The Crystal Cycle and Co-evolution of Demand and Technology: a “History-friendly” Model of the TFT-LCD Industry

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Abstract
The paper aims at building a history-friendly model which replicates the history of the Thin Film Transistor-Liquid Crystal Display (TFT-LCD) industry focusing the crystal cycle and co-evolution of demand, technology and industrial structure. The most interesting characteristic of the TFT-LCD industry is the cyclical behavior of the price and investments. The model is distinctive compared to existing system dynamics models addressing industrial cycles in two points: 1) endogenous demand, technological change and entries are incorporated 2) industrial cycle affects evolution of demand and technology as well as are caused by the change of demand and technology, that is, we consider industrial cycle as a medium of co-evolution of demand and technology. The simulation results show that it can successfully replicate the crystal cycle, and investment-production delay, price delay and endogenous change of demand are factors of the crystal cycle. Moreover, we can see positive feedback between demand expansion and technological advance through medium of the cycle

Key Words:
Crystal cycle, history-friendly model, TFT-LCD
The paper aims at building a history-friendly model which replicates the history of the thin film transistor-liquid crystal display (TFT-LCD) industry focusing on the crystal cycle and co-evolution of demand, technology and industrial structure.

A TFT-LCD is most widely used among flat panel displays. Products that use TFT-LCD as their display device include lap-top computers, computer monitors and TVs. The history of the TFT-LCD industry traces back to 1991 when Sharp, NEC, IBM, and Toshiba began mass production. In spite of short history, the TFT-LCD industry experienced extremely rapid market growth (yearly 40% until early 2000s), very dynamic change of demand, technology and industrial structure, so we can find various interesting aspects of industrial evolution in it: cyclical behavior of the price and investments, co-evolution of demand, technology and industrial structure, anti-cyclical entries, etc.

The most interesting characteristic of the TFT-LCD industry is the cyclical behavior of the price and investments. The cyclical behavior of the TFT-LCD industry is called the crystal cycle in the industry. Industrial cycles are observed in many industries: DRAM, steel, ship building, paper, and so on, but they have been not a main topic of economics. Meanwhile, there have been some attempts to investigate it in business study (Meadow, 1970; Sterman, 2000; Brends and Romme, 2001; Kim, 2005; Mathews, 2005; Noam, 2006). While most of them are verbal explanations, there are some system dynamics models as well. Our aim is to replicate industrial cycle through an agent-based model, but the model is distinctive compared to existing system dynamics models in two points: 1) endogenous demand, technological change and entries are incorporated 2) industrial cycle affects evolution of demand and technology as well as are caused by the change of demand and technology, that is, we consider industrial cycle as an medium of co-evolution of demand and technology.

Among many strategies of agent-based modeling, we adopt history-friendly modeling as methodology. For introduction of history-friendly modeling and its methodological characteristics, refer to Malerba et al. (1998) and Yoon and Lee (2009).

Following the strategy of history-friendly models, the rest of the paper is structured as follows. In the second section, we provide theoretical discussion of cyclical behavior of an industry. The third section provides brief history of the TFT-LCD industry focusing on the crystal cycle. The model is described in section 4. History-replicating simulation results and history-divergent simulation results are shown in section 5 and 6. Finally, we conclude in section 7.

2. Theoretical background

Although cyclicality of whole economy has been the most important subject of economic analysis, cyclicality of an industry has been overlooked. However, there are several (mostly verbal) explanations of cyclical behavior of industries. Main factors discussed in existing literatures are listed.
Most literatures attribute cyclicality to exogenous fluctuation of demand of which causes include change of consumer preference, invention of new usage and business cycle of whole economy. Among these, business cycle is the simplest way to explain industrial cycle and actually important in many industries; but empirical evidence indicate that business cycle is not the only factor of industrial cycles in terms of timing (Noam, 2006). Unexpected shocks due to the change of consumer preference or related technology can cause cyclicality irrespective of whether we assume rationality or bounded rationality of agents.

Change of raw material price

Unexpected change of raw material price can be a factor of industrial cycle in the same way as demand fluctuation

Technological shock

As the real business cycle theory, unexpected technological shock results in cyclicality.

Myopic investment and production delays

The classic example is the cobweb model. Many literatures (Meadow, 1970; Sterman, 2000; Berends and Romme, 2001; Kim, 2005; Mathews, 2005; Noam, 2006) pointed out that myopic investment and production delays is an important factor of cyclicality in capital-intensive industries such as paper, chemistry, DRAM, TFT-LCD and so on. In the agriculture industry which the cobweb model describes, production delay takes place due to long period between seeding and harvest. When it comes to capital intensive industries, it takes long time to complete facility construction, implying delay between investment decision and actual production (we will call this investment-production delay hereafter). Noam (2006) argues that there are other delays such as perceptual or administrative delays, which means delays between market signal and decision. Anyway, various delays contribute to cyclicality along with myopic investment decision.

