The industrial emergence of commercial inkjet printing

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The industrial emergence of commercial inkjet printing

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Abstract

Purpose – The purpose of this paper is to investigate how supply and demand interact during industrial emergence.

Design/methodology/approach – The paper builds on previous theorising about co-evolutionary dynamics, exploring the interaction between supply and demand in a study of the industrial emergence of the commercial inkjet cluster in Cambridge, UK. Data are collected through 13 interviews with professionals working in the industry.

Findings – The paper shows that as new industries emerge, asynchronies between technology supply and market demand create opportunities for entrepreneurial activity. In attempting to match innovative technologies to particular applications, entrepreneurs adapt to the system conditions and shape the environment to their own advantage. Firms that successfully operate in emerging industries demonstrate the functionality of new technologies, reducing uncertainty and increasing customer receptiveness.

Research limitations/implications – The research is geographically bounded to the Cambridge commercial inkjet cluster. Further studies could consider commercial inkjet from a global perspective or test the applicability of the findings in other industries.

Practical implications – Technology-based firms are often innovating during periods of industrial emergence. The insights developed in this paper help such firms recognise the emerging context in which they operate and the challenges that need to overcome.

Originality/value – As an in depth study of a single industry, this research responds to calls for studies into industrial emergence, providing insights into how supply and demand interact during this phase of the industry lifecycle.

Keywords Technological innovation, Co-evolution, Commercial inkjet printing, Industrial emergence, Supply-demand interaction

Paper type Research paper

1. Introduction

Emerging or nascent industries are high-technology industries that build on scientific breakthroughs and which require years, if not decades, of further R&D, product development and market testing before realising their commercial potential in the market. They are "newly formed or re-formed industries that have been created by technological innovations, shifts in relative cost relationships, emergence of new customer needs, or other economic and sociological changes that elevate a new product or service to the level of a potentially viable business opportunity" (Porter, 1980, p. 215). In such industries, "commercial markets do not yet exist or are still too small and uncertain to attract established companies" (de Jong and de Bruin, 2013, p. 46), and industry emergence "continues from the founding of the first organization until industry stability is reached, where stability implies that both participants and observers agree on meanings and boundaries" (Miller, 2012, p. 62).

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While emerging industries play an important role in economic development, recent scholars have noted that "[t]he emergence of new industries is an important phenomenon that remains relatively neglected by researchers" (Forbes and Kirsch, 2011, p. 590). One reason for this is that previous studies of industrial emergence are dispersed across a number of fields of research (Malerba, 2007; Robinson and Propp, 2008), including industrial economics (Klepper and Graddy, 1990; Dosi *et al.*, 1995), marketing (Kotler, 1991), socio-technical systems (Rip, 1995; Geels, 2005; Kaplan and Tripsas, 2008), industrial dynamics (Murmann and Homburg, 2001; Afuah and Tucci, 2003) and systems theory (Windrum and Birchenhall, 1998). The main focus of these models and frameworks is on the growth and maturity phases of the industry lifecycle (Agarwal *et al.*, 2002; Malerba, 2007), although there is evidence to suggest that the emergence phase has distinctive characteristics that distinguishes it from these later phases (Fixson and Lee, 2012).

To gain insights into how structure arises through industrial emergence, this paper approaches the topic from a co-evolutionary, multi-level perspective (Geels, 2006). Recent work along these lines has proposed that there is a "push-pull 'engine' of industrial emergence" in which "demand and supply-side factors, and their interactions, are primary drivers that impact on the process of industrial emergence" (Phaal *et al.*, 2011, p. 228). How does supply and demand interact during industrial emergence? It is this question that provides the motivation for this paper, which builds on theories of socio-economic change to investigate the industrial emergence of the commercial inkjet printing cluster in Cambridge, UK. Our study reveals a number of feedbacks that operated asynchronously during the industry's emergence and highlights the importance of entrepreneurial adaptation in responding to changing technological and market possibilities, and the role of demonstrators in reducing technological uncertainty and improving market acceptance.

2. Interaction between supply and demand in socio-economic change

Variety in socio-economic systems is generated by entrepreneurs and organisations by creating new products, processes, markets and organisational forms through discovery and recombination (Schumpeter, 1928). New technological trajectories are established by radical innovations. Such radical innovations are typically supply-driven, although attempting to meet latent market needs, with the incremental innovations later being made on the basis of market demands (Utterback, 1994).

The direction of innovative activity lies in the interaction between supply and demand, involving the coupling of technical possibilities with market opportunities (Swann, 1994; Freeman and Soete, 1997; Maine and Garnsey, 2006), and does so by building on the endowments of past scientific, technological and industrial activity. Existing technologies and institutions are an important precondition for novelty because they provide the basis for devices and techniques to be modified, along with a rich set of intellectual resources that can be applied to new settings (Bijker and Law, 1992; Mackenzie and Wajcman, 1999). Future innovation and industrial activity is constrained by that which has come before: "the creation of novelty involves guided variation within perceptions of a limited set of possibilities. Innovations are never entirely novel; they are always prefigured in some of their dimensions" (Metcalfe, 1998, p. 99).

