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Forecasting Technological Change via Driving Force Approach based on Innovation Diffusion and Complexity Theory

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Keywords

Technology forecasting
Complexity theory
Complex adaptive systems
Innovation diffusion
Driving forces

Abstract.

Traditional forecasting methods usually predict industry trends and technologies in only a single direction, either upward or downward. Therefore, the forecasting results would often show surprising deviations, particularly for those industries that are complex and may have abrupt changes. Consequently, this study aims to fill this gap and develop a new approach by making industrial driving forces a concrete tool for forecasting technological changes and industry trends. Both qualitative and quantitative data were collected to examine the future direction of OLED (organic light-emitting diode) technology, which is regarded as complex with highly uncertain opportunities and market potential. The forecasted data were then compared with the actual industrial data. The results indicated that both showed the same cyclical pattern. These preliminary findings imply that the concept of driving forces can be utilized as a forecasting tool when integrated with quantitative data analysis.

1. Introduction

Cathode ray tubes (CRT) dominated the monitoring market beginning in 1940, initiating the development of monitor technologies. In the 21st century, people began to pursue higher-quality, more humanized ways of living. By then, monitors had evolved from traditional CRTs to flat panel displays (FPDs). Since the advent of organic light-emitting diodes (OLEDs), this new FPD technology has attracted the attention of industries and academics, furthering their engagement in OLED research and development.

However, the OLED output values and annual growth rates did not meet the expectations of the market research agencies. In 2006, an industrial collapse began, in which annual industry revenue began to show negative growth. During this time, many international companies shut down their OLED departments. This decrease came to a halt in 2007, and output increased again. In 2008, outputs and annual growth rates increased more than they did for other FPDs, showing that the entire OLED industry was gradually gaining ground. Unfortunately, the global OLED production yield showed a recession again between 2014 and 2015, but it rebounded again after 2015 because of the many applications of the Internet of Things.

In view of the abovementioned industrial development phenomena, this study investigated previous OLED research. We found that previous studies have mainly focused on analyzing OLED development strategies and critical success factors; they did not use the concept of driving forces to elaborate on the process of innovation diffusion and did not explain the reasons behind the recession and revival of the OLED industry. Because the emergence of a new technology or product is from being known to personal use. Finally, due to continuous use, new ideas, new concepts or new products are diffused to the entire social group (Rogers, 1995). This is a dynamic process. This dynamic process cannot assume the market model from the static point of view of traditional economic theory, but evolves in a nonlinear dynamic and complex way (Anderson, 1999; Brown & Eisenhardt, 1997). Therefore, this study investigated and addressed the following issues: the diffusion process and the key driving forces behind industrial developments during the recession and revival of the OLED industry, and the reasons why we utilized the key driving forces to forecast future trends in the OLED industry. OLED is an emerging display technology that all walks of life have favored, but it has experienced severe recession and revival. Therefore, this study argues that the recession and revival process of the OLED industry is worth investigating, particularly for research purposes, to demonstrate a new approach for forecasting technological changes in the industry with complexity and abrupt changes.

Using the case study method, penetrative interviews were conducted with experts and secondary data were organized, resulting in a penetrative investigation of the OLED industry development process. During our investigation, we determined the positive and negative factors that caused recession and revival during the industry's diffusion. Furthermore, this study identified the driving factors (driving forces) behind OLED industry development and generalized these factors by explaining both the large and small effects of these driving forces on the industry. Our goal is to become the basis for future forecasts in this industry, and we hope that these findings will serve as a reference for academics and practitioners.

In the remaining of this paper, we first explored the relevant literature used to analyze the development of the industry, such as industry analysis, diffusion of innovation, and complexity theory. To describe the industry's development process, a research framework is derived in the third part, adopting a dynamic innovation process under complexity theory combined with industry analysis and timeline. The fourth section presents a case study of the OLED industry, including its technical background and development history. From the analysis, the driving forces affecting the industry are summarized, and the impact of the driving forces on the development of the industry is examined through quantitative results. Finally, we drew some conclusions, highlighted the study's main contributions to academia and practice, and suggested future research avenues.

2. Theoretical Background

2.1. Forecasting for competitiveness and technologies

General management must consider the structure and changes in the external environment. The industrial structure is the most important of all aspects of the external environment. The industrial structure affects the competitive intensity among enterprises within an industry. Porter (1980) proposed the Five Forces Framework to help understand the primary factors in industrial structure and competition that affect the intensity of competition within an industry. The five forces are as follows: intensity of competitive rivalry, the threat of new entrants, threat of substitute products or services, bargaining power of customers (buyers), and bargaining power of suppliers. According to Porter (1980), these five forces are relevant to industry competition, and the combination of these five forces determines an industry’s competitive intensity and profitability. Therefore, these five forces can be considered the main factors that affect an enterprise’s profitability.

To investigate how a nation obtains international competitive advantages in a certain industry, Porter (1990) conducted in-depth studies of transnational industries in ten different nations and found that a nation not only affects an industry’s decisions and strategies but is also the key to the industry’s creation and continuing its production and technological development. Porter (1990) combined the following four key factors into a bidirectional diamond model within the system to explain national competitive advantages: factor conditions; demand conditions; related and supporting industries; and firm strategy, structure, and rivalry. Porter also added two variables, government and chance, to the discussion on the relationship between a nation’s environment and an industry’s competitiveness. These six factors exert mutual influence, thus creating a complete and dynamic system.

