/rubbing, filling/assembling, sticking, and so on. This process begins by printing and rubbing the alignment layer, filling (dropping and vacuum) the liquid crystal and assembling the TFT array substrate and color filter, then sticking the polarizer on it, and finally, cutting this into several cells as in the case of generation five mother glass size.

The module assembly process is performed at the end of the TFT-LCD module. This process involves subprocesses such as mounting the driving circuits on the cells and assembling the backlight unit.

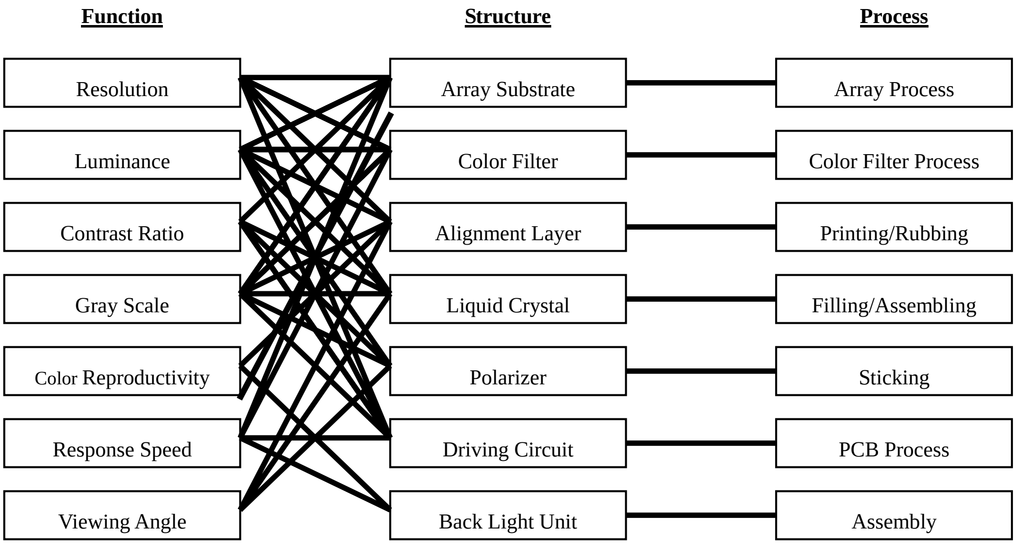


Figure. 5 Process architecture of TFT-LCD panel

Fig. 5 illustrates the process architecture of the TFT-LCD panel. This is similar to integral type 1 in Fig. 2. Although the relationships between the function and process architecture are integral, those between the structure and process are one-to-one relationships. For example, an array substrate is processed by an array process as well as other components (SEMI Color TFT-LCD Committee, 2005; Suzuki, 2005).

The array process consists of repeated subprocesses such as cleaning, deposition, coating, exposure, developing, etching, and ashing; moreover, the components of the subprocesses are highly interdependent. For example, the method of drawing a mask pattern in the exposure process strongly influences the removal of the pattern in the etching process. However, this kind of problem solving is generally done by equipment suppliers (Shintaku, et al., 2007).

Thus, if we analyze the panel process by dividing it into a large unit of analysis, then process architecture seems to be integral (type 1 of Fig. 2). If the relationships between the structure and process of the TFT-LCD panel are modular and open, new entrants with adequate financing can buy the required equipments and material and rapidly set up LCD plants. In fact, the Korean and Taiwanese manufacturers of the TFT-LCD panel bought a lot of equipment with solutions from Japanese suppliers (Shintaku, 2008; Shintaku, et al., 2007). Hence, these countries smoothly set up many plants of generation five size to build the TFT-LCD panel.

The case of flat glass

Next, we analyze the flat glass TFT-LCD panel. Table1 indicates the global shipment shares of the flat glass industry for TFT-LCD by company. This industry maintained oligopoly in the market, which only had four or five glass suppliers from its beginning in the early 1990s. The largest supplier was Corning in the US. AGC (Asahi Glass Company) was the second largest supplier, the third was NEG (Nippon Electric Glass), and the fourth was NHT (NH Techno Glass); furthermore, these companies were Japanese suppliers. (However, NHT exited the market for the LCD-TV in Q4 2007.)