Although these initial conditions have significant consequences for the trajectories followed by the industry and its constituent firms (Dosi, 1982; Malerba, 2007), the direction of future innovative activity is not entirely path dependent. Socio-economic evolution is not

blind or random; agents anticipate market selection forces in the pursuit of competitive advantage and adapt their strategies as a result of these interactions (Bhidé, 1994; Axelrod and Cohen, 2000). Actors within emerging industries "frame issues about the future, coordinate their actions in the present and make sense of what may have transpired in the past" (Karnøe and Garud, 2012, p. 735) in order to bring about path creation. So while the absence of existing markets and the limited availability of ready-made resources is a challenge for aspiring entrepreneurs, the careful selection of certain market niches and sub-markets (Kemp *et al.*, 1998), the leveraging of strong ties within the emerging market (Suarez, 2005) and purposefully shaping the technological frames of other actors (Kaplan and Tripsas, 2008) can improve their probability of affecting the direction of evolution.

The forces of supply and demand interact to define a co-evolutionary process (Arthur, 2007). Co-evolution can take a number of different forms, including that between industries and surrounding social institutions, between producers and user populations and between separate populations of competing technologies (Murmann, 2003). At the micro-level, co-evolution can be seen as a process of co-construction, with there being mutual shaping between the various heterogeneous system elements, while at the meso-level it is seen in how the inter-related activities of different social groups create multiple interacting trajectories that influence one another (Geels, 2006). Through this co-evolutionary process, those innovations and firms that are able to adapt to their selection environment have greater "fitness" and are retained; those that fail to adapt to the environment are eliminated (Saviotti, 1996; Metcalfe, 1998).

As a consequence of this co-evolutionary dynamic, the variety and number of events related to scientific and technological development decline over time as promising technological ideas and concepts are subject to selection processes. Such complex systems can be seen to rapidly "crystallize" (Kauffman, 1995) through positive feedbacks that amplify the effects of past decisions and propagate prior selections (Arthur, 1989). Dominant designs (Utterback, 1994; Murmann and Frenken, 2006) are often the product of this narrowing of technological choice, with complementary technologies based on platform architectures (Gawer and Cusumano, 2002). Although these processes lead to reduced variety and options in the system, they have the positive effect of reducing technological and market uncertainties (Meijer *et al.*, 2007; Tikkanen, 2008), with it posited that science, technology, application and market demonstrators play a significant role in the reduction of these uncertainties (Phaal *et al.*, 2011).

Supply and demand can act as either enablers or barriers to industrial emergence, with the scale and degree of synchronisation influencing the rate at which it proceeds (Suarez and Lanzolla, 2007). On the supply side, factors affecting industrial emergence include the availability or presence of finance, facilities, enabling technologies, skills, organisation, management, business processes, partnerships and networks. On the demand side, factors include the business context, strategy and business models, together with market and sectoral factors and dynamics, such as social, economic, environmental, political and legal trends and drivers (Malerba, 2007).

3. Methodology

The dynamics of industrial emergence are investigated here through a study of the Cambridge commercial inkjet cluster. This industry was identified as an appropriate sector for study for two main reasons.

The first is that many significant commercial inkjet technologies originated in Cambridge, with Cambridge-based firms continuing to be leading technology developers that compete internationally in commercial inkjet markets.

The second basis for selection is that of the evolution of the technology. Commercial inkjet technologies are a printing technique that relies of the jetting of ink droplets from a printhead onto a substrate. To date, commercial inkjet consists of two primary technologies: continuous inkjet (CIJ) and drop-on-demand (DoD) inkjet[1]. Originating in the mid-1970s, CIJ is currently at the mature stage of the technology lifecycle with incremental technological progress and market development. In comparison, since emerging in the early 1990s, DoD technologies have yet to mature, with new applications being sought for their improved functionality. Investigating the latter's evolutionary path and the markets into which it has been applied will provide valuable insights.

3.1 Research process

Between June and September 2010, 13 interviews were conducted (Table I). All interviewees were working in commercial inkjet or related firms, and were either suggested by our first interviewee, a Director of a university research centre, or by subsequent interviewees. Each had significant experience of working in the commercial inkjet industry, with 11 interviewees having worked in the industry for in excess of ten years. It was important to interview individuals with such extensive experience so that a detailed longitudinal perspective on commercial inkjet's emergence could be captured.

Interviews were conducted using a visual mapping process that builds on the semi-structured approach of technology roadmapping (Ford *et al.*, 2011). Before their interview, each interviewee was provided with a summary overview of the mapping process, together with an example map of the type expected to be developed during the interview. The interviews were then conducted face-to-face using two interviewers, with the exception of interview number 8, at which only a single interviewer was present.