Concerning technological forecasting, Martino (1993) first clarified the definitions of technology and forecasting and considered that technology forecasting is a forecasting activity that focuses on the possible changes in future technology. In other words, technology forecasting predicts the future characteristics of useful technology, product, machine, process, or skill. Liang et al. (1999) developed a better technology strategy model by combining technological advantages and technological forecasting viewpoints. In addition, the forecasting method can be applied not only to technical forecasting but also to market forecasting. Frigstad (1996) used several technical forecasting methods (Delphi method, statistical trend analysis, regression model, trend extrapolation etc.) to forecast the market potential of various products. Martino (1993) emphasized the importance of understanding the rationales and dynamics behind the driving forces while conducting forecasting.

2.2. Diffusion of innovations

Rogers’ “Diffusion of Innovation” (1995) was the most quoted among many innovative diffusion models (Steiber et al., 2021). In the process of innovation diffusion, Rogers (1995) noted combinations of the following construct factors and their effects on the diffusion stage. (1) The prior conditions and characteristics of the decision-making unit will affect the cognitive stage. Two constructs that primarily affect the cognitive stage include variables that describe potential adopters. "Prior conditions" emphasized potential adopters' previous experience, perceived needs, personal attitudes toward employing innovation, and social cognition. The decision-making unit uses socioeconomic characteristics, personality variables, and communication habits to analyze potential adopters. (2) Perceived characteristics of innovation and communication channels will affect the persuasion stage. The two constructs that affect the persuasion stage mainly evaluate perceived variables because this stage focuses primarily on exploring potential adopters' attitudes towards innovation.

Rogers (1995) focused on the process of individual adoption. He stated that the adoption process should address the outcomes of communication and adoption through the following four key factors: innovation, communication channels, time, and social systems. Therefore, this study concluded that Rogers views diffusion as a propagation process, emphasizing its two-way interaction characteristics and allowing continuous creation through the interaction between the supplier and the buyer, which forces innovation to continue. This perspective is consistent with the industry characteristics discussed in this study; therefore, we included this schema in the study.

2.3. Complexity theory

Complexity theory is an emerging interdisciplinary field (Anderson et al., 1999) This was the key to exploring the existence of a co-evolution process in a complex, nonlinear, dynamic adaptive system. Complexity theory uses chaos theory as its basis and incorporates three additional important factors (Anderson, 1999). The first factor is the phenomenon of positive and negative feedback. In other words, two types of feedback coexist in complex adaptive systems. The first is negative feedback, which can weaken and regulate the activity force, retaining it within a certain range. The second is positive feedback, which can enhance this effect. However, when positive feedback and negative feedback are combined, a vibrant new balance is created that brings order to chaos (Briggs & Peat, 1999). The second is emergence. This refers to the sudden occurrence of a new structure and function in the system. It also refers to the production of a new function or holistic system from an organic combination of other subsystems. As emergence is created by interactions between factors, this phenomenon may be out of our control or beyond our predictions. The last is self-organization. It resembles the continuous expansion of self-similarity developed in individual cells during their survival activities (Schroeder, 2009). Therefore, self-organization refers to system behavior from a certain regularity produced by the interaction between certain internal units. This development is bottom-up; thus, any slight interaction differences will cause large, unpredictable variations. This self-organization concept dominates changes in complex adaptive systems. (Brown & Eisenhardt, 1997).

From the above description, it can be concluded that the complex adaptive system is constantly changing. This process of change can be divided into three forms: (1) self-organization, (2) dissipative, and (3) self-organized criticality. Self-organization allows a complex system to change its internal structure and interact better with the environment. This is a gradual learning process. Dissipative means that external forces or internal disturbances cause the system to be highly disorganized before the further reorganization. The criticality of self-organization is one form of self-organization. It refers to the ability of a complex system to balance random and stasis. A complex system reaches a critical point where the internal structure is on the verge of collapse but does not collapse. At this time, to adapt to the environment, the rate of internal reconstruction is too fast, but this behavior is necessary for long-term survival. (Bak & Chen, 1991).

