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Evolution Theory of Ink Jet Technologies: Progress by Component or Architectural Knowledge

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Abstract. *Ink jet technology has extended its market by upgrading functions and improving performances of a few key components (printhead, ink and media) under a simple marking process for years. However, this trend has been saturated in the personal market, and the market has been stagnant. In this situation, two directions for ink jet technology progress have become obvious. One is expansion of the ink jet to various applications such as digital fabrications utilizing a simple process and the other is facing challenges (to the commercial printing market) from performance limitations derived by imaging processes that are achieved only by the interaction between ink and media. The differences of technical approaches in each direction also exist. The progress of an elemental technology region (key components) has been noticeable in the expansion of the possibility. The challenge to the limitation has been effective in the progress of system integration or peripheral technology. The former evolution (Concentrating Functions Progress) can generate "Incremental Innovation" and needs component knowledge to improve component performances. The latter (Sharing Functions Progress) demands architectural knowledge to test the optimum combination of components maximizing system performances and is one of the driving forces generating "Architectural Innovation". Generically, venture companies or small start-ups play a role in Architectural Innovation because they are free from resource allocation mechanisms or an organizational form for Incremental Innovation. But in the current commercial printing market, many big companies have introduced ink jet printers with different component combinations (architectures) and the Dominant Design has not been fixed yet. The shift from Incremental Innovation to Architectural Innovation has also occurred in additive manufacturing.* © *2018 Society for Imaging Science and Technology.*
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1. INTRODUCTION

In 1968, the first commercial ink jet printer "Videojet" was introduced into the market. There were some ink recorders said to be the beginning of the ink jet printer such as Kelvin's siphon recorder (1876) or Elmqvist's mingograph (1952). Based on my definition of ink jet given in the next chapter, "Videojet" is considered the first. For that reason, 2018 is the 50th anniversary of the appearance of the ink jet printer. Figure 1 shows the macrotrend of the ink jet printer from its birth to the present. Many printers with small size have been developed and commercialized in the early phase. Second, ink jet printers provide high image quality using small ink drops, diluted inks, and specialized ink jet papers. With the advent of pagewide printheads, ink jet printers have been able to enter the high printing speed market such as high-end office and transactional printing. Today, ink jet printers with high image quality and high printing speed have entered the commercial printing market.

In this article, technology progress of ink jet is expounded. In particular, configuration of technology progress is analyzed and categorized. Market backgrounds requiring each configuration are also explained. Future directions of these progress configurations and difference of innovations created by each configuration are indicated. Finally, technology progress is associated with innovation portfolio, and some suggestions are derived.

2. DEFINITION OF INK JET TECHNOLOGY

The definition of ink jet technology proposed by the author is as follows [1]:

Dropletize liquid including colorants or functional materials, and eject liquid drops to recording target (media) on demand from image (pattern) signal, then bring colorants or functional materials to recording target (media).

Defining technology is important to identify invention of course; not only that, it is important to consider extensions and applications of technology. As is clear from this definition, ink jet is not a technology only to realize printers.

The marking process by ink jets is very simple in either serial printers or line printers with pagewide printhead, and ink jets have many merits such as small size, low cost, small power consumption, high process stability and high scalability, which come from simplicity of marking process. The simplicity of the ink jet process leads to the high possibility of applying ink jets to various applications but it also imposes limitations. This is because the marking process is achieved by only an interaction between ink and media. These two aspects are fundamental to my ink jet evolution theory described here.

3. CONCENTRATING FUNCTIONS PROGRESS (CFP)

Under a simple marking process completed with only a few key components of printhead, ink, and media, these key components have led to the progress of prime performances of printers. The prime performances of printers are absolute image quality and printing speed. Printhead performance progresses contribute to printer performance progresses, and ink performance improvements lead to printer performance