The interview process began with the interviewee establishing the scope of what they would talk, whether it was the entire history of the industry, the period over which their own company had been operating, or the development of the inkjet technology with which they were most familiar, along with the timeframe for these developments.

Interviewee	Position	Organisation
1	Director	University Research Centre
2	Former CEO	Commercial Inkjet System Technology Developer
3	Business Development Director	Industrial Inkjet Component Technology Developer
4	Technology Manager	Commercial Inkjet Printhead Developer
5	Former Chief Technology Officer	Commercial Inkjet Printhead Developer
6	Managing Director	Inkjet Consultancy
7	Business Manager	Commercial Inkjet Component Technology Developer
8	Director, Global Digital Technology	Ink Technology Developer
9	Strategic Product Director	Commercial Inkjet Technology Developer
10	Chief Technology Officer	Industrial Inkjet System Technology Developer
11	Marketing Manager	Industrial Inkjet System Technology Developer
12	Product Engineering Director	Inkjet Printed Electronics System Technology Developer
13	Managing Director	Commercial Inkjet Distributor

Table I. Interviewees

The timeframe was set as the horizontal axis for the map, with initial technology, application and market categories used for the map's vertical axis. The interviewee was then invited to provide their perspectives on the events and activities that they considered to have significantly contributed to the emergence and evolution of the commercial inkjet sector. These perspectives were captured by the interviewee on Post-it notes and placed on the map, while their verbal comments associated with the event or activity was captured by voice recorder. The interview proceeded in this fashion, with the interviewee able to use the map they were generating as a means for identifying those significant events and activities they had neglected to mention, and to move and replace the location of Post-it notes on the map.

Following the completion of the interview, the maps were converted into a digital format and the audio recording transcribed. These documents were then returned to the interviewee for verification. Four thumbnail examples of the maps generated from the interviews and their digitised formats are shown in Figure 1. Following the completion of the data collection process, the transcripts were then coded, categorised and grouped into themes (Saldaña, 2009). This allowed the authors to generate a historical narrative of the industrial emergence of commercial inkjet, an abbreviated version of which is provided in Section 4, and to identify the most importance characteristics and dynamics related to the emergence of commercial inkjet (Section 5).

4. A very brief history of commercial inkjet in Cambridge, UK[2]

Early scientific breakthroughs in the area of CIJ were made in the 1960s by Richard Sweet at the Stanford Research Institute. Sweet was not involved in the commercialisation of the science. Instead, two firms drew on his breakthroughs to develop the technology: the technology consultancy Cambridge Consultants Ltd (CCL) in the UK, and the printing firm A.B. Dick Company in Chicago, IL. These two firms were themselves the progenitors for the first two firms to commercialise inkjet technology for commercial applications: Domino, which was spun-out from the Printing Systems Group (PG) of CCL in 1978, and Videojet, which was spun-out from A.B. Dick in 1980. Both were using similar technology: single nozzle CIJ using solvent inks.

CCL's spin-out of Domino was motivated by new European legislation coming into effect in 1980 that required dates to be marked on products. At the time there were no printing technologies that could print onto fast moving, cylindrical objects. CCL PG leader, Graeme Minto saw the potential opportunity that the legislation represented and this led to the formation of Domino. This was the origin of the "coding and marking" market that provided the first significant entry point for CIJ firms.

Following the spin-out of Domino, CCL maintained an interest in inkjet printing through its PG. The technical knowledge developed by this group resulted in further new ventures based around CIJ being created by its members: Linx Printing Technologies and Elmjet. In the later 1980s, the use of multiple printheads in inkjet printers opened up another market in billing and addressing, and led to development of array CIJ (also known as binary inkjet).

Xaar was the next spin-out from CCL in 1990. In contrast to the earlier spin-outs on CIJ, Xaar was developing a different technology: piezoelectric DoD printheads. The first piezoelectric DoD printhead patents had been filed in the late 1970s by Kyser and Sears at Silonics but they had not been able to develop the technology to commercial viability. It was not until Xaar and competitor Spectra began to produce more robust printheads that applications for the DoD printheads began to grow. In the years immediately following its spin-out, Xaar pursued a licensing strategy, with early