2.4. The Dynamic diffusion of innovation process under complexity theory

Many studies have used the complexity perspective as an integrated framework to re-examine phenomena in various fields, expecting to generate new insights. Tuner and Baker (2020) were the first researchers to identify and test creativity and innovative processes as complex adaptive systems. McCarthy et al. (2006) used the concept of CAS, especially three of the key concepts: non-linearity, self-organization and emergence, to metaphorize the new product development process to reflect the non-linear nature within the new product development process. Breslin et al. (2021) drew further on the ecological metaphor to present a view of innovation ecosystems as complex adaptive systems in which patterns of change emerge from microlevel coevolutionary interactions between actors. Wang and Wu (2011) employed the important concepts of CAS, combining them with the process of innovation diffusion, to develop a dynamic model to affect innovative diffusion. In this model, many important factors in CAS were combined with the innovation diffusion concept of social systems to create an analog. The contents of this dynamic model are as follows. (1) The innovator's network position. Many studies have found that the network location of the innovator or innovation importer plays a very important role in the successful diffusion of innovation (Rogers, 1995; Tushman & O'Reilly, 2002). In an innovative system, an opinion leader can provide innovation-related information to many others within the system. (2) Openness and freedom of systems. The openness of a boundary affects the possibility of old and new agents entering or exiting the system and the possibility of external energy input. Therefore, boundaries play an important role in a great deal of innovation diffusion (Cool et al., 1997). (3) The possibility of reinvention. Reinvention refers to an adopter's degree of alteration in the process of adoption and application during innovation. When technological information is exchanged under highly uncertain conditions, reinvention is the primary dynamic driving force of innovation (Rogers, 1995; Cool et al., 1997; Müller et al., 2021). (4) Diffusion incentives. Many incentives affect the diffusion of innovation, such as economic and non-economic incentives. Rogers (1995) indicated that motives for people's willingness to share and diffuse information could not be completely explained from an economic perspective. (5) Number of adopters. Many studies on innovation diffusion have found that the more adopters there are, the more likely they are to adopt an innovation (Bianchi et al., 2017; Rogers, 1995; Zanello el al., 2016).

3. Research Framework and Methods

3.1. Research framework

Based on the theoretical background, this study concluded that the best way to describe the dynamic diffusion process of industrial development is to produce an analog using the concepts of complexity theory and innovation diffusion. Therefore, the research framework (see Figure 1) was formed by selecting a partial construct in the dynamic innovation process of complexity theory. Along with system openness and freedom, the possibility of reinvention and diffusion incentives are important factors in the diffusion of industrial development.

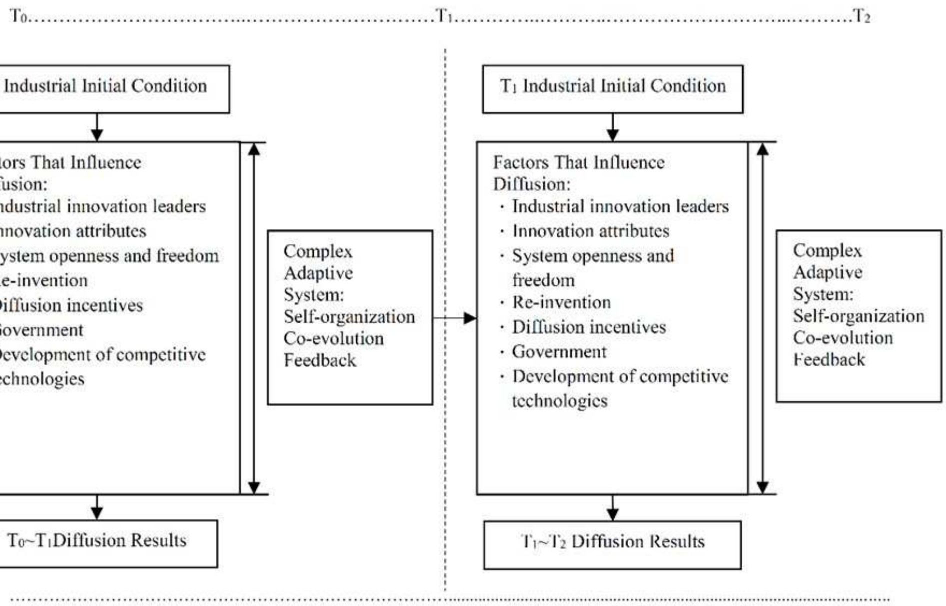


Figure 1: Research Framework.

Furthermore, fierce competition and the threat of "substitute technologies" in the market will affect the benefits to individual industries. Government attitudes and strategies are important for the development of emerging industries. Therefore, this study incorporates the "threat of substitute products or services" from Porter's five-force model and the role of "government" from the diamond model. Additionally, this study included a timeline that presents the industry's diffusion process to distinguish the processes of its decline and expansion. Consequently, important driving factors can be identified by constructing a framework to analyze the entire process.

Timeline T0 to T1 is the first stage of this study, reflecting the period from the beginning to the end of 2006. The second stage is timelines T1 to T2, the period from the beginning of 2007 to the end of 2008.

3.2. Methodology

This study is in accordance with the exploration research method because there are no prior studies on the development of the OLED industry and because case studies are also applicable to studies that are principally exploratory (Benbasat et al., 1987).

This study generalizes the key driving forces that affected the industry's development using the constructs of the research framework. The study also summarized experts' opinions acquired through in-depth interviews and quantified these opinions as to the driving factors. Once the negative factors offset the positive factors, we can determine whether these factors influenced the different stages of industry development that led to expansion or constriction in the industry. This study used 5-point Likert scales to obtain quantitative data. Finally, the global OLED industry was considered the research object in this study. The forecasted results were then compared with actual industrial data.