While it is hard to find related literatures except some verbal explanations in economics, industrial cycle has been one of the oldest topic in system dynamics literatures in business study (Meadows, 1970; Sterman, 2000; Berends and Romme, 2001; Kim, 2005). System dynamics literatures mostly focused on various exogenous delays. Therefore, although system dynamics approach is based on systemic approach and circular reasoning, actual casual relations is one-directional in that delays causes the cycle.

The most important point of the model is that new factors and its interacting feedback with the cycle are considered. Specifically, the model of this paper is different from existing models in three points.
Endogenous change of demand

Whereas existing models assume fixed demand (Meadows, 1970; Berends and Romme, 2001) or exogenously fluctuating demand (Kim, 2005), demand changes endogenously in the interaction with the cycle in this model. Expanding demand can be an important force to pull the industry from the recession. In opposite direction, the recession can stimulate the expansion of demand, which does not mean the increase of the quantity of demand but the shift of demand curve. Low price at the downturn along with technological advancement achieved during upturn spurs the development of new application or usage by the advancement of related technology or experimental usage. The actualization of this mechanism in the TFT-LCD industry will be exhibited in the next section.

Entries

Many empirical studies indicate that steady growth of sales in an industry facilitates entries; but others find no evidence of connection between them. Even Mathews (2005) argue that downturn is good opportunity for entrants in the TFT-LCD industry because they can use knowledge and innovative labor leaked from incumbents and acquire equipments at a low cost. It is certain that there is important relation between entry timing and industrial cycle, but actual pattern seems to depend on individual industry. Of course, in turn, entry timing affects cycles. If entries take place in upturns, industrial bubble will be big; if entries are clustered at downturn, it would extend downturn period but can decrease amplitude of cycle in the subsequent upturn.

Technological change

Technological advance is also related with cycles. In upturns, productivity of production can grow faster due to large scale production than in downturns. If entries tend to entail the adoption of new technology, technological change is indirectly related with cycles because entry timing is related with cycles. In opposite direction, technological change affects cycles through stimulating new usage or application, which, in turn, expands demand.

In the next section, we will provide brief history of the TFT-LCD industry focusing on the crystal cycle and discuss how the framework explained in this section is applied in the TFT-LCD industry.

3. History of the TFT-LCD industry: the Crystal Cycle

Since the TFT-LCD industry began in 1991, it has experienced periodic upturn and downturn (Polga, 2003; Mathews, 2005). According to Mathews (2005), TFT-LCD firms tend to invest more in upturn because of high price; but facilities which firms begin building in upturn are
completed in downturn. Conversely, firms cut back on investments in downturn, which results in short supply in upswing. This is consistent with an explanation shown in section 2, myopic investment decision and delays. But, in the TFT-LCD industry, more interesting mechanisms are observed concerning the crystal cycle.

First of all, in the first two downturns of the TFT-LCD industry, explosive expansion of demand for new applications is an important factor to rescue the industry from the depression. TFT-LCDs were used for lap-top computers at first, but monitors for desktop PCs and TVs began employing TFT-LCDs in the first and second downturns successively. In downturns, demand for new application product explodes but supply is limited due to investment-production delay, which make the price skyrocket.

Then, what is underlying mechanisms of emergence of new applications? It is evident that lower price and higher quality of TFT-LCDs by technological advance enable new uses of the products. Here, we can find positive feedback between demand and technological development. That is, technological advance of TFT-LCDs enabled them to be used in PC monitor, and in turn, expanded demand for TFT-LCD by LCD PC monitors accelerated technological advance of TFT-LCD so that TFT-LCD could be used for LCD TVs. We coined the term “stepping stone application” to depict the role of LCD PC monitor in TFT-LCD jumping from laptop computers to TVs. Stepping stone applications are very important in the expanding use of a product, because technological development is exposed to huge uncertainty (in Knightian sense). No one is sure that TFT-LCD has potential to be used in large scale TVs and can win against competing technologies such as PDP ( Plasma Display Panel) and HTPS ( High-Temperature Polycrystalline Silicon) (Mathews, 2005). So, it is impossible to invest to develop process and product technology to produce TFT-LCDs for TVs at the first phase of the industry. But as TFT-LCD became to be used in PC monitors, it was improved to be large and have faster response speed; in the end, TFT-LCD came to be cheap enough and have good quality to be used in TVs. This mechanism suggests co-evolution of demand and technology.1

Then, why the demand of new application exploded in downturns? The expanding demand of new applications in downturns is not a coincidence. The low price in downturns fosters uses of TFT-LCD in new applications. More uses stimulate the technological development of the application product. Moreover, consumers of applications can learn usefulness of new product from the experience (learning by using). So, even though the price of TFT-LCD goes high later, the use of new applications can be extended. In other words, downturns can be a trigger of the expanding demand of new application product. It should be noted that the crystal cycle is a cause as well as a consequence of demand dynamics. The explosion of demand for new application product pulls the industry out of recession which provides the base on which new application take off.

