A System Dynamics Model of the TFT LCD Industry Development in Taiwan

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Abstract

The TFT LCD (Thin Film Transistor Liquid Crystal Display) industry is one the most rapid growth high-technology industry in recent decades. The development process of this industry is complex and dynamic, requires the accumulation of technology capability, capital, production capacity, and human resources. For a late coming country, the development process also involves with tense interactions of the national innovation systems and international industrial networks. Taiwan has become the second largest TFT LCD producer within two decades; the underlying structure behind the success is an interesting topic to explore. This study used system dynamics to analyze the development process of Taiwan's TFT LCD industry. A qualitative model illustrating the resource accumulation structures was derived based on the development history. Implications of this study are also discussed.

Keywords: Industry development, TFT LCD, system dynamics

1. Introduction

Flat Panel Display (FPD) has become the mainstream of display devices in present information technology and consumer electronics market, and the TFT LCD is the dominating technology in the FPD industry. The TFT LCD technology was initially developed and prototyped in the U.S., but the mass production was achieved in Japan, and then followed by the scaling-up effort from Korea and Taiwan (Murtha et al 2003, Hart 2008). Korea and Taiwan overpass the forerunners and together seized near 90 percent of the current market. The industrialization and development process of this industry is very dynamic and interesting.

On analyzing the catching up process of the East Asian latecomers, various accounts existed in the literature. Mathews matched the latecomers' penetration strategies with industry cycles (Mathews 2005). Chen identified the contribution of low cost and potential market of China to Taiwanese LCM manufacturers (Chen 2004). Spencer identified the role of firms' knowledge-sharing strategy of the innovation system in the flat panel display

industry (Spencer 2003). Lin et el. analyzed the supply and demand of the TFT LCD industry among Korea, Japan, China, and Taiwan to forecast future demand in the industry. (Lin et el. 2006). Hu and Tseng identified the role of the chemical industry in the development of TFT LCD industry (Hu and Tseng 2007). These researches identified various important factors or roles during the development process, but there still lacks a structural understanding of the long-term evolution of the industrial system.

System dynamics (Forrester 1961) has been widely used in practice and industrial research to identify underlying structures behind complex behaviors and improve policy making (Roberts 1978, Morecroft and Sterman 1994, Coyle 1996, Ford 1997, Coyle and Morecroft 1999, Jan and Hsiao 2004, Chen and Jan 2005). The pragmatic philosophical foundation makes it a useful methodology to handle complex and dynamic phenomenon in the real world (Barlas and Carpenter 1990). Although a system dynamics model may include various unstructured data from mental or verbal sources, the validity of a system dynamics model can still be verified in a systematic way (Forrester and Senge 1980). This study used the system dynamics approach to analyze the development process of Taiwan's TFT LCD industry. Major loops for the accumulation of developmental resources were identified, and a qualitative causal loop diagram for the industrial system was derived. The implications of this research were also discussed.

2. Important characteristics of the TFT LCD industry

The TFT LCD industry is multi-technology, capital intensive, and has close relations to large portions of information technology (IT) and consumer electronics products. Major important characteristics of the industry are briefly described as follows:

- Capital and technological intensive

The cost to build a TFT LCD production plant increased from US$ one billion for fifth generation to US$ 3 billion for eighth generation. The investment is bigger than a 300mm wafer plant. The manufacturing technology advanced in an extremely rapid speed. It only took 15 years to arrive the eighth generation technology from the first generation one.

To produce a TFT LCD panel involves wide spectrum of technologies which can be divided into array, cell, and module assembly part. The array part is very similar to the processes of semiconductor wafer fabrication, therefore the two industries can share and in some way competing for the same human resources and technology in this part.

- With many competing technologies

TFT LCD panels can do nothing but for display purposes. The light weight and low energy consumption feature make TFT LCD the best display technology for portable devices. However, as the application of TFT LCD expands, there is a wide variety of display technologies competing with TFT LCD. In the small-scale display applications such as cell phone, PDA, etc., TFT LCD is competing with OLED (organic light emitting diodes), and TN/STN LCD. In the large-scale non-portable applications like computer monitor and television, plasma, TFT LCD has to compete with field emitting display, backlight projector, traditional CRT, and possibly some emerging technologies like carbon nano tube or flexible display. Since many competing technologies already existed for the same display purpose, cost per unit display area of the technology becomes a critical competing factor.

- High material cost

The cost structures of common TFT LCD products are illustrated in Fig. 1. As we can see that material costs is as high as 70% to 80% is most applications. Currently most of the technologies needed by basic materials such as liquid crystal, glass subtract, and manufacturing equipment for TFT LCD array processes are controlled by Japanese and U.S. companies.