4. The Case of The OLED Industry

In 2006, many manufacturers withdrew from OLED R&D investment, production, and market. Only a few companies participated in OLED R&D, and only a small number of manufacturers produced OLEDs. AMOLED (active-matrix OLEDs) has been comparatively slow. However, global panel makers were shocked when Chi Mei Optoelectronics Corp. exhibited the world's largest AMOLED display panel at Japan's FPD International in 2006. Taiwan became the world leader in the AMOLED technology race, which forced Sony to demonstrate a 27-inch AMOLED display panel and market 11-inch AMOLED TV products. After 2008, Japan and South Korea successively began to develop and produce AMOLEDs, which once again led Taiwanese companies to devote resources to production.

4.1. The 1^{st} stage of OLED development in 2006

4.1.1. Initial conditions during the 1^{st} stage

At this stage, there were few AMOLEDs in the OLED markets; most were PMOLEDs (passive-matrix OLEDs). However, the maturity of the PMOLED technology processes far exceeded that of TFT-LCDs, and the PMOLED application areas overlapped with the small-sized TFT-LCDs, resulting in reverse competition. The development of the OLED industry in Korea surpassed its development in Japan in terms of the production and number of patents.

4.1.2. Influencing factors of diffusion

(1) Industry innovation and opinion leaders. At the beginning of OLED development, the Japanese pioneer was the industry explorer, the first company to commercialize OLED technology. Companies in other countries immediately entered the industry, leading to fierce competition among Taiwan, Japan, and Korea. However, the development of OLED technology in Japan at this stage was unsuccessful, and many large companies exited the industry. By contrast, South Korean companies never stopped investing actively. Therefore, South Korea began to obtain competitive advantages for OLED.

(2) Innovation Attributes. Compared with the small TFT-LCDs, PMOLEDs' color saturation, response speed, and wide viewing angle performance are better, giving PMOLEDs a technical advantage.

(3) System openness and freedom. Upstream materials were controlled by a small group of manufacturers; machinery manufacturers functioned as oligopolies, and there was no standardized equipment. All the above conditions made it very difficult for companies to enter the industry.

(4) Possibility of reinvention. The lifespan of luminescent materials has improved tremendously. Neither AMOLED nor PMOLED panel makers use fluorescent materials; instead, they attempted to develop phosphorescent materials because they are more efficient than fluorescent materials. However, the process technology still needs to reach a breakthrough. The yield rates and costs continue to be problematic.

(5) Diffusion incentives. Most OLED applications are for portable panel-based consumer electronic devices, including MP3 players, cell phones, PDAs, DSCs, and car audio devices. Some companies are willing to apply OLEDs in high-end products, but most believe installing TFT LCD panels in PMOLEDs or OLEDs is not sufficiently attractive.

(6) Development of alternative technologies. TFT-LCDs developed quickly into a fully mature technology that OLED display technology could not compete with. The interviewee observed: "At that time, when the display panel factories decided to transfer below a 4.5 foundry production line capacity to small- and medium-sized panel applications, they caused a structural change in the industrial competition ecology of small- and medium-sized panels. The TFT-LCD, relying on its abundant production capability and competitive prices, became superior in the small- and medium-sized panel industries. It was too difficult for the OLED to compete with TFT-LCD on price".

(7) The role of government. The governments of both South Korea and Japan supported the OLED industry. The South Korean government supports equipment manufacturers in assisting with industry development. In Japan, a professor from Yamagata University conducted OLED R&D through a government grant program.

4.1.3. Complex adaptive systems

(1) Coevolution and Feedback. Owing to the threat of strong competition and failure to achieve breakthroughs in technology, the advantages of positive feedback have never been accumulated.

(2) Self-organization. At the beginning of the commercialization of OLEDs, many companies were attracted to the market, but they conducted OLED research and development in their respective research areas, and there was seldom any communication among them. Because the interaction among industry members was low, the phenomenon of self-organization was not obvious.

4.1.4. Diffusion results

The manufacturing, packaging, and measurement of OLED devices were yet to be established during the first stage, which resulted in low yields, high production costs, and delays in time to market. Therefore, the goals of OLED manufacturers were to integrate the middle and downstream industry chains, simultaneously improve the process technology, and enhance the autonomy of the base material to increase yields. Another problem faced by OLEDs was that their market position overlapped with that of LCDs. TFT-LCDs, with their years of research and mature technology, have a cost advantage in studying the history of small panel development, including competitor technology in the field. Thus, it was difficult for OLEDs to develop markets at this stage.

4.2. The 2nd Stage of OLED development (2007∼2008)

4.2.1. Initial conditions in the 2nd stage

It was initially difficult for AMOLEDs to overcome technology bottlenecks, resulting in production difficulties and low yields. However, beginning in 2007, manufacturers began to break through these difficult conditions, and we can say that 2007 was the first year of AMOLED development. Since 2007, AMOLED technology has matured and entered the stage of mass production, which marks the beginning of large-scale OLED development. The main force behind the industrial growth of OLEDs is the development of AMOLEDs. At the same time, the annual growth rate of PMOLEDs was slow.

4.2.2. Influences on diffusion

(1) Industrial innovation and opinion leaders. Sony first launched an AMOLED TV in the market at this stage, which stimulated other manufacturers.

(2) Innovation Attributes.OLED technology has gradually shifted from small PMOLEDs, which were once exclusive, to AMOLEDs with the ultimate goal of installing them in large televisions. In 2007, AMOLEDs entered the mass production stage of OLED TVs and other emerging applications. With regard to large-size flat panel display technology, in addition to TFT-LCDs and PDPs, OLEDs should be the most mature and best able to mass-produce next-generation display products.