Another interesting point regarding the crystal cycle is anti-cyclical entries. The TFT-LCD industry saw entries by Japanese firms, Korean firms and Taiwanese firms at the first, second and third downturns respectively (Polgar, 2001 and Mathews, 2005). Anti-cyclical entries may sound irrational because the low price and doomed prediction at the downturn is not good environment for entrants. On the other hand, downturn can be an opportunity for entrants to acquire technologies and engineers leaked from advanced firms, and buy equipment from suppliers at a lower cost. Still, anti-cyclical entries need entrepreneurship to bear risk. Judging from the result in actual history, anti-cyclical entries turned to be successful because upswings came to them when their equipments were ready for production.

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1 In fact, “stepping stone applications” are found in various industries such as the flash memory and computer industries.
Much innovation in the TFT-LCD industry is conducted by production equipment suppliers. TFT-LCD fabrication line is differentiated by the size of glass substrate. The larger glass substrate is, the higher technologies are required. But, once fabrication line is settled, large glass substrate permits larger panels or more panels to be cut at lower cost. So, the TFT-LCD industry evolved from smaller to larger glass substrate. In real history, entrants adopted new generation (larger substrate) of process equipments while incumbents are stuck in older generation process lines. This decision reflects also entrepreneurial initiative in that it seems very risky to start with immature technology. Judging from the result, this strategy was also successful since new process generation stimulates the emergence of new applications through enabling larger size panels at a lower cost. So, we can say that the introduction of new process generation affects anti-cyclical entries and expanding demand of new applications. In opposite direction, anti-cyclical entries and new applications affect technological advances in that entrants were eager to adopt new process generation compared to incumbents and new applications provide additional demand required for the success of new process generation.

In summary, the TFT-LCD industry is characterized by co-evolution of technology and demand. There is positive feedback between technological advance and expansion of demand. Technological advance is closely related with clusters of anti-cyclical entries. The crystal cycle is a result of co-evolution of technology and demand as well as a medium of co-evolution.

4. The Model

Economy

There are five firms at the initial period. The firms produce one product, TFT-LCD. No product differentiation is assumed for simplicity.

Demand Function

There are three applications: laptops, desktop monitors, and TVs. The total demand at the period \( t \) is the sum of the demands for three applications.\(^3\)

\(^2\) For readers who are interested not in detailed model but in rough story, some part of the model is omitted in this section. Detailed description is found in Appendix 1. The simulation is conducted by Java JDK6. The program is available from authors on request.

\(^3\) In fact, each application requires technically different type of TFT-LCDs, but we suppose that all TFT-LCDs are homogeneous except the size for simplicity. The price of this model actually means the price per certain square size of a panel.
\[ D_j = \sum_{j=1}^{3} D_j \]

where \( D_{l}, D_{m}, \) and \( D_{t} \) denote the demands for laptops, desktop monitors, and TVs, respectively. The total demand equals the total revenue of firms because the demand function is as follows.

\[ P_t = \frac{D_t}{Q_t} \]

where \( R_t \) and \( Q_t \) represent the price and the total output. To avoid too sharp fluctuation of the price, the actual price in the model is assumed to be the moving average of \( R_t \) of past five periods.

**Demand dynamics**

At the initial period, there is only the demand for laptops. The demand for desktop monitors and TVs are awoken by sufficiently low price of panels. The threshold price of desktop monitor is higher than that of TVs. Once the demand awoken, it grows along a logistic curve.

\[ D_{jt} = \frac{D_j^{max}}{1 + \exp \left( \frac{c_j - D_j^{min}}{g_j} \right)} + g_j \cdot T_{jt} \]

where \( T_{jt} \) is periods passed until the demand for product \( j \) was awoken. The reason that we adopt logistic curve here is that logistic curve is most widely used in describing diffusion process. The expansion of demand can be considered the diffusion process of usage. In addition, to reflect the fact that demands for laptops and desktop monitors still keep growing, we suppose a continuous trend growth \( g_j \).