Therefore, the question that arises is why did the flat glass TFT-LCD industry maintain oligopoly and how did the existing suppliers sustain competitiveness while the existing Japanese manufacturers were rapidly losing competitiveness in the TFT-LCD panel industry?

First, capital was believed to be one of the entry barriers in this industry. The glass industry is capital-intensive because it takes a long time to earn a profit. However, it costs only about 5 to 10 billion dollars to set up a flat glass plant for TFT-LCD, as against the setting of a TFT-LCD panel plant that requires 200 billion dollars. In spite of this fact, it was difficult for new entrants to enter this market.

Thus, the technology barrier was believed to be a more important entry barrier. Since the flat glass for TFT-LCD was very thin (0.7 mm), it was very difficult to achieve high productivity in its production. Thus, the question was how to produce the flat glass for TFT-LCD?

Table 1 global shipment shares of flat glass for TFT-LCD by company

Glass Supplier	2003	2004 Q4	2005 Q4	2007 Q3	Country
Corning	50.0%	61.0%	65.0%	56.9%	US
AGC	30.0%	17.0%	16.0%	20.6%	Japan
NEG	11.0%	15.0%	14.0%	17.8%	
NHT	9.0%	7.0%	5.0%	4.5%	
SCHOTT	-	-	-	0.2%	Germany
Total	100.0%	100.0%	100.0%	100.0%	

Source: Nikkei Sangyo Shinbun(2004), EM Data Service(2006), Display Research(2007)

This type of flat glass was manufactured by the following two methods. One was the fusion process, which was used by some glass suppliers; the other was the float process, which was used only by AGC (EM Data Service, 2006; Iida, 2006; Suzuki, 2005).

The fusion process was a major flat glass process for TFT-LCD that was invented by Corning. This process enabled flat glass manufacturing by not touching the impurities contained in the material in the melting chamber. It had sufficiently high physical reliability and did not require the polishing process. Therefore, it needed smaller investment than the float process. However, it could only narrow the size of flat glass for TFT-LCD and tended to achieve lower productivity.

Pilkington invented the float process in the UK in 1952. This process introduced many glass suppliers including the AGC and was used in construction and automotive glass. It was a horizontal drawing forming method with a large capacity furnace. In addition, it needed a polishing process for TFT-LCD, and AGC needed a larger investment to set up a plant. However, it was helpful for manufacturing wider flat glass for TFT-LCD.

Thus, this paper focuses on the float process. Further, we analyze this process from a process architecture-based approach because we believe that it is not important for the flat glass industry to analyze product architecture. As mentioned above, product architecture is defined as the relationships between function and structure. The flat glass for TFT-LCD is composed of several raw materials such as sand, soda ash, dolomite, limestone, cullet, and so on. However, these materials are melted in the melting furnace to form the specified structure (element) of the melting glass. Further, we try to analyze the relationship between function and process.

The main function of flat glass for TFT-LCD contains several subfunctions such as the coefficient of thermal expansion/shrinkage, substrate thickness variation, surface cleanness, bubble, transmittance, density, and chemical durability. The main float process for flat glass for TFT-LCD involves several subprocesses such as compounding, melting, forming, annealing, cutting, polishing, and cleaning.

A detailed float process is as follows. Raw materials are fed into the melting furnace by a batch charger at the optimum compound conditions. They are heated by the natural gas burners to approximately 1,600° in the melting furnace. The molten glass flows into the working end where the glass is allowed to cool slowly to about 1,100°. Next, the liquid glass flows into the float bath furnace and lands atop a bath of molten tin on which it floats; this is called the float method. The bath furnace is a sealed unit with a controlled atmosphere of nitrogen and hydrogen. As the temperature gradually decreases to 600°, the liquid glass forms a thin layer, called a “glass ribbon.” The thickness of the glass ribbon can range from 0.5 to 25 mm. Its natural propensity is supposed to be 6.8 mm thick. If the ribbon thickness is set at less than 6.8 mm, the speed of the annealing leer must be faster; conversely, if the thickness is greater than 6.8 mm, the speed of the annealing leer must be slower.