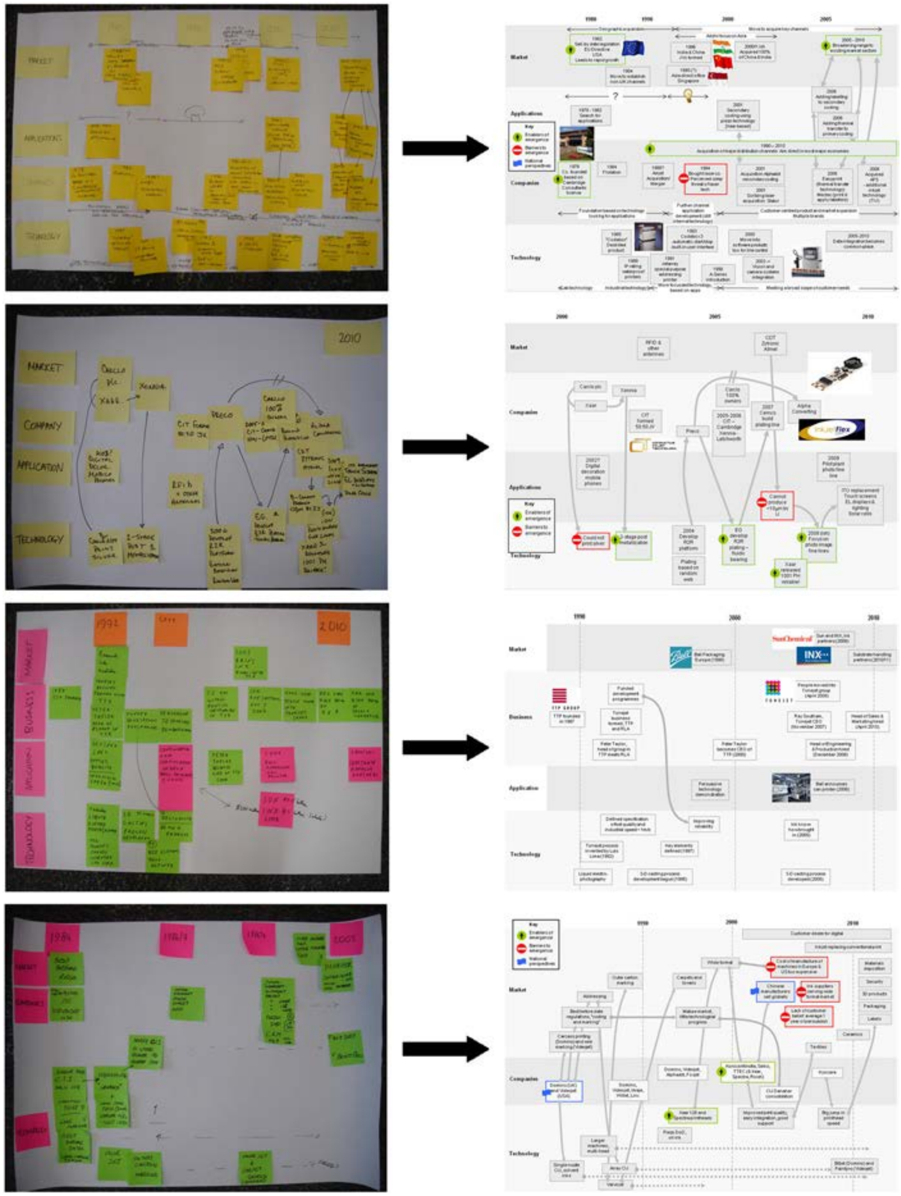

Figure 1.
Maps generated during interviews (left) and post-interview digitised version (right)

licensees including Toshiba Tec, Minolta, Seiko Instruments and IBM. Many of these licensees have since contributed to the further development of the DoD technology. Improvements in DoD printhead reliability and print quality have led to a number of new application markets. In 2000, another spin-out from CCL, Inca Digital, was formed to address one of these, the wide format print market. Other markets that are beginning to be addressed include transactional and promotional materials ("transpromo"), labels, ceramics and textiles, along with more exotic applications in 3D printing.

5. Supply-demand dynamics in the industrial emergence of commercial inkjet printing

From our present vantage point in time, two broad technological trajectories based around CIJ and DoD can be identified. While the former has now reached maturity and is seeing only minor incremental improvements to the technology and the markets to which it is being applied, the trajectory of DoD technology is itself splintering as firms begin to address a number of new market applications where specific technological approaches are required

At the heart of commercial inkjet printing's industrial emergence there has been a tension between the capabilities of the new technologies and the willingness of customers to adopt these technologies. A further tension exists between the development of the different components of the inkjet printing system, primarily the printheads and the ink, with the failure to match these effectively creating significant impediments to successful commercialisation. In this section, we draw on the data collected from the practitioner interviews to investigate these co-evolutionary supply-demand dynamics that have driven industrial emergence in commercial inkjet.

5.1 Relative advantage of inkjet technologies

For particular applications, commercial inkjet products offer a number of advantages over traditional printing techniques such as screen, offset and silk printing. These advantages include increased flexibility, cost effectiveness and versatility, along with the non-contact nature of the print process.

Inkjet printing provides much greater flexibility, allowing variable data to be printed and short runs to be produced. The ability of variable data to be printed allows versioning and can be used to produce almost infinite variety in decorative applications. The capacity to produce short runs allows highly customised printing. The flexibility of inkjet often provides cost advantages over other printing methods. For example, CIJ is used in applications such as direct mailing because it is more cost effective than laser printing.