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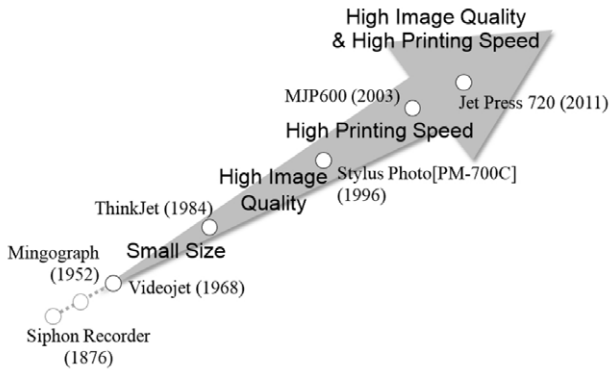

Figure 1. Macrotrend of ink jet printer.

improvements. Particularly, decrease in drop volume or increase in nozzle density has achieved high image quality, and high firing frequency or high ink penetrability has supported high printing speed. In this way, progress of system (ink jet printer) performances has been influenced mainly by the progress of key components' performances. I named this technology progress configuration *Concentrating Functions Progress* (CFP). Ink jet technology has evolved in this manner, Concentrating Functions Progress, for many years. This Concentrating Functions Progress has maintained many merits of ink jets, which come from process simplicity.

Now we turn to the upgrading of prime printer performances by actual data. Figure 2 shows the trend of minimum drop volume ejected from a printhead [2]. The minimum drop volume is closely correlated with image quality. It had decreased significantly and reached 1 pl finally in 2005. Figure 3 shows changes of sensory evaluation score for image quality [2]. Sensory evaluation score is image quality quantified from visual aspect. Image quality on ink jet specialized paper had increased uneventfully and linked strongly with the minimum drop volume trend. Ink jet image quality on specialized paper exceeded electrophotography in 1996. In the 1990s, improvement of image quality was remarkable and image quality had improved every year as apparent results for general customers. This improvement was sufficient to enhance customers' desire or passion to buy new printers even if their printers were not broken. However, making the drop volume smaller than 1 pl does not contribute to significant improvement in image quality for the general customer because the resolution of the normal human eye (20/20 vision) is about 40 μm at a distance of 20 cm from images [3]. 1 pl corresponds to 13 micrometers of drop diameter, and equivalent to 20 or 30 micrometers of dot diameter on usual media. Therefore, decreasing the drop volume has stopped since 2005.

Not only decreasing the minimum drop volume but also increasing the number of color ink cartridge has contributed to image quality improvement by extending color gamut. Now some pro-use inkjet printers with 12 kinds of ink are available in the market. Providing multiple color more than 6 has value for few professionals now; meanwhile, a printer with four or six colors is sufficient for general consumers.

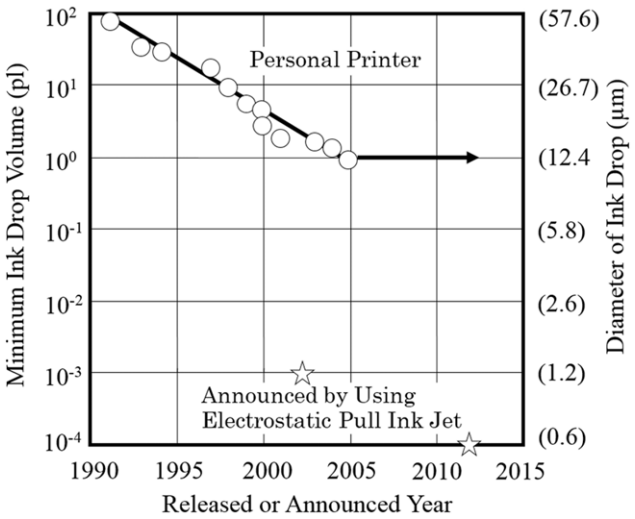

Figure 2. Trend of minimum ink drop volume [2].