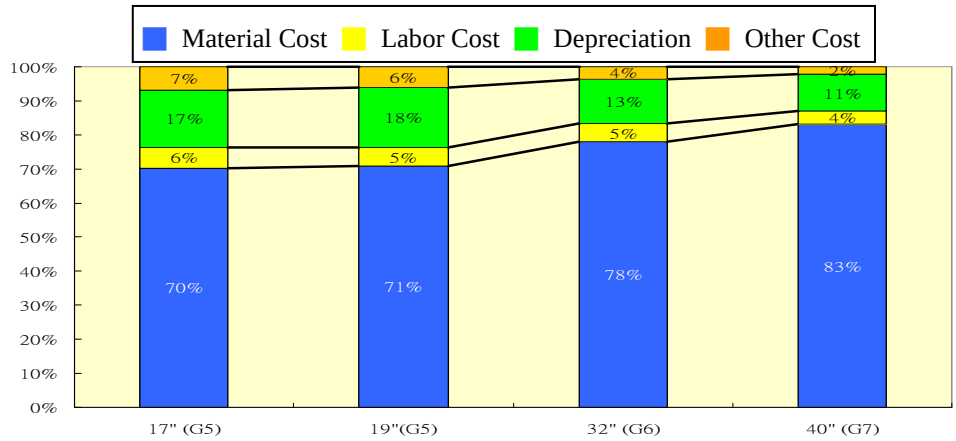

Fig. 1. Cost structure of TFT LCD panels (Source: Displaysearch, 2006/05)

- Application and generation specifications determines the cutting efficiency

The major application product of TFT LCD has gone through several mainstream product shifts. It began at the panels for laptop computers, then shifted to desktop monitors in replacement with CRT monitors, and finally came to the replacement of CRT TV set.

The change in the size of display area of the end product would result in different cutting efficiencies for different sized TFT panels. Therefore every TFT panel manufacturer will design a different subtract size of TFT LCD production line based on their targeted application product. For every new application specification, there would be a new subtract layout for best cutting efficiency, and this is the major force pushing the manufacturers into a generation competition. For example, the sixth generation subtract can be optimally cut into 8 pieces of 32-inche panel or 6 pieces of 37-inche panel. But the fifth generation subtract can be cut into 3, and 2 pieces accordingly and with higher portions of unused slack area.

Table 1. Major applications of large-scale TFT LCD

Product	Display size	Critical features	Efficient generations
NB	10-15 inches	Light weight, low power consumption	G5
Monitor	15-26 inches	light weight, brightness, contrast, response time	G6

TV	26-47 inches	Color saturation, view angle, response time	G7

3. The development history of Taiwan's TFT LCD industry

Taiwan acquired its first LCD technology as early as in the 70s. The first Twisted Nematic (TN) LCD technology was transferred from a U.S. company Hughes for digital watch (Wang 2003). But the progress toward mass production of large scale TFT LCD was not seen until 1996 that CPT transferred the technology from Japanese firm Hitachi. Before the 1997 Asian financial crises, Japan was the leader in the TFT LCD industry. After that, the generation competition between Korea and Taiwan become the main theme of the industry development. In 2007, Taiwan seized more than 42% of the large scale TFT LCD panel market and together with Korea controlled 88% of total market share. The development process of Taiwan's TFT LCD industry could be divided into the 1976-1991 TN/STN LCD stage, the 1992-1996 small scale TFT LCD stage, and 1997-2007 large scale TFT LCD stage. The development process within each stage was explained in the following sections.

3.1 The preparation stage from 1976 to 1991 (TN/STN LCD)

Taiwan adopted an Export Processing Zone (EPZ) policy in 1966. Many foreign investors were attracted by the cheap labors and low tax rates. The EPZ policy also attracted labor-intensive section of TN and STN (Super Twisted Nematic) LCD process moved in. Based on the technology transferred from Hughes, a local company ChinYeh Electronics established Taiwan's first TN LCD production line in 1976 for digital watch panels. There were several followers entered this industry including Chung Shang, Mesostate LCD Industries, Shih Tai Electronics, Jay Hwa, and Picvue (Wang 2003). Based on locally developed technology, these followers dedicated themselves to TN LCD packaging, testing, and process management; but most of them ran out of business afterwards. In 1992, the Picvue transferred STN technology from a U.S. company Polytronix (Anonymous 1999) and thus became the first local company with STN technology.

Three Japanese companies Hitachi, Epson, and Sharp invested TN/STN LCD facility in Taiwan in this stage. They also recruited and trained local engineers to work on cell process, module testing, assembly, and product design. For example, the Hitachi-KaoHsiung began producing black-and-white (B/W) STN LCM in 1983, and in 1987 the process expanded to a complete STN LCD production line. Epson acquired a local company Taiwan Leiter LCD and established Taiwan Epson for TN LCD production in 1985 (Wang 2003). The process expanded to B/W STN in 1992, and to product design in 1995. Sharp established Sharp-Taiwan in 1986 and began producing TFT LCM for laptop computers in 1994. These Japanese companies' operations incubated the initial local human resources. Some of the local branches are merged by Taiwanese firms as later stage. For example, Epson closed its LCD department of Epson-Taiwan in late 2003 and sold to a local LCD company VBest Electronics in 2004.

3.2 The small-scale TFT LCD stage from 1992 to 1996

The 90s is the golden expansion age for Taiwan's semiconductor industry. But for the LCD sector, the industry was still unable to obtain the technology to mass produce large-scale TFT panels. Taiwan already had the technology of small-scale TN/STN LCD manufacturing at this time, and there were some attempts to establish TFT technology undertaking both in the private and public sector.

The growing demand on the TFT panels attracted some private investors to establish manufacturing capability. One of the major Taiwanese wafer foundry, UMC, recruited some U.S. returnees and established the UNIPAC Optoelectronics in 1990, and transferred LCD technology from an U.S. company OIS. In 1992, UMC remodeled some 4-inche wafer fabrication facility into a TFT LCD production line, which was the first TFT LCD line in Taiwan.