As a non-contact printing process, inkjet technology is particularly important in applications where the substrate is uneven or brittle and liable to fracture. For example, in the ceramic tile market, challenges such as edges and uneven substrates give inkjet advantages over conventional printing. One method of solar panel printing involves printing onto very thin silicon, a substrate too delicate for contact printing. In addition, inkjet also offers advantages over traditional printing because it has a smaller physical footprint, produces less wastage due to customisation and more mature inkjet systems require less skilled operators.

5.2 Printhead development

The development of printheads for CIJ and DoD have followed similar technological trajectories as they have each needed to provide the necessary speed and print quality demanded by customers, along with satisfying issues of reliability, robustness and ease of operation. For the sake of brevity, only the development of DoD printheads is considered here.

The development of piezoelectric printheads can be traced to the work of Kyser and Sears at Silonics in the 1970s, with the first patent being granted in 1976. However, Silonics was unable to commercialise the technology and it was another decade before further market advances were made. It was at CCL in 1987 that David Paton and Steve Temple started work on a new venture based on a DoD technology. Paton and Temple

had been thinking about DoD since the early 1980s as a way to gain higher resolution prints and led the spin out of Xaar from CCL in 1990. Upon launch, Xaar's business model was to license both ink and printhead technology to a wide range of licensees. The main target market for Xaar's technology was to replace applications served by thermal inkjet (TIJ). Xaar's offering was not just the generic printhead design, but also their "wafer scale manufacture" process, offering a low cost and low-risk manufacturing methodology for their customers. The process and printheads could then be customised by customers for their own use. Licensees included Toshiba Tec, Minolta (Konica Minolta), Seiko Instruments and IBM.

The first piezoelectric DoD printheads of the early 1990s had reliability issues and were prone to ink blockages. However, customers valued the functionality delivered by the printheads and were willing to tolerate these setbacks. Over the following years, the printheads became more sophisticated, being able to deliver smaller inkdrop volumes with a higher nozzle density, so providing a faster and more cost-effective printing process. Importantly, they have also become more robust and reliable. It took several years for this to be achieved because the firms involved in the development activity, Xaar and Spectra (its main competitor), were small enterprises. The pace of progress was limited as a result of most of the printhead development being done by these small firms, along with the absence of accessible markets. It was only when printhead manufacturers started to generate revenues from licensing and ink sales were they able to generate the funds necessary for reinvestment in development activity. However, in 1995, Xaar recognised that its licensing business model was unsustainable; its licensee market was becoming saturated and the target market of TIJ was proving difficult to access as DoD was too expensive. This prompted Xaar to move into the manufacturing itself, a move supported when it bought back its license from IBM in 1999 and also acquired IBM's Swedish manufacturing facilities.

From the mid 1990s, the availability of a reliable source of robust piezoelectric printheads using solvent and UV curable inks from Xaar and Spectra allowed OEMs to innovate and develop new products. The performance of these printheads allowed entry into the wide format and flatbed graphics markets. Entering these markets once again tested printhead reliability. The development of wider printheads was limited by the need to trade-off technical and economic considerations; wider printheads have a greater probability of manufacturing defects and are also more likely to become blocked during operation. Concurrently, customer demands for improved print quality led to the development of greyscale technology. Using this technology allowed different droplet sizes to be jetted and provided a significant advance in the apparent resolution of DoD from 360dpi to over 1,000dpi.

Improving the reliability of printheads to increase customer confidence in the technology and to allow the application of DoD to new markets has been a constant process. To overcome problems with system reliability and improve the performance of DoD technology, a number of firms, including Xaar, Dimatix, Epson, HP and Xennia, have developed recirculating ink systems. Released in 2007, the Xaar 1001 printhead is another significant milestone in the development of DoD printheads because its use of a recirculating ink system made it the first reliable printhead for roll-to-roll (R2R) technology. This can provide customers with significant increases in the speed and cost effectiveness of DoD print systems.

Improvements in print quality have continued, with developers increasing the nozzle density on the printhead, further increasing print speeds. Many of these

technical advances have been led by East Asian firms, including many of the firms to whom Xaar had licensed its technology in the early 1990s.

5.3 Ink development

The parallel development of inks is an important part of the commercial inkjet development story. One of the reasons for inkjet's versatility is its ability to use a wider range of ink types than traditional printing and the development of new inks has allowed inkjet printing onto new substrates and for new markets to be entered. Some examples include:

- In the 1990s it became possible for R2R inkjet printers to use aqueous inks, creating a new wide format market for indoor posters. This wide format aqueous market spawned the textile market.
- Solvent inks allowed wide format and grand format printing of 2-3 m on vinyl substrates. These solvent inks allowed large-scale outdoor applications without any stitching of images.
- The development of UV curable inks by Sericol and SunChemical enabled the growth of wide format, including point of sale and signage. These inks improve system reliability, particularly for single-pass inkjet printers, because UV curing post-print prevents printhead blockages and improves reliability. Their application in the flatbed printer market also made it possible to print onto rigid substrates.
- Most recently, novel inks have been developed for functional inkjet applications. One example is nanosilver ink, which is used to print conductive tracks.