As the formed glass ribbon moves out of the float bath furnace, it is left to cool on the annealing leer in free air. It is necessary to bring the ribbon to an ambient temperature in order to gradually produce glass without distortion. The cooled glass ribbon exits the annealing leer and is sent to the cutting process. The glass passes the on-line inspection system to eliminate any defects. Then, it is cut into sizes that meet the customer's requirements. Normally, the cut glass is transported to the customer; however, the glass for TFT-LCD necessitates an optional process called "polishing," which minimizes the glass (substrate) thickness variation.

The relationship between function and process has a high interdependency and is complex (see Fig. 6). For example, in order to minimize the coefficient of thermal expansion and shrinkage, some parameters of the process such as compounding, forming, and annealing must be fine-tuned (EM Data Service, 2006; Iida, 2006; Suzuki, 2005). Other functions must be performed as well. Furthermore, the required equipment is manufactured by the existing suppliers themselves.

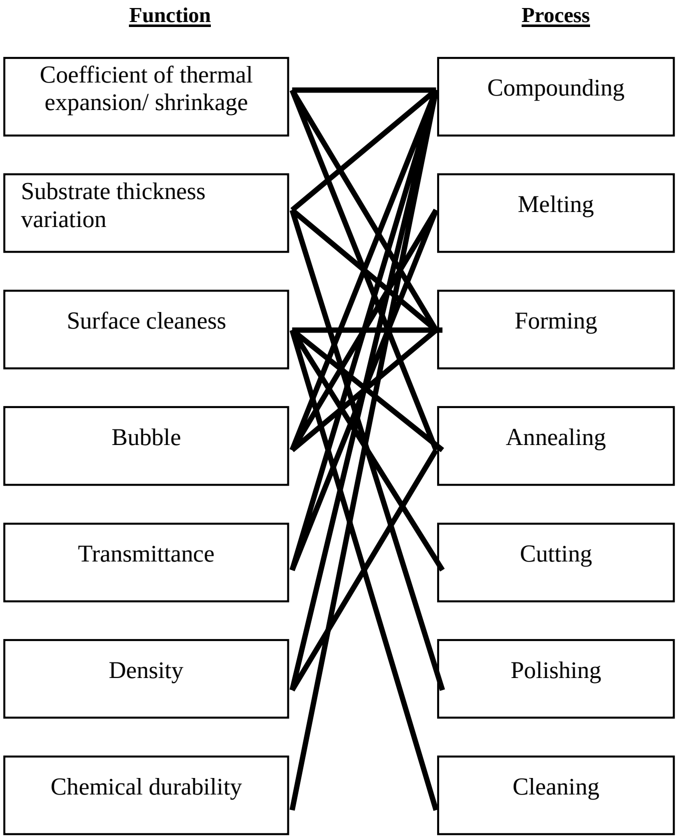


Figure 6 Process architecture of flat glass for TFT-LCD

Therefore, the process architecture of flat glass for TFT-LCD is integral (type 4) and closed, thus, making it difficult for developing countries to rapidly reproduce flat glass for TFT-LCD. As mentioned above, this industry is still holding oligopoly in the market. We believed that the source of the competitiveness of the existing suppliers has organizational capabilities, i.e., integral quality control, and coordination between the upstream and downstream processes (Tomita & Ogami, 2008).

DISCUSSION

We compare the LCD panel with flat glass in the TFT-LCD industry. If the type of process architecture of a product differs, the sustainability of global competitiveness changes in the same industry. As observed in the case of LCD panels, the relationships between function and structure are integral. When the relationships between structure and process are modular and open, developing countries can rapidly catch up with developed countries.