(3) System openness and freedom. Governments fostered planned industrial development. In addition, development alliances were organized by companies in this field. All these efforts help foster institutional openness.

(4) Possibility of reinvention. Owing to the challenges of process issues and low yields, which caused manufacturers a number of problems during their AMOLED development, solutions have emerged.

(5) Diffusion incentives. The wide variation in OLED applications forces improvements in OLED market demand, just as with AMOLEDs, because AMOLED technology could support large panel sizes, and the companies applied it to producing AMOLED TVs. Lighting is the latest application of OLED technology at this stage.

(6) Development of substitutive technologies. The growth of medium-sized and small TFT-LCDs slowed down. At the same time, OLEDs can no longer compete directly with LCDs.

(7) The role of government. Governments were optimistic about the development of OLEDs. Governments in Japan and Europe, to foster OLED development, invited people from industry and academia to cooperate in organizing national alliances. These governments jointly developed technologies and exchanged information.

4.2.3. Complex adaptive systems

(1) Coevolution and feedback. In the second phase of OLED proliferation, we clearly saw the evolution and effects of positive feedback. There were positively reinforcing effects in diffusion incentives and possibilities of reinvention. In addition, the number of industry manufacturers participating in the R&D process increased. Originally, the tendency for conducting research in the OLED industry was not prevalent, but it was eventually revived, which helped accumulate the energy of diffusion.

(2) Self-organization. In the second phase of OLED diffusion, the self-organization was more obvious than in the first stage.

4.2.4. Diffusion results

According to this study, during the 2nd stage, OLED technology was gradually transformed from small PMOLED technology, for which it was used exclusively, to the ultimate goal of applying it to large TVs. The year 2007 was the key year for the development of AMOLEDs. Many manufacturers have gradually developed sufficient knowledge to overcome technological bottlenecks. AMOLEDs began to enter the mass-production stage owing to emerging applications, such as OLED TV. However, AMOLEDs was only in the initial stages. Many technological bottlenecks still need to be addressed to achieve improvements. In addition, considering the continuous improvement of small-product applications in Korea and Taiwan, it was anticipated that functional AMOLED prices in the future would fall faster than the prices of TFT panels.

4.3. The Driving Forces in the OLED Industry

In-depth interviews with experts were conducted, and 8 driving factors were identified. These factors were considered by experts to be the driving forces that most profoundly affected the diffusion of OLEDs. In this study, experts' opinions on OLED industry development and its 8 driving factors were quantified on a Likert scale. These 8 driving forces had both positive and negative impacts on the industry, as summarized in Table 3.

To estimate the impacts of these positive and negative driving factors on the industry's development, this study developed a Likert-scale quantitative index based on the aforementioned propositions to illustrate the industry's decline and resurrection processes. Table 4 and Table 5 shows the result of translating the experts' opinions into a Likert scale in the 1st and 2nd stage stage.

After we totaled the data in the 1st stage, the sum of the 4 positive driving forces was 53, and their average was 2.65; the sum of the 4 negative driving forces was 85, and their average was 4.25, indicating that overall, the negative forces were more powerful than the positive forces.

Table 3: The positive and negative driving forces behind OLED development.

Positive Driving Factors	Contents
Public policy and government support of the industry	Public policy to intervene in the industry's scope to foster industrial development using regulations, infrastructure, pollution prevention, trade promotion, and R&D tax incentives and training.
Technology level	The technical maturity of OLED's lifetime luminescence and colorization.
Market demand	OLED's willingness to adopt the system integrators and consumers' acceptance of OLEDs.
Product application	The breadth of OLED's applicability.
Negative Driving Factors	Contents
Pressure from competitors in the same market	The degree of OLED price competition.
Production costs	OLED's production costs.
Process technology	The maturity and yields of OLED technology.
Development of alternative technology	The technical maturity of the alternative technologies, such as TFT/STN-LCDs.

Table 4: The result of the experts' opinions into a Likert scale in the 1st stage.

	E1	E2	E3	E4	E5	Total	Average
1. Considerable government support for the OLED industry	3	4	3	3	3	16	3.2
2. Better OLED technology	3	4	4	2	2	15	3
3. High OLED market demand	2	3	2	2	2	11	2.2
4. Broad applicability of OLED	2	2	3	2	2	11	2.2
Total score of the positive driving forces						**53**	**2.65**
5. High competition and pressure among OLED market competitors	4	5	4	5	5	23	4.6
6. Highly developed alternatives to OLED technology	5	5	5	5	5	25	5
7. High OLED production costs	5	5	5	5	5	25	5
8. Immature OLED process technology	2	3	3	2	2	12	2.4
Total score of the negative driving forces						**85**	**4.25**

When we totaled the data in the 2nd stage, the sum of the 4 positive driving forces was 77, and their average was 3.85; the sum of the 4 negative driving forces was 70, and their average was 3.5, indicating that overall, the positive forces were more powerful than the negative forces.

5. Findings and Discussion

This section discusses the findings of this study, which resulted from expert inter-

Table 5: The result of the experts' opinions into a Likert scale in the 2st stage.