**Production**

A firm has some amount of equipments of each generation. Because the productivity of each generation is different one another, the total output of firm \( i \) is the sum of output by equipments of each generation; when \( A_i^g \) denote productivity of equipment of generation \( g \), and \( E_i^g \) denote the amount of equipments of generation \( g \), the total output is determined as follows.
Learning-by-doing

Like the semiconductor industry (Gruber, 1992), learning-by-doing effect regulates the productivity in TFT-LCD production (Jovanovic and Rousseau, 2002 and Park et al., 2003). Therefore, we assume that the productivity of a firm depends on its production experience in equipment generation G ($R^G$):

$$E^G_{it} = E^G_{t-1} + K^G_{t-1} \cdot (1 + \epsilon_{it}^G)$$

And the productivity is determined as follows.

$$A^G_{it} = \frac{A^G}{1 + \text{Exp}[c^{it} - c^{t+1} \cdot E^G_{it}]}$$

where $\epsilon_{it}^G$ is a disturbance term, and $A^G_1$ and $A^G_2$ are the minimum and maximum productivity available by equipment generation G. The minimum productivity of generation 2 is lower than the maximum productivity of generation 1, but the maximum productivity of generation 2 is higher than the maximum productivity of generation 1. That is,

$$A^G_1 < A^{g+1} < A^G_2 < A^{g+2}$$

Investment

Following Nelson and Winter (1982) and Kim and Lee (2002), firms are assumed to have a target markup rate and make an investment decision to achieve it. The intended investment of firm i depends on the gap between current margin over cost ($m_i$) and fixed target markup rate ($m^*_i$).
\[ I^*_t = \max \left[ c \left( \delta + \frac{\nu t - \theta t^*}{\theta t} \right) \right] \]

The intended investment is not fully performed because financial constraint is imposed as follows:

\[ G_{it} = f \cdot \pi_{it} \]

where \( f \) is a parameter of the model and \( \pi_{it} \) is the profit of firm \( i \) at period \( t \).

\[ \pi_{it} = p_t \cdot q_{it} - C_{it} \]

\( C_{it} \) denote total cost.

\[ C_{it} = VC_{it} + FC_i = VC_i \cdot K_{it} + FC_i \]

VC and FC respectively represent variable cost and fixed cost. And VCK is variable cost per unit of capital. VCK and FC are parameters of the model.

Finally, the capital stock of firm \( i \) is determined by the following formula;

\[ K_{it+1} = (1 - \delta) \cdot K_{it} + I^*_t \]

Therefore, firms tend to invest more in upturns. There is some investment-production delay; in other words, equipment construction is completed after some time.

Anti-cyclical entry

Anti-cyclical entries require entrepreneurial initiative and are conditioned on previous experience in related industries such as semiconductors. So, it is not endogenous phenomena but exogenous in the model; in other words, we assume that there are some cohorts of entrants in every downturns. After seeing entries of firms with latest generation of equipment, incumbents also convert to that generation from old generation. But, as entries occur at downturns, incumbents lag behind in investment of up-to-date equipment, subsequently in productivity.
5. History-replicating Simulation

At the initial period, there are five firms producing TFT-LCDs for laptops. As the demand for laptops grows, the price goes up so that firms increase investments. Shortly, demand growth slows down, but the supply continuously increases as the productivity of the first generation equipments improves and equipment construction begins to be completed. The short demand results in price plunge. This is the story of the first crystal cycle in the model.

The price continues to drop below the price level at the previous downturn because of productivity advancing during upturn. It finally meets the threshold of the demand for desktop monitors; the demand growth along with sluggish supply pulls the industry out of the recession. Meanwhile, investments contracted due to the low price rebound, but supply does not instantly expand because of investment-production delay. So, the price rises continuously. We assume that some entrants enter into the market with new generation equipments in the downturn. But, when they completed equipment construction, the price is at the high level so that they can reap some profit in spite of poor productivity. As the price soars, investments also expands but the demand grows slowly. The expansion of supply is accelerated by very fast productivity advancement of new generation of technology. So, the short demand pushes the industry into the downturn now. This is the process of the second crystal cycle. The third crystal cycle has the same process as the second.

The simulation results show that the model can replicate the crystal cycle. Figure 1 represents the movement of the price overtime, in which three cycles are definitely identified. Note that the long-run trend of the price is downward. This is due to entries by firms with latest generation of equipment at downturns.

Figure 2 depicts the change of total production capacity, which lags behind the movement of the price.

Finally, Figure 3 illustrates the change of demands. The industry launched with demand for laptop computer only, but demand for desktop monitor and TV emerges subsequently as the history says. Moreover, the timing of the emergence of new demand is around downturn periods.