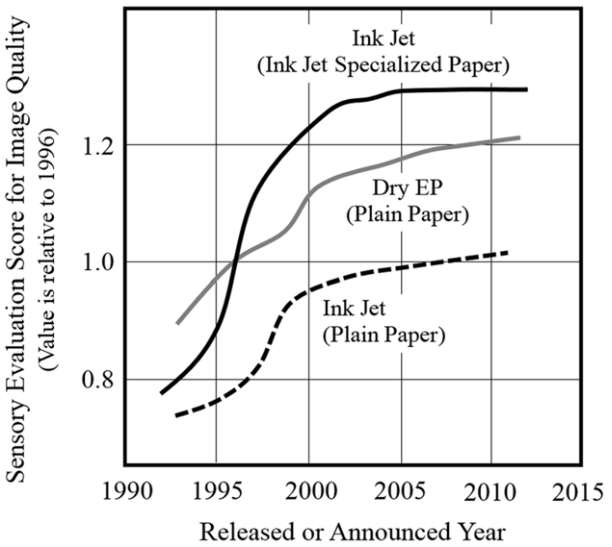

Figure 3. Trend of image quality [2].

In fact, improvement of image quality (sensory evaluation score) has been saturated since 2005 as shown in Fig. 3.

The trend for another prime performance, printing speed, is analyzed next. Speed factor SF is a formula symbolizing the relation among factors regarding printing speed in ink jet printers and it is described as in Equation (1) [1].

$$SF = \frac{F_r \cdot N_n}{N_m \cdot R_p \cdot F_{pd}} - T_m - T_o, \tag{1}$$

where F_r and N_n are the firing frequency and the number of nozzles of a printhead, respectively; N_m, R_p and F_{pd} are the number of multi-path printing, resolution of printing and factor for printing direction in a serial printer, respectively; T_m and T_o are the times required for maintenance and other operations without printing, respectively.

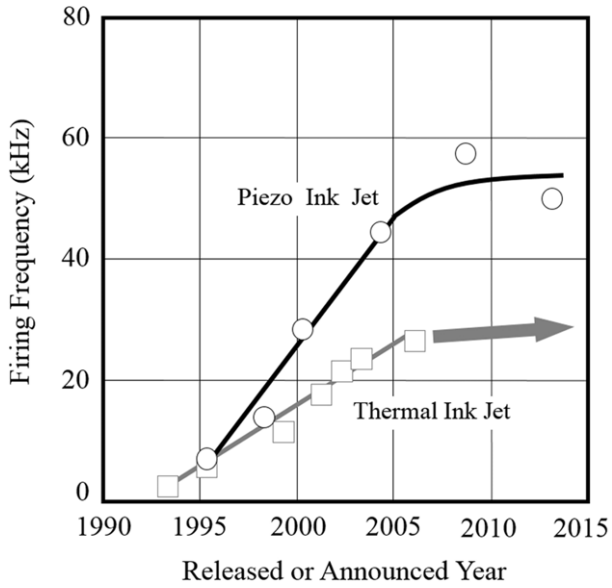

Figure 4. Trend of firing frequency [2].

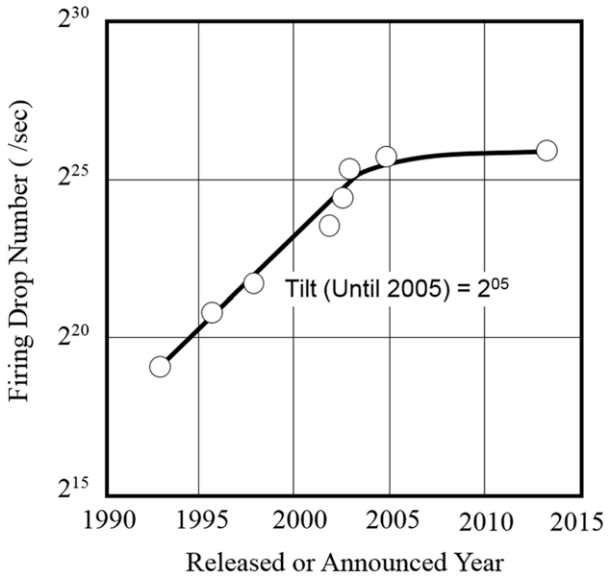

Figure 6. Trend of fired drop number [2].