The Taiwanese government went in another way and initiated some R&D projects of TFT manufacturing technology through a public research institute, ITRI. Another local company, the YFY Group, licensed the technology and established the Prime View International (PVI) in 1992. After ITRI successfully test ran a 6.4-inche TFT production line in 1994, PVI licensed the developed technology and jointly established Taiwan's first second generation TFT LCD line with ITRI in 1995.

Taiwan attempted to acquire the necessary capability for large-scale TFT mass production through returnees or local research institute. Although some initial technology was established in the private sector, the lacking of mass production skill resulted in the low yields that made these efforts economically infeasible at this time. These attempts on the other hand speeded up the accumulation of technology absorbability, which turned out to be an important factor for next stage's growth. Until the China Picture Tubes (CPT) transferred technology from Toshiba in 1996, and successfully commercialized its 11.3-inche STN LCD panel for notebook PC, Taiwan was able to produce large-scale panels.

3.3 The expansion stage from 1997-2007 (Large scale TFT LCD)

Since the Korean entered the TFT LCD market in 1996, the pressure of price competition forced Japanese firms to consider alliances with Taiwan. The capital and experiences in semiconductor manufacturing made Taiwan the best complementary partner to Japan. Moreover, Taiwan had become the biggest manufacturer of laptop computer in the world, combining a stable panel supply into the supply chain would greatly enhance the competence of that industry. Japanese companies' attitudes toward Taiwan's request for technology transfer thus adjusted. In 1997, the China Picture Tube (CPT) received a technology transfer from Mitsubishi, which opened the window for Taiwan to enter the large-scale TFT LCD technology.

After CPT's break though, several Taiwanese companies include Unipac, Acer Display[1], HannStar, Quanta Display[2], Innolux transferred TFT mass production technology from Japanese companies like Toshiba, Matsushita, IBM Japan, and Sharp. In this stage, more than seven Taiwanese companies entered this industry; most of them licensed their initial

[1] Unipac and Acer Display merged into AUO in September 2001
[2] Quanta Display was merged by AUO in October 2006

technology from Japan. In 2007, Taiwan's TFT LCD industry has become the biggest player in the world, with biggest TFT LCD manufacturing capacity and shipped most units of TFT panels. There's another company Toppoly[3] dedicated in low temperature poly silicon (LPTS) TFT products.

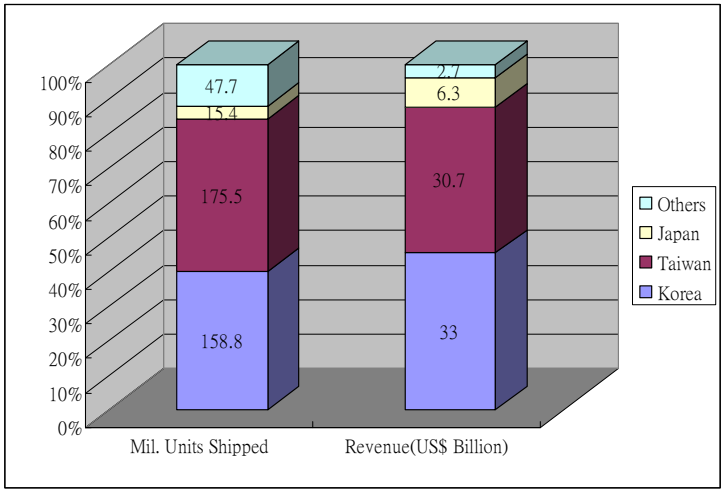

Fig. 2. The 2007 ranking of major large-scale (10''+) TFT LCD manufacturing countries (Source: DisplaySearch Quarterly Large Size TFT LCD Shipment Report 2008/01)

4. The resource accumulation structure of Taiwan's TFT LCD Industry

The manufacturing processes of TFT LCD could be classified into TFT array (Array), liquid crystal cell (LC Cell), and liquid crystal module (LCM) process. The array process is similar to semiconductor fabrication process, except that the TFT panel is fabricated on glasses instead of silicon wafers. Due to the proliferated semiconductor industry, Taiwan has already accumulated a lot of experiences and human resources that can be used on the TFT LCD sector.

The LC Cell process is the weakest section of Taiwan, and the technology to mass production on large size LC cells had long been the target to transfer from Japan. Because the process in this section is the most critical part for the yield of the production line, it was the major barrier for Taiwan to commercially produce large scale TFT LCD panels.

The final process is the LC module assembly and testing. This process is less technical and more labor intensive. Taiwan has established superior experiences from previous TN/STN LCM assembly. The yield in this process is higher than 99% in most Taiwanese LCM firms.

Taiwan had different ways to accumulate its competence in each of the three processes in different development stage. There are three important reinforcing structures in Taiwan's TFT LCD industry, including the spillover of pre-accumulated resources, the role of Japanese technology transfers, and the effect of industry clustering. Each of the structures are explained in the following sections.