	E1	E2	E3	E4	E5	Total	Average
1. Considerable government support for the OLED industry	4	5	4	4	4	20	4
2. Better OLED technology	3	4	4	4	4	19	3.8
3. High OLED market demand	4	4	3	3	4	18	3.6
4. Broad applicability of OLED	4	5	4	3	4	20	4
Total score of the positive driving forces						**77**	**3.85**
5. High competition and pressure among OLED market competitors	3	2	2	3	2	12	2.4
6. Highly developed alternatives to OLED technology	5	5	5	5	5	25	5
7. High OLED production costs	5	3	3	4	4	20	4
8. Immature OLED process technology	3	3	3	2	3	13	2.6
Total score of the negative driving forces						**70**	**3.5**

views and actual OLED industrial data. The analysis and comparison of the driving forces between the two stages are discussed.

5.1. Analysis of the 1st Stage and 2nd stage

Based on the results of the Likert scale adopted in this study, the positive and negative driving forces that affected the OLED industry development are illustrated in Figure 2. The year 2006 was difficult for the OLED industry in contrast to the optimistic public and forecasting reports regarding the industry. The experts noted that competitive pressure and the development of alternative technologies were the 2 main driving forces behind the industry's decline.

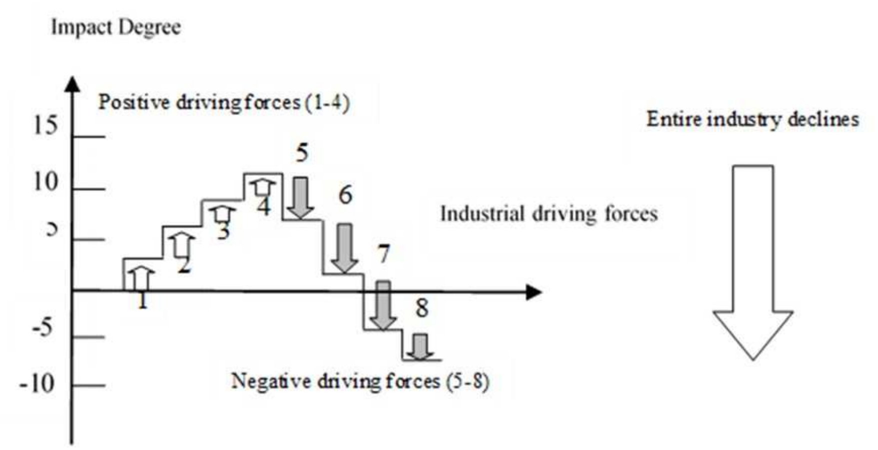


Figure 2: Analysis bar chart of the 1st stage.

Figure 3 shows the results of the Likert scale index, which illustrates the impact of the

2nd stage's positive and negative driving forces on the development of the OLED industry. This study found that although the performance of the OLED industry declined in 2006, there were signs of recovery after 2007. In the 2nd stage, the AMOLED technology had matured, and the OLED panels no longer suffered from a limited supply. Until the outbreak of the financial crisis in 2008, the sales figures in each quarter were all strong, which prompted many large factories to return to OLED R&D, and even governments in Europe, America, and Japan invested in and led OLED R&D projects. In this diffusion stage, the positive driving forces were more powerful than the negative ones, particularly in the areas of application and market demand.

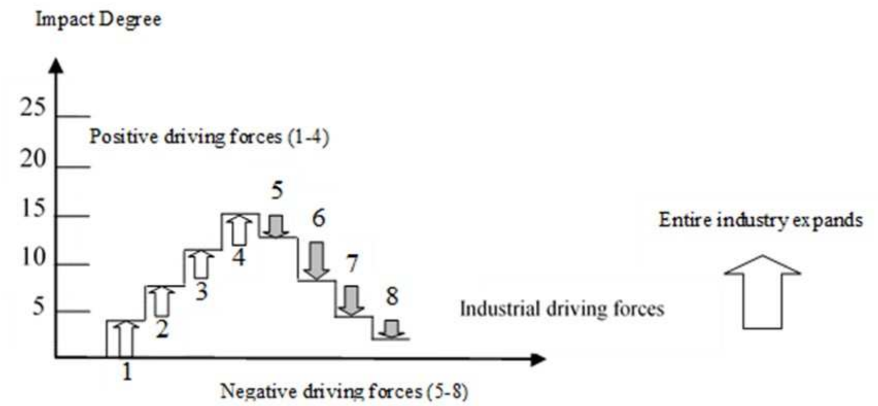


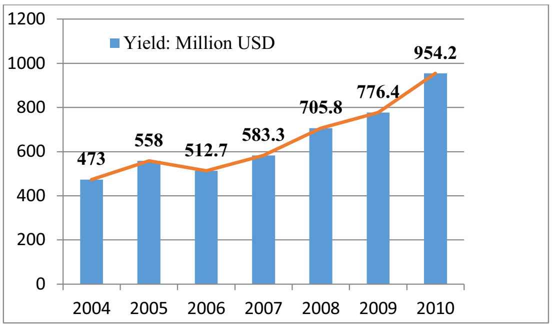
Figure 3: Analysis bar chart of the 2nd stage.