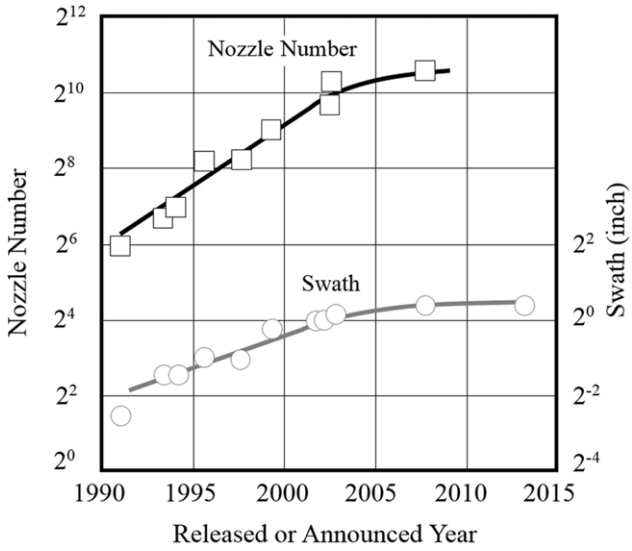

Figure 5. Trend of nozzle number and swath [2].

Figures 4 and 5 represent the trends of firing frequency F_r and nozzle number N_n of personal ink jet printer, respectively [2]. The increase in firing frequency has slowed down since the latter half of 2000. One of causes dulling increase of firing frequency is stop of minimum drop volume decrease. In line printers with pagewide printhead, the nozzle number rises from the trend in Fig. 5, though the nozzle number of the personal ink jet printer has also been saturated. These facts mean that the increase of the numerator in Eq. (1) equivalent to the printing speed of a personal printer has been saturated too as shown in Figure 6. Now, it is amazing that the tilt of the numerator before 2005, shown in Fig. 6, is about $2^{0.5}$ and agrees with the famous Moore's Law for the integrated circuit size rate of semiconductors.

In this manner, upgrading of key components' performances has been almost saturated in the present day. Then progress of personal printer performances (image quality, printing speed) has slowed down since 2005. Despite these facts, many new products for personal ink jet printers have been released every year. The reason can be that ink jet companies cannot play the game to win but they are under the necessity of playing the game not to lose. To describe in an extreme manner, if additional activities for technology developments focusing on personal printers stop, no customer will be inconvenienced. It does not mean all technology development of ink jets should be discontinued, and it is highly unlikely that technology progress of ink jet will stop.

Concentrating Functions Progress is still required in other markets with different performance axes, for example, digital fabrication, which is not for the personal market. In digital fabrication, inks generating various functions are required, and printhead ejecting high-viscosity ink, ultra-small drops or ultra-large drops is required. Namely, Concentrating Functions Progress is expected. Printed electronics, one kind of digital fabrication, is adopting various patterning technologies including ink jets. Ejecting small drops to make fine patterns or ejecting high-viscosity liquid to make layers thick is required in printed electronics.

Concentrating Functions Progress is not the only configuration of technology progress in ink jets. System approaches other than printhead or ink have been developed and will be explained in the next chapter.

4. SHARING FUNCTIONS PROGRESS (SFP)

A new type of technology progress of ink jet has been necessary for new printer markets with new difficult challenges. One of the new important markets with hard

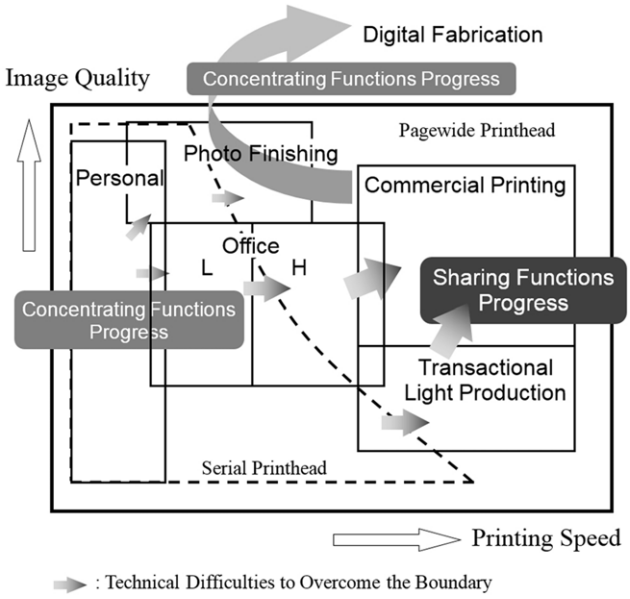

Figure 7. Plane view of ink jet market.