The pace of printhead and ink development has not always operated in tandem, with the quality of inks often lagging behind the quality of the printheads. This lag arises because the printhead and ink must be matched for particular applications and substrates, with some types of printheads limited to using certain types of inks. Each ink requires its own formulation and customisation of the ink to the printhead is expensive. For emerging inkjet applications, the initial volumes of ink required are low and the pace of growth is uncertain. As a result, the large ink suppliers have limited interest in these specific inks. Instead, they prefer to sell into markets that are already established, such as the traditional print markets. As a result, printhead developer firms have often needed to develop their own inks or establish standards for inks (e.g. Xaar developed an "open ink model") that specialist ink firms can produce to specification, before the market is proven and the larger ink suppliers are attracted.

5.4 Print systems development

When a range of reliable printheads from technology suppliers became more widely available it meant that development costs were no longer as significant a barrier to developing an inkjet system. These more reliable printheads also stimulated developments in the mechanical operation of printers, with "singlepass" printers starting to be seen in the early 2000s. The earlier generation of DoD printers had been "scanning" printers, in which the printhead moved across the substrate. In contrast, in single-pass printers the printheads remained fixed in position, providing benefits for the print throughput. The first single-pass printers were demonstrated at Drupa 2004, an international print fair, but it was another six years before there was widespread industry acceptance of the reliability of the process. For applications using flexible

substrates, there have been similar transitions from flatbed to R2R, aided by the development of recirculating ink systems.

Underlying these advances there have been a number of persistent technical barriers, with a longstanding lack of understanding of the basic science of inks (e.g. reduction or elimination of micro-satellite formation during jetting) and the complexity of ink management systems (e.g. aqueous inks for transpromo). These are problems that lead to nozzle failure and reliability issues. To address these challenges, the Inkjet Research Centre at the Cambridge University Engineering Department was established in 2005 to investigate the basic science of inkjet, co-funded by a consortium of Cambridge area firms and the UK's Engineering and Physical Sciences Research Council.

A number of complementary developments outside the industry have also affected its emergence. A persistent barrier to the development of new inkjet technology has been the development and integration of complementary technologies and peripherals. High-speed printing requires a high-speed datapath and places demands on software and electronics, with advances in these often lagging behind the progress of mechanical functionality. Inadequate processing power for page array printing in the mid-1980s was a limitation on progress until the development of parallel processors. It was only when this development was made that colour print processing became possible. Around the same time, MEMS advances were necessary before printheads could be manufactured at a sufficiently small scale.

5.5 Market demand

Within emerging markets there is significant uncertainty because the fundamental strategic ground rules have yet to be established (Macdonald, 1985). The success of firms entering such a market is based not only on the initial market and technological conditions (Windrum and Birchenhall, 1998) but also on their timing of entry with regard to the synchronisation between the pace of technical and market evolution (Suarez and Lanzolla, 2007). In the same manner as many environmental technologies and advanced materials, DoD inkjet firms have faced the challenge of selling into markets that are already being served, in this case by screen, offset and silk printing.

In a number of cases, demand for commercial inkjet initially came from customers desiring specialist products. For example, it was interest from the Chief Operating Officer of a contact lens packaging manufacturer that kick-started the CCL project to develop a wide format print system and which led to the subsequent spin-out of Inca Digital. These lead customers provided the resources to fund development work, allowing firms to accumulate inkjet expertise. The inkjet technologies had functionality that traditional printing did not possess; customers valued this functionality and were prepared to accept less reliable products as development was ongoing.

In established industries where technical change is slow and investments are long-customers prefer to work with those suppliers with whom they have existing relationships. For inkjet firms attempting to sell into these markets, there have been a number of challenges when selling their products, the majority of these being associated with customer conservatism.

Foremost among these has been a lack of customer belief in the reliability of the technology. Customers do not want to take on what for them is a disruptive technology until they can see that it works. For inkjet firms it has been difficult to prove the system's robustness and reliability at volume until a customer has adopted it. This vicious circle proved a barrier for business development. For example, in the mid-1990s, it was not until both Xaar and competitor Spectra had developed more

robust DoD printheads that customers were convinced of printhead reliability. This arose because their customers, print system integrators, wanted the insurance of a reliable second source of printheads should the performance of one firm's product prove to be deficient. Meanwhile, when Inca Digital first began to sell its wide format print systems in 2000, adoption was slow. However, once a customer in particular region had bought a machine, further orders from the same region followed shortly afterwards.

Significant persuasion is necessary to convince customers in these industries that they should switch from conventional printing technologies. Such customers need to see multiple demonstrations of the technology as it is developed before they are reassured of its capabilities and reliability. There is further discussion of demonstrators in Section 6.2.