According to the data analysis in this study, we found that the most powerful negative drivers of the OLED industry in its 1st stage were competition, which affected OLED panel prices, and the greater maturity and mass commercialization of alternative technologies. However, in the 2nd stage, the influence of these negative driving forces decreased, and the influence of the positive forces increased dramatically, mainly because market demand increased gradually and new application possibilities were identified. There was a new segmentation in the OLED market, and the OLED panels no longer needed to directly compete with the TFT-LCDs. These positive forces made the diffusion of OLED more successful in the 2nd stage than in the 1st stage.

5.2. Comparison of the results with the actual industrial data

Figure 4 illustrates the global OLED production yields from 2004 to 2010. This reflects the fact that the global yield in 2005 was 558 million USD which declined to 512.7 million USD in 2006. The worldwide OLED industry appears to have faced a downward trend, which is consistent with the results of this study regarding the 1st stage of the industry. The study results found that the negative driving forces were more powerful than the positive ones in the decline of the OLED industry, which is consistent with the actual industry circumstances.

In 2007, the global OLED production yield immediately reached 583.3 million USD and was 705.8 million USD by 2008. The industry appears to follow an upward trajectory,



Source: ITRI IEK

Figure 4: Global OLED production yield from 2004 to 2010.

which is consistent with the findings from the 2nd stage of this study. These results demonstrate that the positive driving forces were more powerful than the negative ones, leading to the expansion of OLEDs, and this conclusion is also in line with the actual industrial situation.

5.3. Research validation from 2013∼2015

In 2019, a study on the OLED industry was conducted again in the same way, adopting the same research method. Market data showed that from 2014 to 2015, due to the continuous squeeze of TFT LCD panel products and the impact of compressed product unit prices, the revenue of small- and medium-sized AMOLED panels was squeezed. In addition, large-scale AMOLEDs have not yet gained market share, resulting in the stagnant development of AMOLEDs. Therefore, the global OLED production yield was in recession again between 2014 and 2015, but it rebounded after 2015 (see Figure 5).

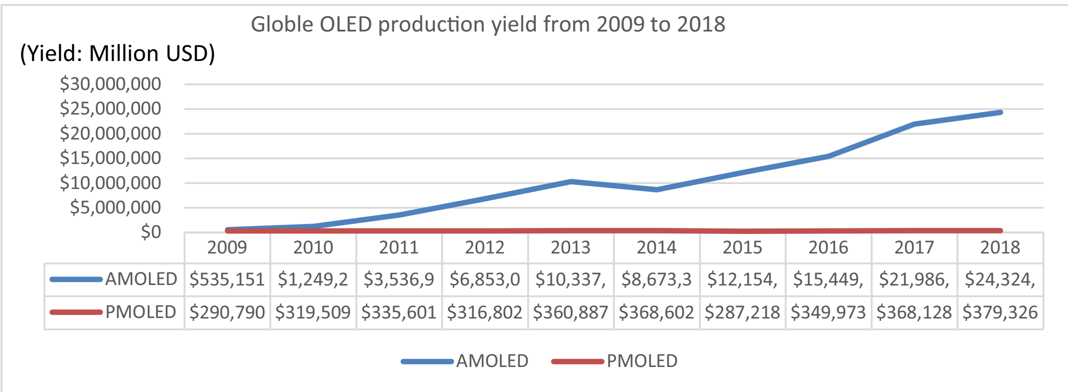


Figure 5: Global OLED production yield from 2009 to 2018.

In response to the ups and downs of the OLED industry during this period, this research collected quantitative data on 8 driving factors from 9 experts. The results from 2014 to 2015 are shown in Table 6 and Figure 6. The results after 2015 are shown in Table 7 and Figure 7.

Table 6: The result from 2014 to 2015.

	E1	E2	E3	E4	E5	E6	E7	E8	E9	Total	Average
1. Considerable government support for the OLED industry	3	5	4	5	3	4	3	3	2	32	3.56
2. Better OLED technology	3	4	2	2	3	3	2	2	2	23	2.56
3. High OLED market demand	4	4	4	5	4	4	2	4	4	35	3.89
4. Broad applicability of OLED	4	5	4	4	4	5	4	4	4	38	4.22
Total score of the positive driving forces										**128**	**14.22**
5. High competition and pressure among OLED market competitors	4	3	4	4	4	4	1	5	1	30	3.33
6. Highly developed alternatives to OLED technology	3	3	4	2	5	3	5	2	2	29	3.22
7. High OLED production costs	5	5	4	5	5	4	5	5	5	43	4.78
8. Immature OLED process technology	4	4	4	4	3	3	5	4	4	35	3.89
Total score of the negative driving forces										**137**	**15.22**

Table 7: The result after 2015.