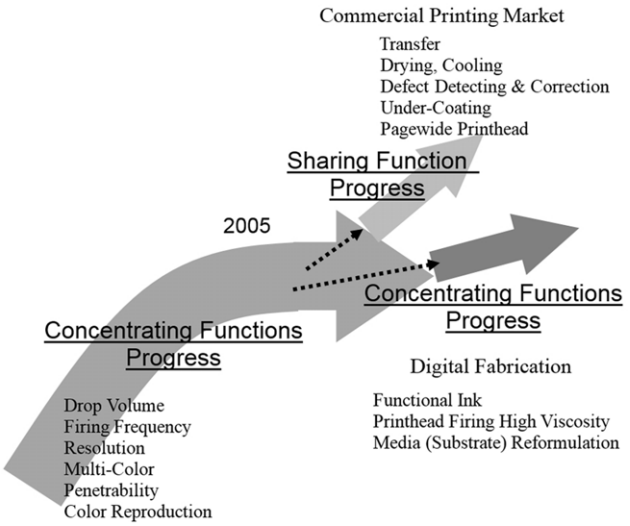

Figure 8. Evolution directions of ink jet technology [5].

issues for ink jets is a commercial printing market. I named this new type of progress as *Sharing Functions Progress* (SFP).

Figure 7 illustrates a plane view of the ink jet market with the axis of prime printer performances, printing speed and image quality. In the past, ink jet extended its market from personal printers to photo finishing, office, and transactional printing by Concentrating Functions Progress. This Concentrating Functions Progress also continues to the new market with a different axis out of this figure, for example, digital fabrication, as described above. The commercial printing market requiring both high printing speed and high image quality presents some hard issues for ink jets. It is difficult to enter here by the traditional progress configuration Concentrating Functions Progress and it needs another configuration of progress, that is, Sharing Functions Progress.

There are two big issues for ink jets in the commercial printing market. Ink jets usually adopt permeable media like a paper in the traditional ink jet market (personal or office). However, non-permeable offset coated paper is rightly used in the commercial printing market. It is hard to form and fix fine images on this non-permeable media by ink jets. This is the first issue or a major hurdle for an entry with ink jet technology. High productivity is required for the commercial printing market. Consequently, it is necessary to adopt pagewide printhead and one path printing. In addition to this, ink jets must achieve high image quality equivalent to offset press without any defects by one path printing. This is the second issue or another major hurdle. To challenge these hard issues in the commercial printing market, a new progress configuration that does not pose these issues on only printhead or ink is necessary. This is the Sharing Functions Progress.

Sharing Functions Progress in the commercial printing market is explained by giving a specific example. Jet Press 720 was introduced into the commercial printing market in 2011 [4]. For this printer, the printhead and ink developed typically. This printer tried to overcome high hurdles confronting the commercial printing market by adoption and combination of other surrounding technologies. To achieve high image quality without any defects by one path printing, it is no wonder that printheads are expected not to generate any nozzle clogging or any misdirectionalities. But on the assumption that defects of printheads exist, detecting defects by inline sensors and defect compensation using image processing and drive waveform control have become indispensable technologies. To form and fix fine images on non-permeable media, not only latex ink but also under-coating instruments, drying or air conditioning system have been introduced. In this way, performance progress of printhead or ink, and sharing various functions among surrounding system technologies, namely Sharing Functions Progress, are necessary to enter the commercial printing market. However, many ink jet merits available before are lost here.

Summarizing the above by using Figure 8 [5], the past progress of ink jet technologies was Concentrating Functions Progress. Since 2005, the performance progresses of key components and printer have been slowed down under Concentrating Functions Progress. But by changing the performance axis from the past, for example in digital fabrication, Concentrating Functions Progress will fulfill its role. To challenge the commercial printing market with the same performance axis as in the past but with more difficult issues, a new progress configuration, namely Sharing Functions Progress, has started.