[3] Toppoly and Philips' Mobile Display System merged into TPO in June 2006

4.1 The spillover from pre-accumulated resources

There was important development resources accumulated in Taiwan before the TFT LCD industry began to prosper. The human resources for Taiwan's TFT LCD industry come from three major sources. The first source is from the private sector. The semiconductor industry and the TN/STN LCD industry incubated a lot of experiences and human resources in the array and LCM process. The second source is the diffusion of people from public research institutes, especially from ITRI. The third source is the young talents from local universities. Due to the long-term accumulation, the supply of human resources for the rapid growth of this industry did not have too much difficulty. As the TFT LCD industry demonstrated higher profitability, the industry became more attractive and thus attracted more human resources from the pre-accumulated talent pool.

Besides the flow people, there's also a flow of technology during the development process. The process of spillover from the various source are discussed in following sections.

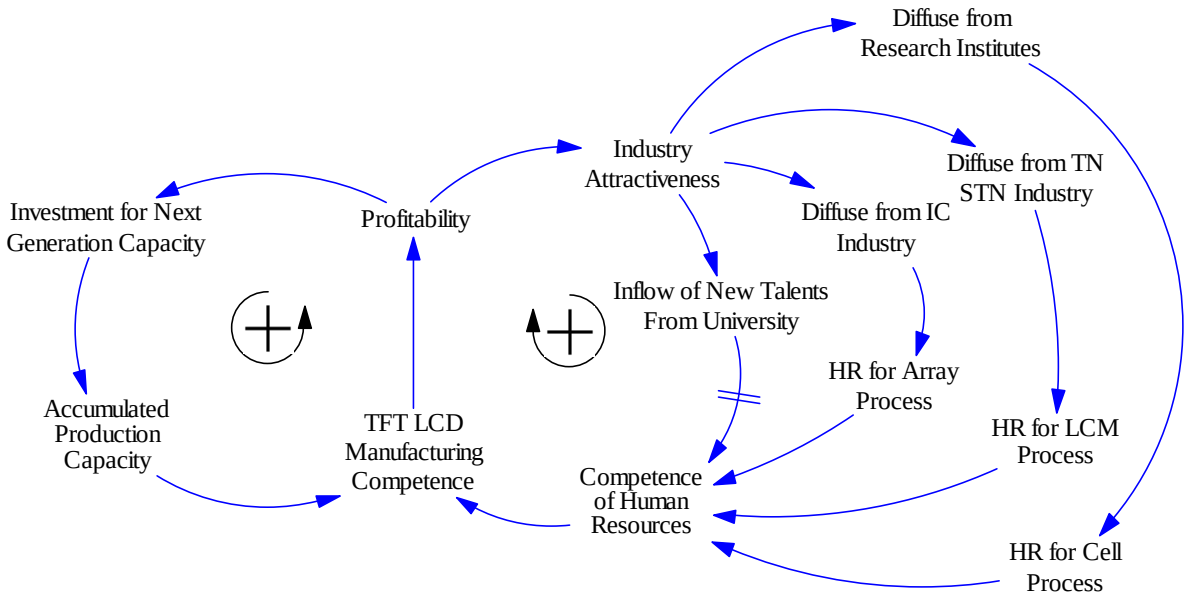

Fig. 3. HR flows for the TFT LCD industry

4.1.1 The spillover from TN/STN LCD industry

Although Taiwan was unable to mass produce large-scale TFT LCD panel until 1997, the development of TN/STN LCD had begun as early as in the 70s. In the 80s, many Japanese firms moved their old-fashioned TN/STN manufacturing process to Taiwan. These Japanese invested companies incubated the initial local human resources of TN/STN LCD cell and module assembly processes in Taiwan. It is argued that the established foundation is essential to Taiwan's technology absorbability in later stage when Taiwan transfers TFT LCD from Japan.

Because Taiwan has a constraint that only locally owned company (more than 50%) are allowed to go public in Taiwan's stock market, these foreign direct invested companies could not use the same employ-stock-sharing compensation system which prevailed in Taiwan's high-tech industry. When the rush of TFT LCD investment began in Taiwan in 1997, those human resources accumulated in Japanese affiliated panel manufacturers became the recruiting target and flew to Taiwanese TFT LCD companies.

4.1.2 **The spillover from the semiconductor industry**

Taiwan's proliferated semiconductor industry has important contributions to the technology absorbability in the TFT LCD sector. Because the array part of TFT LCD process has roughly 70% very similar to that of the semiconductor fabrication, the TFT LCD companies can leverage the equipment and human resources from the semiconductor sector. Similarly, it would be easier for an existing semiconductor company to enter the LCD industry. For example, both the UNIPAC (by UMC) and the HannStar (by Windbond) were founded by semiconductor companies. On one hand the child company can leverage the technology, equipment, and human resources from its parent company, but on the other hand the TFT LCD industry as a whole would have resource competition with the semiconductor industry (Chen and Chen 2004).

Two significant flows of human resources from the semiconductor sector to the TFT LCD sector has been observed in Taiwan in past years. The first movement appeared in 1999 when Taiwan just entered the large-scale TFT LCD manufacturing. Due to the overlapping clean facility and manufacturing processes in TFT array section, these new TFT LCD companies attracted many employees from local semiconductor fads with employee stock sharing compensation systems. The second human resource flow appeared during the downturn of semiconductor industry in 2001. Many of the R&D engineers in the semiconductor industry switched to panel manufacturers to work on next generation technologies like LPTS.