Barriers to inkjet adoption also derive from the perceptions of inkjet technology. These perceptions are coloured by the reliability issues experienced by early industrial inkjet printers and the knowledge of the low throughput of desktop inkjet printers. In some cases when customers have seen the potential of inkjet technology they have attempted to develop the technology in-house and failed. Their failures have in turn contributed to wider perceptions of the reliability of inkjet. In other cases, customers have placed too many demands on the specification of their equipment. In attempting to satisfy these demands, inkjet firms have tried to extract maximum performance from the technology and the resulting technology has not been fit for purpose.

The adoption of inkjet also raises issues about how the customer captures value. Although one of the main benefits of inkjet is the ability to produce short runs, to take advantage of this benefit the customer may need to change their business model. An inability to make this change can lead to the suboptimal use of the inkjet printing system. Furthermore, the structure of the value chain means that the customer's acquisition of an inkjet system may not lead to them directly benefiting financially. For example, in textile printing, it is the textile printers that need to make the investment in inkjet equipment. However, the savings from flexible short runs and reduced inventories are realised elsewhere in the value chain.

6. Discussion

In looking to explain how supply and demand interacts during industrial emergence it is apparent that there are a number of feedbacks at work that have both driven and hindered the industry's emergence. The first of these feedbacks can be seen on the supply-side. As noted in Section 5.2, inks must be customised for the inkjet printhead and industrial ink suppliers. Before they developed these customised inks, the industrial ink suppliers needed to be convinced that the inkjet market was going to grow to a profitable size. Feedbacks can be observed between the print systems and customers, with the relative advantages of commercial inkjet technologies providing a customer pull. Prior investments in traditional print systems and customer hesitation due to a lack of understanding and a lack of belief in the technology, and negative prior experiences, have slowed the adoption of inkjet technologies and the growth of the industry. These feedbacks are depicted in Figure 2.

Supply and demand have not operated perfectly in tandem as there have been significant asynchronies. While niche markets provided initial customers for inkjet technologies, it took significant development time for these niches to be served. Then as the technology became more mature it took time to convince new customers in other markets of the merits of inkjet technology. As part of the co-evolutionary process, these

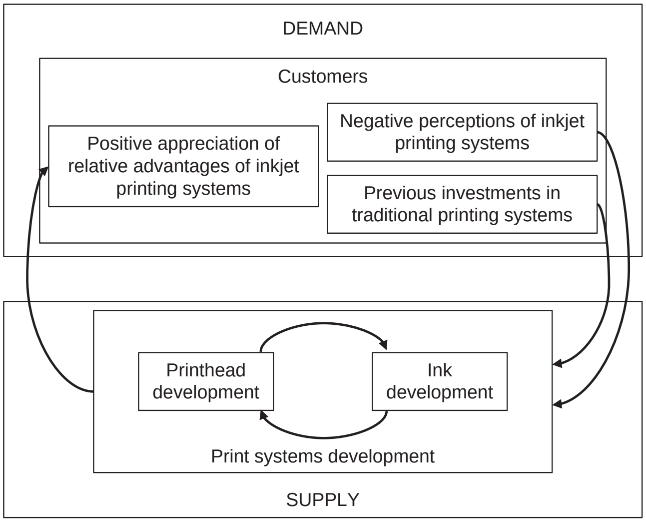

Figure 2.
Feedbacks between supply and demand in the industrial emergence of commercial inkjet

asynchronies are not unexpected. To examine how they have been resolved it is necessary to reflect on how supply and demand interact through the efforts of entrepreneurial ventures bringing the technologies to customers, and the demonstration of the relative advantages and reliable functionality of the technologies.

6.1 Entrepreneurial agency

The emergence of commercial inkjet in Cambridge has been characterised by a high degree of entrepreneurial activity, with a large number of these new ventures being spin-outs from CCL. Graeme Minto (Domino), Mike Keeling (Linx), Graham Martin, Colin Gray and Will Eve (Elmjet), David Paton, Mark Shepherd, Mike Willis and Steve Temple (Xaar) and Bill Baxter and Will Eve (Inca Digital) are among those that have led spin-outs from the PG at CCL, leading to the development and commercialisation of the technology in ways that was not possible within CCL.

As the performance of DoD printheads has improved, other entrepreneurs have recognised their capabilities and potential application to new markets. Such markets include transpromo, textiles and ceramics, along with functional applications such as conductive inkjet. Xennia, itself a spin-out from Domino, has targeted the textiles and ceramics markets, while Conductive Inkjet Technology (CIT), which began its existence as a joint venture between Xennia and technical plastics firm Carclo, produces print systems for electronic circuit manufacturing. Each of these firms has been able to make significant advances through applying the recirculating ink printhead technology.