5. INK JET TECHNOLOGY PROGRESS AND INNOVATION PORTFOLIO

In 1990, Henderson and Clark presented a portfolio for innovation shown in Figure 9 [6]. In this portfolio, the horizontal axis consists of reinforcing core component

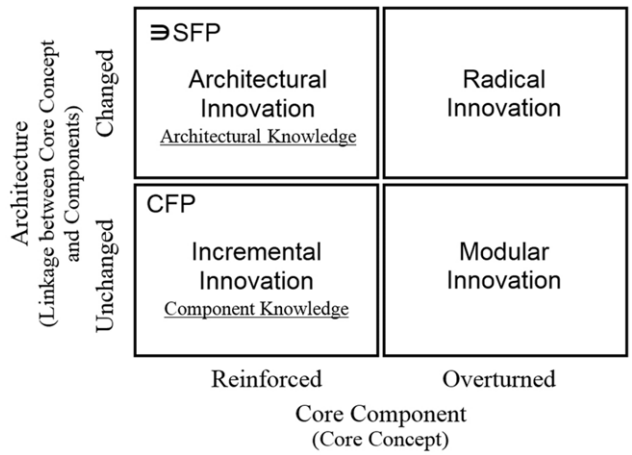

Figure 9. Innovation portfolio [6].

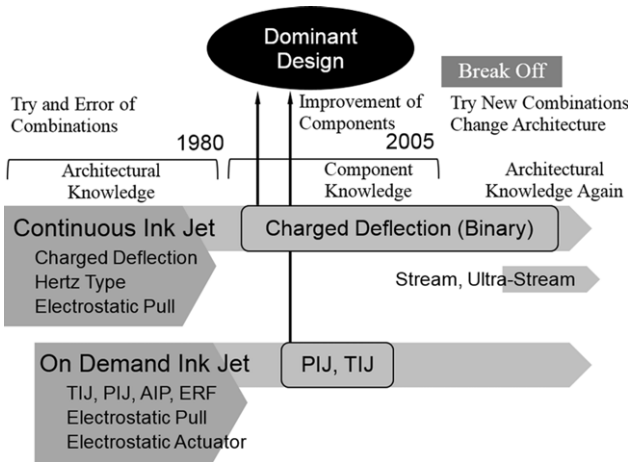

Figure 10. Technology progress of ink jet.

and overturning core component. The vertical axis sorts out keeping the system architecture from changing the architecture. They provided four kinds of innovation arising from the different kinds of technology progress in this way. In this chapter, the left area of this portfolio is focused because progress with the same technology, ink jet, is described here. The lower left part of the portfolio, *Incremental Innovation* is brought about by reinforcing the core component under the same system architecture. Namely, Concentrating Functions Progress causes Incremental Innovation. The left upper part, *Architectural Innovation*, is brought about by changing the system architecture to maximize system performance and resolve the hard issue. In Sharing Functions Progress, allocation of functions is changed by adopting new system technologies; it is thought that Sharing Functions Progress is one of the approaches generating Architectural Innovation. In this manner, my evolution theory with two types of technology progress is associated with the innovation portfolio. From here, technology progress of ink jet will be examined based on this integrated idea.

Until the 1980s, many types of ink jet had been researched and proposed. Since the 1980s, in the category of continuous ink jets, the binary charged reflection type has been mainstream as shown in Figure 10. In the category of on demand ink jet, piezo ink jet (PIJ) and thermal ink jet (TIJ) have become the dominant technologies. The printer system or system architecture using these ink jet types that print images on paper directly has been established. This surviving and optimized system architecture is called *Dominant Design*. Once Dominant Design is established, technology developments in accordance with Concentrating Functions Progress start to increase performances of components configuring Dominant Design; that is, decreasing drop volume or increasing firing frequency of printhead. As shown before, this Concentrating Functions Progress almost ended and increase in system performances almost stopped around 2005. To break away from this situation, it is the time to try a new combination or change the architecture. Architectural Innovation, in other words, Sharing Functions Progress,