4.1.3 **The spillover from the research institute**

Taiwan's public research institute has long been an essential role in the high-tech industry. Because Taiwan's industry is mainly composed with small and middle sized enterprises (SMEs), the government used a policy to support those SMEs through public research institutes. The Industrial Technology Research Institute (ITRI) is the largest and probably the most important one, especially for the semiconductor industry and the TFT LCD industry. ITRI was founded in 1973. Since then it has supported many industries to upgrade their technology level through foreign or self-developed technologies. ITRI has significant contributions to the development of semiconductor, information technology, TFT LCD, bicycle, and machine tooling industry (Jan and Chen 2006).

Based on the government research projects, ITRI recruited and trained a lot of young and talented engineers to work on pre-competition technologies which may be needed by Taiwan's industry. Because every young male Taiwanese has to serve a two-year military service, the Taiwanese government passed a policy that young man can waive their military duty with a four-year working contract of some selected research institutes. It is quite common to see many young male engineers worked in ITRI for four years, and left for the

industry to develop their career.

Many of the top management of Taiwan's high-tech companies were ITRI alumni. In the TFT LCD field, ITRI began its research on TFT LCD technology since the 1989 "Technology Development Project on Flat Panel Display." Many of the project members acquired important positions in major TFT LCD companies. For example, Dr. Benson Wu joint ITRI in 1987. He was one of the first TFT LCD researchers of ITRI after he received his PhD of Electronics Engineering in NCKU. He left ITRI and entered Prime View International (PVI) in 1993, and finally switched to CMO as VP of R&D. Dr. Da-Gang Wu entered ITRI in 1987 after he received PhD of Chemical Engineering in the U.S., also left and joint PVI in 1993, and finally became a vice president of the HannStar in 2000. Another example is Dr. Yi-Wei Wu. He left Zerox and joint ITRI as the Deputy General Director of ERSO. He led ITRI's LPTS TFT research project, and ended up into a transfer of technology and researchers together into Toppoly Optoelectronics Corp. (TPO). ITRI had a big contribution to the diffusion of technology and human resources to the development of the industry.

In the technology aspect, although ITRI's contribution to the TFT LCD industry was not as huge as that in the semiconductor industry, its research still had the impacts. ITRI began its TFT LCD research since the government sponsored "Project of Flat Panel Display Development" in 1989, which aimed to develop small-scale TFT LCD panel. Technologies for 3 to 6 inches TFT panel were developed in 1990, and a 10.4-inche TFT LCD production line for trial run was established in 1994. A local company PVI transferred the technology and used the facility in ITRI for small batches of production. ITRI also helped PVI to build a first mass production line in Taiwan. Unfortunately ITRI did not have enough resource to establish a complete set of TFT LCD technology to reproduce the spin-off model as in the semiconductor UMC and TSMC case. Members participated in the research and the PVI project produced the initial local TFT LCD knowledge that became an important foundation for the industry in later stages. As described earlier in this section, many of the project members became top management executives of leading TFT LCD companies in Taiwan.

4.2 The role of Japanese technology transfers

Japan is the forerunner in mass production of large scale TFT LCD panels. The leading position was unthreatened until of Korean companies entered the industry in 1995. The Korean firms established their technology through formal technology transfer from U.S. companies and informal advisory service of senior Japanese technicians, plus their own heavy investment on research and development. During the 1996 Asian financial crises, Japanese companies were threatened by Korean firms' cost competition, while on the other hand running short of capital to invest on next-generation technology. The situation gave Taiwan an opportunity to acquire technology from Japan, especially for the technologies in the cell process and the knowledge to integrate the whole required processes.

The CPT transferred the third generation TFT LCD technology from ADI-Mitsubishi in 1997（Including plant design, production line, and production processes）. It is the first case that a Taiwanese firm successfully transferred TFT LCD mass production technology from Japan. After that, a sequence of technology transfer from Japanese firms to Taiwan occurred. During 1998 to 2003, seven Taiwanese TFT LCD companies were founded and invested in new generation plants. Except the CMO who acquired its technology from local sources, almost all companies started from Japanese technology transfers, as shown in the table below. The technology transfer from Japan shortened Taiwan's learning curve, and the ambitious

expansion in production capacity resulted in a faster industry clustering effect, which will be discussed in next section.

Table 2. Technology sources of major Taiwanese TFT LCD manufacturers

Company	Investor	Technology Source	Relationships
CPT	Tatung	Mitsubishi ADI	Technology transfer Priority Capacity Option
AUO*	Acer, UMC	Panasonic IBM Japan	Technology transfer
CMO	Chi Mei	Fujitsu	Strategic alliance, 1998 Priority Capacity Option
		IBM Japan	Acquire TFT LCD department, 2001 Joint venture on IDTech
HannStar Display	Walsin Lihwa Windbond	Toshiba	Technology transfers, 1998 and 2001 Priority Capacity Option
		Hitachi	Technology transfer on AS-IPS, 2002
		Sharp	Technology transfer on OA LCD, 2003
Quanta Display Inc.	Quanta Computer	Sharp	Technology transfer, 1999 Priority Capacity Option
TPO	Kinpo Group Uni-President Group Teco	ITRI	Technology transfer on LTPS 1999
		Sanyo	Technology transfer on LTPS 2003