On the contrary, as observed in the flat glass case, if the relationships between the function and process are integral, then developing countries cannot rapidly catch up with developed countries. In other words, a product with type 4 integral process architecture may sustain higher competitiveness than a product with type 1 integral process architecture (see Fig. 2).

From our discussion, it is observed that the source of sustainable competitiveness is within a series of production process. We propose the following hypothesis:

Hypothesis: A product with a type 2, 3, or 4 integral process architecture has higher sustainable competitiveness than a product with a type 1 integral process architecture (Fig. 2).

Moreover, whether a product has a process architecture of the open or closed type is very important factor. Even if a product has a modular process architecture—in the case where the architecture is closed—the speed of technology transfer from developed countries to developing countries will be slower because the required equipment or raw materials are not traded. However, a product with a modular and closed process architecture will not have sustainable competitiveness because it is believed that it is easier to reverse engineer and reproduce the product.

As seen in the case of flat glass for TFT-LCD, the source of sustainable competitiveness is organizational capabilities, i.e., integral quality control and coordination between upstream and downstream processes (Tomita & Ogami, 2008). In fact, the basic manufacturing method of flat glass was already published after its development. However, the importance of these capabilities has yet to be established.

These discussions lead to the following implication. A product with high technology does not always have high competitiveness. From the perspective of the process architecture-based approach, even if the relationships between function and structure are integral—in the case when the relationships between structure and process are modular and open—developing countries (firms) can rapidly catch up with developed countries (firms).

However, a product with low technology may be able to achieve high competitiveness. If the relationships between function and process are integral, or the relationships between structure and process are integral, then a product with such a process architecture may be able to sustain higher competitiveness. The strategic implication is that it intertwines production know-how or coordination know-how with a product and sells the product overseas. As a result, its global competitiveness may become higher and sustainable. This strategic logic is called the “capsulization of coordination know-how” (Shintaku, et al., 2006b).

CONCLUSION

We have analyzed the global competitiveness of the LCD and flat glass in the TFT-LCD industry using the process architecture-based approach. In the TFT-LCD panel industry, although Japan had first developed and commercialized the TFT-LCD panel in the early 1990s, Korea and Taiwan rapidly caught up with the process, and surpassed Japan in the early 2000s.

As a result of our analysis, in the case where the relationships between the structure and process of the TFT-LCD panel are modular and open, Korean and Taiwanese panel manufacturers purchased a lot of equipment with solution from Japanese suppliers and smoothly set up many plants of generation five to produce the TFT-LCD panel. (Shitake, et al., 2007; 2008). This type of phenomenon has also been observed in the semiconductor industry or optical storage industry since the late 1990s (Shintaku, 2006).

From the early 1990s, the flat glass for TFT-LCD industry maintained oligopoly in the market, which comprised only four or give glass suppliers. As a result of our analysis, in the case where the relationships between function and process are integral and closed, this type of process architecture makes it difficult for developing countries to rapidly reproduce the flat glass for TFT-LCD.

Further, we compared the LCD panel with the flat glass in the TFT-LCD industry. If the type of process architecture of a product differs, the sustainability of global competitiveness changes in the same industry. We proposed the hypothesis that a product with an integral process architecture of types 2, 3, or 4 has higher sustainable competitiveness than a product with a type 1 integral process architecture (Fig. 2). As seen in the case of the flat glass for TFT-LCD, the source of sustainable competitiveness has been its organizational capabilities.

The strategic implication is that it intertwines the processes of coordination know-how and a product, which is called the “capsulization of coordination know-how” (Shintaku, et al., 2006b), and sells such a product overseas. As a result, its global competitiveness may become higher and sustainable.

We will attempt to analyze these two industries in more detail and test the abovementioned hypothesis in our future research. Furthermore, we will attempt to analyze the cause-and-effect relationship between global competitiveness and architecture in other process industries.

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