	E1	E2	E3	E4	E5	E6	E7	E8	E9	Total	Average
1. Considerable government support for the OLED industry	3	4	5	4	3	4	3	3	4	33	3.67
2. Better OLED technology	4	4	3	4	3	4	4	4	2	32	3.56
3. High OLED market demand	5	4	4	4	4	4	2	4	5	36	4
4. Broad applicability of OLED	5	5	4	4	4	5	2	4	5	38	4.22
Total score of the positive driving forces										**139**	**15.44**
5. High competition and pressure among OLED market competitors	4	4	4	5	4	5	5	5	1	37	4.11
6. Highly developed alternatives to OLED technology	3	4	4	2	5	4	5	4	2	33	3.67
7. High OLED production costs	4	3	4	4	4	4	5	3	4	35	3.89
8. Immature OLED process technology	2	2	4	2	3	3	4	2	2	24	2.67
Total score of the negative driving forces										**129**	**14.33**

6. Conclusions, Contributions and Limitations

Based on the research results, this study draws the following conclusions: First

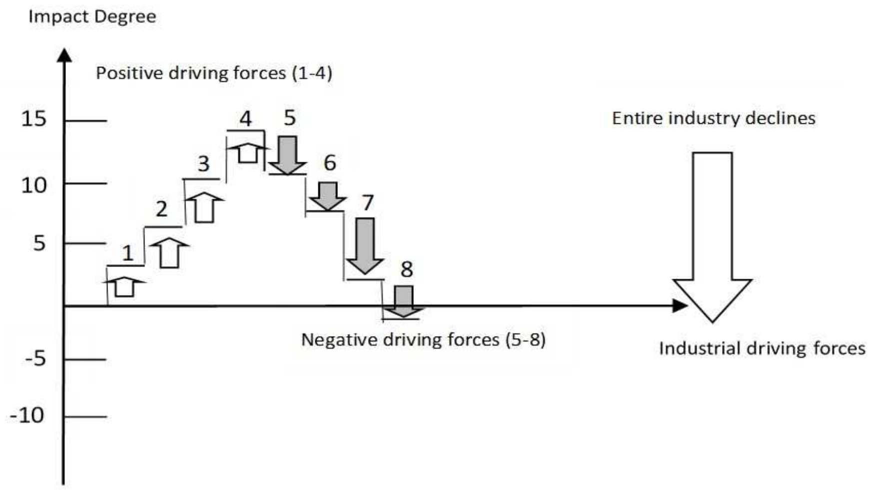


Figure 6: Analysis bar chart between 2014 to 2015.

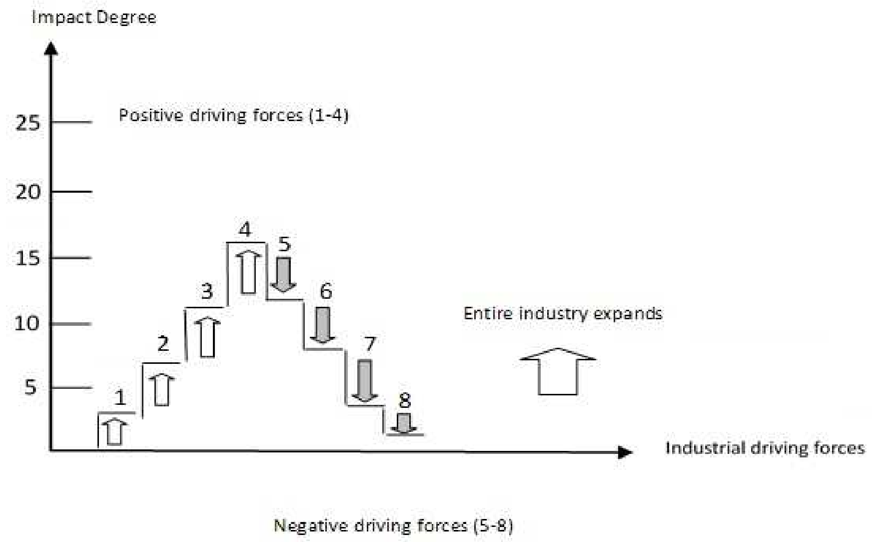


Figure 7: Analysis bar chart after 2015.

of all, driving forces can be used as a method of technological forecasting change. By reviewing the diffusion of the OLED industry and conducting penetrative interviews with experts, this study preliminarily validated our approach using actual industrial data and concluded that driving forces could be used as a useful tool for forecasting technological change. Second, the maturity of technology during the early stage of industry diffusion determines whether future development is successful. In addition, when compared with competing technologies of the same period, which technology or service is superior or inferior also affected the development of the industry. Finally, the degree of openness and freedom affect the entry and exit barriers of the industrial system. High levels of openness and freedom allow new entrants to the system, injecting new energy that benefits the development of the emerging industry. The government can serve as a catalyst for promoting system openness.

As mentioned earlier, traditional forecasting methods always predict industry trends and technologies only in one direction and often produce forecasting results with surprising deviations, particularly for industries that are complex and uncertain with abrupt changes. This study proposed and preliminarily validated a new approach using driving forces to forecast technological change. It is believed that this new approach can contribute to both academia and industry.

However, this study had some limitations. First, this was a retrospective study. Most interview information and relevant documents may be somewhat distorted because of memory constraints; therefore, it is impossible to describe the situation 100in this study to explore one industry's diffusion process. Future studies should investigate more cases to enhance the generalizability of the results. Finally, in the process of data collection, the knowledge background of the interviewees affects their cognition of the problems addressed in the study, which in turn affects the research results.

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