Source: Annual reports from various companies, 2004

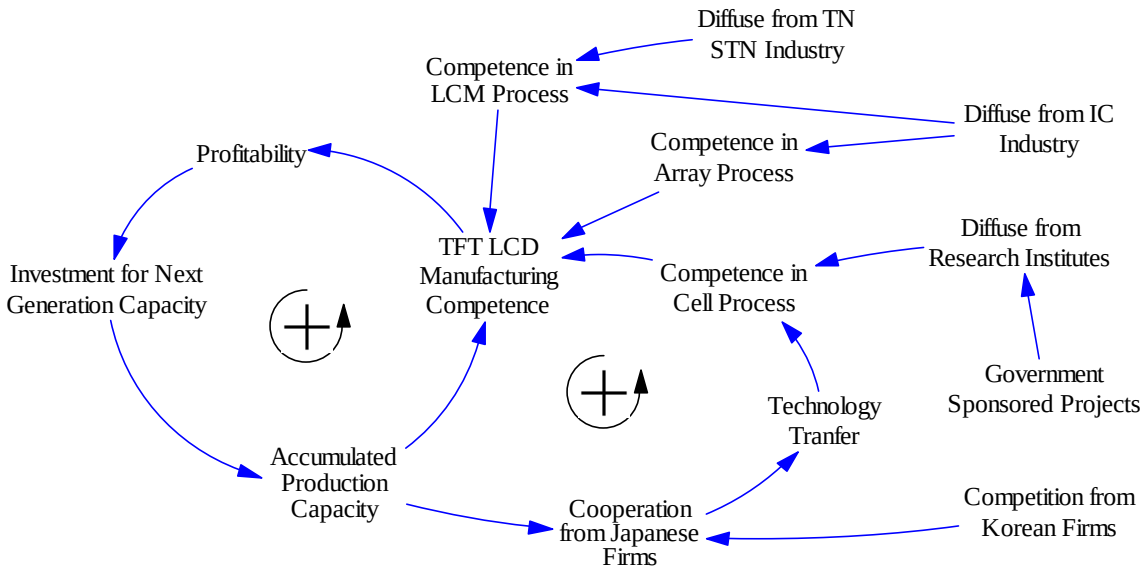

Fig. 4. Technology accumulation of the TFT LCD industry

4.3 The reinforcing loop of industry cluster

Taiwan's TFT LCD industry was supported by other industries in three aspects. The first is the diffusion of technology and human resource from Taiwan's semiconductor industry and TN/STN LCD industry, as described in previous chapter. The second aspect is the nearby demand from Taiwan's highly-proliferated IT manufacturing industry. The third aspect is the proliferation of upstream supporting industry for TFT LCD manufacturing after Taiwan achieved an economics of scale in TFT LCD production.

The advancement of TFT LCD technology was accompanied by the new generations of production capacity. Since Sharp's mass production of first generation TFT LCD line in 1991, the glass substrate size increased from 320mm x 400mm to the 2160mm x 2460mm specification of the eighth generation. It is risky for a newcomer trying to enter such a rapid changing, highly capital and technological intensive industry. In Taiwan's case, Taiwan is the biggest laptop computer manufacturer, produced roughly 90% of the notebook PC in the world. Taiwan is also the biggest producer of flat panel monitor with roughly 70% market share. The huge demand of TFT LCD panels but without local panel manufacturing support had long been an issue for Taiwanese IT producers. Because the LCD panel occupied the most significant portion in a laptop's cost structure (about 30%), major laptop manufacturers like Acer (founded Acer Display), Quanta Computer (founded Quanta Display), and Compal (founded TPO) became the forerunners in investment of TFT LCD industry.

Japan is the biggest upstream supplier of materials and equipments for TFT LCD manufacturing. During the expansion stage of Taiwan's TFT LCD industry, most of the needed technology, equipment, and key materials have to import from Japan. As Taiwan's TFT LCD manufacturers achieved a economics of scale, the accumulated capital and rising bargaining power enabled Taiwanese firms either to self develop the technology (such as color filter, polarizer, backlight module) or ask the suppliers to establish local supporting facility, which subsequently increased the efficiency and flexibility of the whole supply chain. Currently there are three major TFT LCD industry clusters in Taiwan. One is clustered around AUO and CPT near Hsinchu-Lungtam Science Park, one is clustered around AUO in Taichung Science Park, and the other is clustered around CMO and HannStar in Tainan Science Park. Both clusters have attracted foreign companies like Corning and local companies like Optimax and many others to form a complete TFT LCD supply chain.