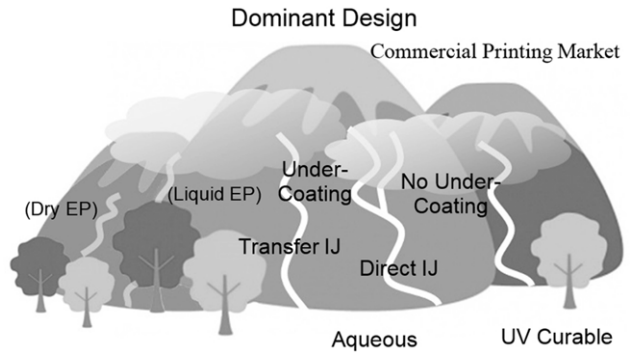

Figure 11. Digital architectures in commercial printing market.

is necessary in the commercial printing market. In fact, some architectures have been attempted, and some printers with different architectures have been introduced in the commercial printing market.

Figure 11 illustrates the situation that there are some ink jet systems introduced (or announced to introduce) with different architectures in the commercial printing market. Jet Press 720, explained in the previous chapter, is using aqueous ink; on the other hand, KM-1 is adopting ultraviolet curable ink. If the ink used is different in the system, assignment of functions and system formation, namely system architecture, is different. Even in the case of aqueous ink, ejected aqueous ink is formed on the media directory in Jet Press 720; Landa's system or Voyager by Canon/Océ makes images on media through a transfer instrument (a belt or a drum). Furthermore, to fix images on non-permeable media, some systems employ under-coating; others do not. Various architectures have been attempted in the commercial printing market. It is natural that various combinations or architectures exist in the early phase of Architectural Innovation. These are screened and Dominant Design is established before long. However, Dominant Design of an ink jet system in the commercial printing market has not been established yet.

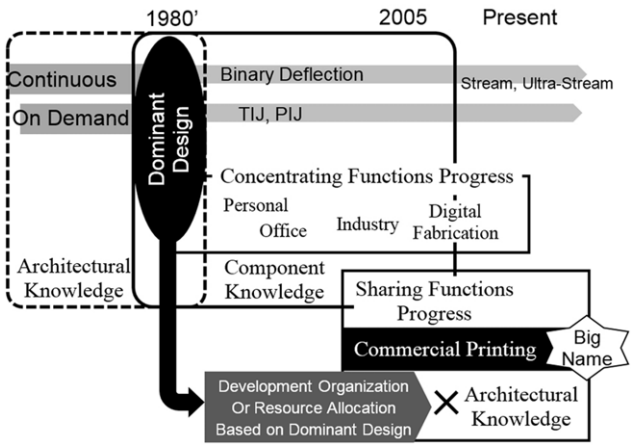

Figure 12. Contradiction of progress in commercial printing market.

6. CONTRADICTION OF TECHNOLOGY PROGRESS IN COMMERCIAL PRINTING MARKET

Technology progress is marshaled in connection with the consideration of innovation in Figure 12. Once Dominant Design is established, technology development is organized according to this Dominant Design. Resource allocations or the reporting route also obeys this development organization. This system is optimized to increase component performances in Concentrating Functions Progress. However, in the architectural progress phase, this organization disturbs architectural progress. This is because aspiring architectural progress means to change or destroy this system including the present organization. For that reason, venture companies or start-ups are assumed to make architectural progress and generate Architectural Innovation essentially. How about players in the current commercial printing market requiring architectural progress? Every player is a big name. A unique progress of ink jet technology and a contradiction of progress exist in the commercial printing market.

Venture companies or start-ups should bring about Architectural Innovation essentially. But even in Architectural Innovation, ink jet is still the core technology in the commercial printing market. Big ink jet companies have developed ink jet components and stored technologies and know-how in the past. Therefore, only big companies can enter this market. Here the contradiction of progress exists. It matters little if big companies join the commercial printing market. The true problem is no start-up can join the process where Dominant Design is selected. Dominant Design may not be determined forever because of only big companies' convenience.