6. History-divergent Simulation

The most important factor of the crystal cycle is investment-production delay, so its effect is firstly checked by history-divergent (or counterfactual) simulation. In other words, we removed delay between investment and production (Figure 4). We can observe that removing the delay shortens cycle time and decreases amplitude. This result indicates that the delay actually reinforce the crystal cycle. Moreover, it can be said that the delay makes the market inefficient because the price is low overall in the case of no delay, inducing faster emergence of new applications.

In the model, we suppose another delay of price determination. Figure 5 shows the simulation result when there is no price delay. This also shortens cycle time and decreases amplitude, but the

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4 All results shown here are the averages of the results of 100 simulation runs.
effect is smaller because investment-production delay is long and direct while we assume very short and indirect price delay (moving average of 3 period prices).

Figure 6 illustrates the simulation results when both delays are removed. As is expected, cycle time is shortened and amplitude decreased more.

To investigate the role of stepping-stone application, we assume that the demand for monitor never emerges (Figure 7). As is expected, it takes longer time for industry to escape from the first downturn, but amplitude of cycle is much smaller. Smaller demand means slower learning-by-doing, which, in turn, make the price higher. As a result, the demand for the third application, TFT-LCD TV, takes off much later (period 152 in the history-replicating scenario compared to period 186 in this case).

It is assumed that there is no entrant in Figure 8. This shortens cycle time but increase amplitude.

We remove all factors of delays, new applications and entries in Figure 9. The result is disappearance of the crystal cycle. The movement of price just conforms to learning curve.

If new generation equipment does not emerge (Figure 10), the price does not go below sufficient level for take-off of demand for new application products. Therefore, cycle time lengthens and the price is higher compared to the standard case.

What if learning-by-doing slows down? Figure 11 shows that cycle time lengthens. In this case, the third application, TV does not emerge at the second downturn, implying positive feedback between technological advance and emergence of new demand.

7. Concluding remarks

In this paper, we built an evolutionary simulation model to investigate the crystal cycle of the TFT-LCD industry and co-evolution of demand and technology through the medium of the cycle. The simulation results show that it can successfully replicate the crystal cycle and investment-production delay, price delay and endogenous change of demand are factors of the crystal cycle. Moreover, we can see positive feedback between demand expansion and technological advance through medium of the cycle. In other words, no new demand slow down technological advance and slow technological advance results in late or no emergence of new demand. Figure 12 summarizes the mechanism of the crystal cycle in the model.

This model should be understood with its limitation. This model is not the history-friendly model of the TFT-LCD industry. We simplify many factors and mechanisms for making the model clear and concentrating on one aspect of the industrial dynamics, i.e., the crystal cycle. Moreover, some assumptions might be not empirically accurate, so need to be elaborated through future research.

5 We assume that new generation of equipment comes with entrants in the history-replicating simulation. Since there is no entrant here, it is assumed that new generation emerges at the same time as entrants enter in the history-replicating simulation.
References


Appendix 1. The Value of Parameter

Initial demand for laptop computer = 0.1
Capital at initial period = 0.25
Initial number of firms = 5
Initial capital of entrants = 0.25
Initial productivity = 0.2
Investment-production delay = 15
Fixed cost = 0.001
Variable cost = 0.1
Max productivity of generation 1 equipment = 0.3
Max productivity of generation 2 equipment = 0.55
Max productivity of generation 3 equipment = 0.75
Min productivity of generation 1 equipment = 0.2
Min productivity of generation 2 equipment = 0.27
Min productivity of generation 3 equipment = 0.43
Number of entrants at the first downturn = 2
Number of entrants at the second downturn = 2
The price threshold of emergence of desktop monitor = 0.4
The price threshold of emergence of TV = 0.25
Max value of logistic curve of demand = 0.2
Constant growth rate of demands = 0.0005
Depreciation rate = 0.01
Price delay = 3
Figure 1. The Price of TFT-LCD panel

Figure 2. The Total Production Capacity
Figure 3. Demands for Laptops, Desktop Monitors, and TVs

Figure 4. No Investment-production Delay
Figure 5. No Price Delay

![Graph showing price changes over time with 'base' and 'no price delay' lines.](image)

Figure 6. No Delays

![Graph showing price changes over time with 'base' and 'no delays' lines.](image)
Figure 7. No Second Application

Figure 8. No Entrants
Figure 9. No delays, entries and new applications

Figure 10. No emergence of new generation equipment
Figure 11. Slower learning-by-doing

Figure 12. Mechanism of the Crystal Cycle