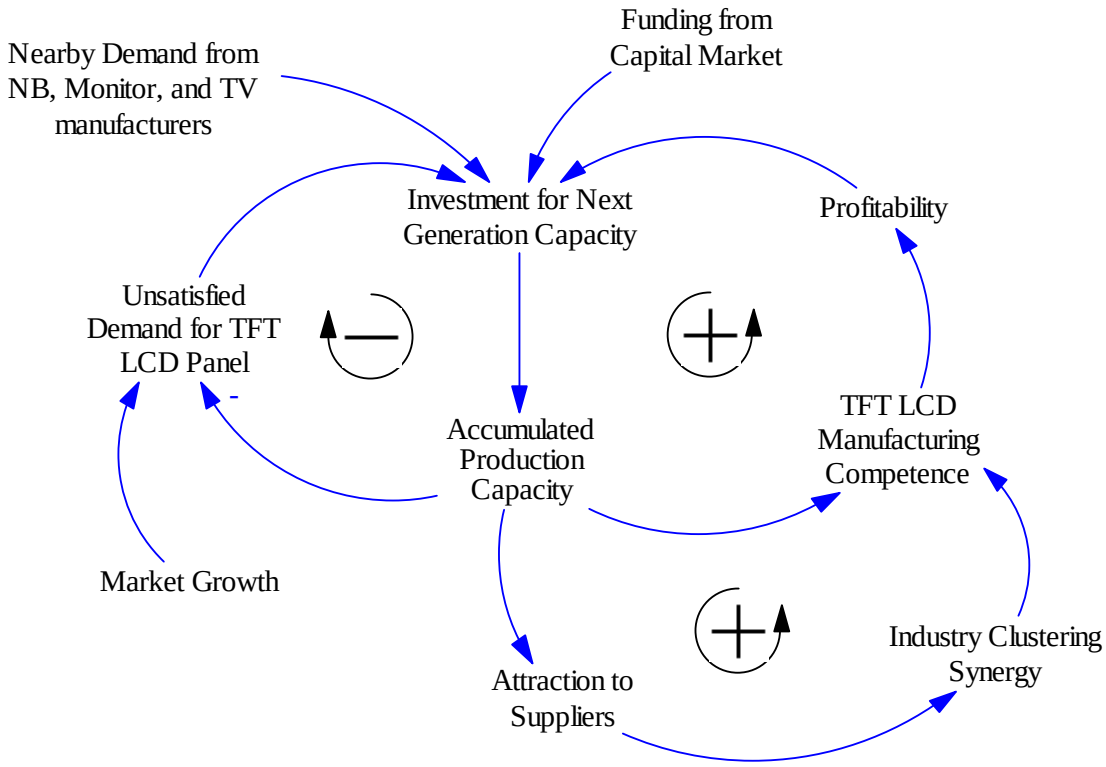

Fig. 5. The industry cluster loop

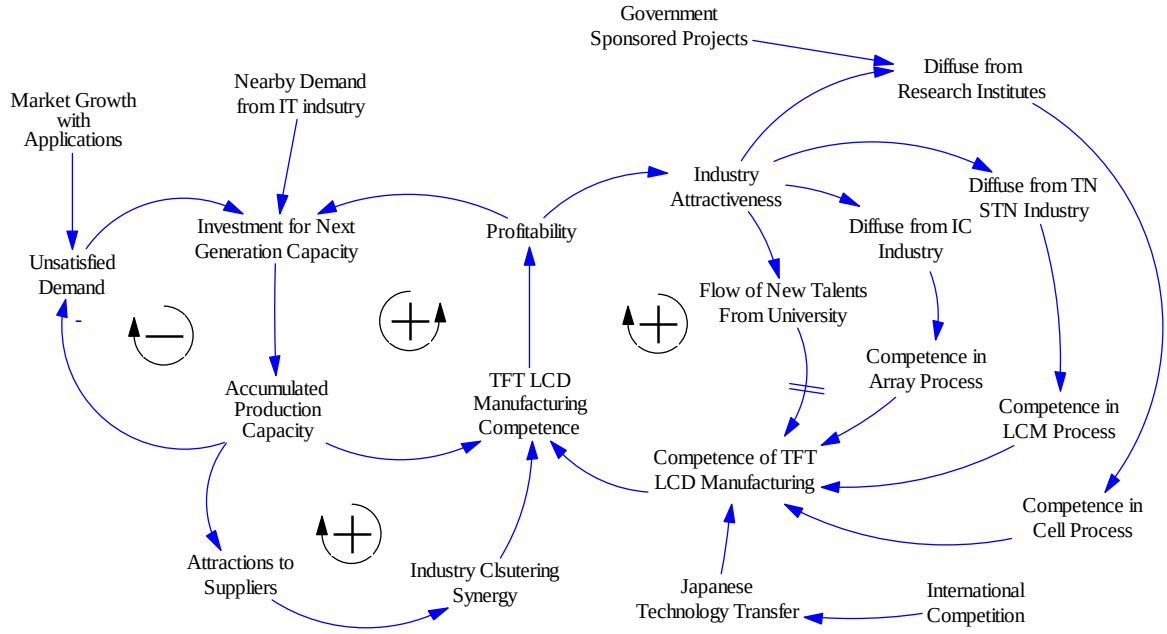

Fig. 6. The integrated model of Taiwan's TFT LCD industry

5. Conclusion and discussion

The development of Taiwan's TFT LCD industry is a dynamic and complex process. This study examined the development history of Taiwan's TFT LCD industry, identified major resource accumulation structures, and derived an integrated model in terms of causal-loop diagrams. According to the derived model, several findings from this research can be addressed and discussed as below:

5.1 The development process of Taiwan's TFT LCD industry

The development of Taiwan's TFT LCD industry can be classified into the pre-TFT LCD stage, the small-scale stage, and the large-scale stage. In the pre-TFT LCD stage, local and foreign invested TN/STN companies are the major roles in the development process. Although most of the activities they engaged were low-end and more labor intensive processes, those companies established the initial knowledge of LCD manufacturing in Taiwan. In the small-scale stage, more local actors attempted to explore the possibility to produce TFT LCD panels. There were some local computer companies, semiconductor companies, and research institute engaged in startups or research projects aiming to establish mass production facilities of TFT LCD. These attempts end up as extending the basis and resources accumulated in the first stage. The third stage was evoked by the technology transfer from Japan. Taiwan established an effective resource attraction mechanism to absorb the pre-accumulated resources in the environment. In this golden decade, Taiwan successfully established vast amount of latest generation capacity and competitive manufacturing management.