The situation where big companies hold technology assets and impact the determination of Dominant Design in the commercial printing market requiring Sharing Functions Progress is explained. This situation also militates against Concentrating Functions Progress. In digital fabrication aspiring Concentrating Functions Progress, many companies or research institutions are trying to apply ink jet to all kinds of applications. Most of them have few ink jet technology assets, and some have a problem ejecting their outstanding functional liquid stably from printheads. They have used a lot of energy to overcome the first step.

I do not expect ink jet companies to transfer all their technology assets to challengers because ink jet companies have acquired their assets by investing huge money and resources. However, even full-blown technologies owned by ink jet companies should be transferred or licensed to new challengers to activate new applications or new markets. This will be a big step for them. Ink jet companies should not enclose their full-blown technologies for the already sluggish market.

Another important thing to activate new applications is forming technical communities. Engineers, researchers in ink jet companies and new challengers meet, discuss, and share common information and full-blown technologies there. Participators in the technical communities do not have to know everything held by other members. It is important to know "who knows what". That is called *Transactive Memory* [7].

7. ARCHITECTURAL PROGRESS IN ADDITIVE MANUFACTURING

Methodologies for additive manufacturing (three-dimensional [3D] printer) are categorized into seven methods in standard classification [8]. All these seven methods were invented in the 1980s or 1990s. About 30 years have passed since the current methods have been proposed. During this time, increasing the manufacturing speed or acquiring forming accuracy, namely incremental development, has been mainly implemented. The use case of additive manufacturing has been shifting from prototyping to production in recent days. Now some activities aim to seek new architectures also in additive manufacturing to challenge high hurdles in production. Multi Jet Fusion by Hewlett-Packard can be considered a hybrid of binder jetting and powder bed fusion. Da Vinci color 3D printer by XYZPrinting (not for production) can be considered a hybrid of material extrusion and sheet lamination. In the research and development phase, many new processes not categorized into the seven existing methods, namely new architectures, have been researched and proposed.

8. CONCLUSION AND SUGGESTION

2005 was a significant turning year for ink jet technology progress. Two kinds of configuration for ink jet technology progress have existed. One is Concentrating Functions Progress (CFP) and the other is Sharing Functions Progress (SFP). Concentrating Functions Progress finished its role in the personal market once, but is still required for digital fabrication with different prime performances from the personal printer market. Sharing Functions Progress is necessary to enter the commercial printing market with hard issues. Concentrating Functions Progress generates Incremental Innovation, and Sharing Functions Progress is one of the approaches to generate Architectural Innovation.

In the commercial printing market, Dominant Design of ink jets has not been established yet. The full-blown tech-

nologies owned by ink jet companies should be transferred or licensed to new challengers to activate both Concentrating Functions Progress and Sharing Functions Progress. The technical community and Transactive Memory obtained there are also important to activate new applications or a new market using ink jet technology.

REFERENCES

[1] M. Fujii, *Ink Jet* (Tokyo Denki University Press, Tokyo, 2008), p. 1.
[2] M. Fujii, "Footstep and future prospect of ink jet technology," J. Imaging Soc. Japan **47**, 241 (2008).
[3] A. Ushiroda, "Tone reproduction technology for inkjet printer," J. Soc. Photogr. Sci. Technol. Japan **68**, 296 (2005).
[4] S. Tatsumi, "Sheet-fed inkjet printer (Jetpress720) for commercial printing," J. Imaging Soc. Japan **51**, 392 (2012).
[5] M. Fujii, "Ink jet technology," J. Imaging Soc. Japan **51**, 148 (2012).
[6] R. Henderson and K. Clark, "Architectural innovation: the reconfiguration existing product technologies and the failure of established firm," Adm. Sci. Q. **35** (1990).
[7] D. M. Wegner, T. Giuliano, and P. Hertel, "Transactive memory in close relationship," J. Personality and Social Psychology **61**, 923 (1991).
[8] ASTM International, *Standard Terminology for Additive Manufacturing Technologies* (ASTM, West Conshohocken, PA, 2012).