Taking the development process as a whole, we can see that the development began at accumulating resources in the TN/STN industry, semiconductor industry, and the research institute at first, and then started to establish connection among the accumulated sources in the second stage. These connections finally triggered by the inflow of Japanese technology and made the resource attraction loop begin to operate. The resource attraction loop brought up the accumulation of manufacturing competence and the accumulation of production capacity, thus to the reinforcing industry clustering loop.

After years of expansion, this industry is currently in a downturn that the crisis of limit-to-growth became an issue of concern. Either the market limit or resource limit could be an issue to the future growth of this industry. At the market demand side, the demand has been dramatically expanded from the notebook, LCD monitor to LCD TV. But the source of demand for future growth is still unclear. The industry is still looking for a new large scale demand after the TFT TV.

At the resource side, the development of TFT LCD had taken advantages from the pre-accumulated quality engineers and diffusion of knowhow from the Semiconductor industry. When the Taiwan TFT LCD industry gradually expanded to such a large scale, the relationship of two industries might become a co-opetition relationship (Nalebuff and Brandenburger 1996). Each of the two could enhance the demand for each other's market, while on the other hand competing for common resources such as local talents and capital. The development structure of the TFT LCD industry for the future should be somewhat different than the old days.

5.2 Surviving from a demand-pull market to a supply-push market

The initial environment for the burgeoning of Taiwanese TFT LCD industry was in a demand-pull situation, where nearby IT producers were eagerly waiting for controllable outputs from the TFT LCD sector. The market is more like an import-replacement market. Thus we can see that most of the pioneering TFT LCD companies are founded either by local computer manufacturers or semiconductor companies.

As the scale of manufacturing capacity expanded, the fierce cut-throat competition between Korea and Taiwan made the cost of TFT LCD panels dropped rapidly. The cost down competition eventually made TFT LCD become a replacing technology to traditional CRT display. The subsequent penetration into desktop monitors and television market inevitably attracted Korea and Taiwan entering a generation competition, which further drive the cost downward and reinforced the penetration into existing CRT market.

Taiwan had its unique structure to accumulate most of the required developmental resources for TFT LCD and thus being capable to catch the opportunity when Japan finally agreed to transfer the technology. The structure supported the development in the early stages may not be as supportive in later stages. For example, the diffusions from the semiconductor industry may be reversed if the TFT LCD industry enters a recession cycle. When Korea and Taiwan jointly cutting each other and made the TFT LCD market a bloody ocean, the lowered profitability might disappoint the talented engineers of the TFT LCD industry and then decide to switch to the semiconductor or even the prospective photovoltaic industry. As the scale of TFT LCD industry becomes so huge, besides the competition from Korean competitors, the TFT LCD industry may have to compete with Taiwan's semiconductor industry for local resources.

Since the seeking of next killer application after TFT LCD TV is still unclear, Taiwanese TFT LCD companies may need to find strategies to survive from the limits-to-growth crisis before next large scale application emerges. Some ideas like panel-foundry model that panel manufacturer could extend its service like a wafer foundry, or the utilization of cutting residues, could be possible directions for further study.

5.3 Implications to other newcomers

Taiwan had its unique structure and timing when developing the TFT LCD industry. In the current market situations, it would be more difficult for a new player trying to enter this industry. On the other hand, the 1997 Asian financial crisis gave Taiwan an opportunity to transfer technology from Japan, the 2008 financial crisis happened in the U.S. may provide some chance for a newcomer to jump in.

Taiwan entered the industry at time that the mainstream application of TFT LCD panels is on laptop computers. Taiwan was in a situation that the demand and technology were partially in control. The application shifted from portable devices to desktop monitor, and then the TV set in the consumer electronics market in the next ten years. The market evolved in a trajectory of scaling up and costing down, which was the trajectory Taiwan has been good at. Taiwan successfully expanded its scale and built up the competence in the ten years. For a newcomer tempting to enter the industry in current situation, the initial investment is huge, and the market structure is in a cut-throat oligopoly competition that not much room is left for a new player. Until the next generation killer application appears, there seems not much visibility to find a new niche market with high volume and high margin. And even if

the next killer application appears, it may be in another display technology like flexible display. TFT LCD could be the one to be replaced. It seems too risky for a new player to go through the development process over again.

The 2008 financial crisis is still underway. Taiwan took advantage from the last financial crisis and gained access to the needed technology. Would the current crisis provide an opportunity for a new player to jump in? We've seen mergers among the existing players, and buying an existing company could be a possible way to enter. This issue should worth further inquiry and is strongly encouraged.

This study used system dynamics to explore the resource accumulation structure behind the development process of Taiwan's TFT LCD industry. Although without a quantitative modeling and simulation, the identified structure could have its impact to clarify the mindset toward the complex industry development process. The identified qualitative model could also be a base for further quantification and subsequent simulations.

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