As the sector has grown, there has been need for specialist support technologies, with numerous other ventures have also been created by entrepreneurs. These include industrial inkjet, which was formed by a former Xaar employee, John Corrall, in 2003 in response to demand for integrated system support, and Global Inkjet Systems, which was founded in 2006 to provide software and drive electronics solutions to the industrial inkjet market. These new ventures have been created to capture value that other organisations either cannot achieve or which is on a scale that is unattractive.

At the inception of new markets it can prove very difficult for new ventures to access venture capital. Along with the market unfamiliarity, venture capitalists traditionally

prefer to fund ventures as close to revenue generation and profitability as possible. To overcome this difficulty, CCL used consultancy projects to support technical development prior to the spin-outs of Xaar and Inca Digital. This approach was also used by another technology consultancy, TTP, at which a different inkjet technology, Tonejet, has been developed. At both CCL and TTP, client networks have been exploited to fund technical progress, with this "soft start-up" model a low cost-low risk means for advances to be made (Connell, 2004). However, the specifications of these projects are subject to the requirements of the customer and can lead to the firm following the source of funding more than is desirable, slowing the pace of development.

The emergence of commercial inkjet has been characterised by entrepreneurial ventures recognising when selection conditions have been unfavourable and adopting alternative strategies. Xaar did so when it transformed its business model from that of a licensing-based firm to a manufacturing-based firm. For Inca Digital, the initial target market was the packaging industry. However, they soon realised that there were many costly regulatory and quality issues that needed to be addressed to successfully enter this market. After exhibiting at the IPEX printing conference in 1998, they found that there was greater interest for their technology from the sign and display industry and so adapted their strategy prior to spin-out. Similarly, the target markets for CIT have shifted from printing metallic decoration on mobile phone cases, to radio frequency identification tags and mobile phone antennas, to capacitive touch screens. As a consequence of these adaptations to firms' strategies, the opportunities for other agents change, bringing about the continuous shaping of the selection environment, which in turn affects future variety.

6.2 Reduction of uncertainty through demonstration

As the variety and number of events related to scientific and technological development decreases over time as technologies and products are subject to selection processes, so too does technological and market uncertainty (Meijer *et al.*, 2007; Tikkanen, 2008). Demonstrators have been central to the reduction of technological and market uncertainty during the emergence of the DoD inkjet industry. Drawing on the demonstration classification of Phaal *et al.* (2011), seven distinct types of demonstrator can be identified as being used during the industry's emergence. Table II describes these demonstrators, with examples from DoD and wide format graphics.

Along with the development of the type of demonstrator through time, the focus of demonstration changes; from internal demonstration for securing funding to support further development and commercialisation, to external demonstration to convince potential customers and distributors of the value of the products. During this external demonstration, the sequence of demonstration generally progresses in order of product maturity, from events to in-house demonstration to customer site demonstration.

In Europe, Drupa and IPEX are the largest print trade shows, with each held every four years. These shows provide firms with the opportunity to demonstrate their prototypes and products to customers, distributors and competitors. Based on their target markets, firms also elect to showcase their technologies at market-specific trade shows. For instance, as Xennia has been attempting to enter the tile market it has demonstrated its products at Tecnargilla, the premier trade show for the ceramics and brick industry.

Getting partners to demonstrate products has also played a role in commercialisation. When Inca Digital launched its first machine, the Eagle 44, it distribution partner, Sericol, brought customers to Inca Digital to see the machine in operation. The customer's

Type of demonstrator	Description (Phaal *et al.*, 2011, pp. 223-224)	Examples
Supporting science and technology demonstrators	Demonstration of fundamental new scientific knowledge or generic platform technology, normally via experiment and/or simulation	Lord Rayleigh demonstrates the deflection of electrostatically charged ink in a magnetic field (1878)
Applied science and technology (feasibility) demonstrators	Demonstration of the feasibility that the underpinning scientific or generic technology has practical potential within a market-directed application domain, normally via proof-of-concept experiments	First piezoelectric printhead was produced in the 1970 s by Kyser and Sears at Silonics. Patented in 1976
Technology demonstrators	Creation of prototypes demonstrating that the technology is sufficiently robust to be integrated into functional systems	CCL collaboration with AMI to develop prototype DoD printhead
Application demonstrators	Demonstration of the potential functional benefits of a system under non-laboratory conditions	CCL wide format demonstrator model built with Xaar printheads for IPEX 1998
Commercial application demonstrators	Creation of a sustainable business venture with market growth potential	Spin-outs of Xaar and Inca Digital from CCL for DoD printheads and wide format inkjet markets, respectively
Price-performance market demonstrators	Demonstrate the feasibility of a mass market, in terms of price and performance	Xaar's first product, the XJ500 for narrow format printing. Inca Digital's first product, the Eagle 44
Mass market demonstrators	Demonstration of substantial industry, market and business growth	Xaar's first single-pass printhead, the Xaar 1001, released in 2005

Table II.
Demonstrators during the emergence of DoD inkjet

desire to own the machine increased once they had seen it in operation. Reputation and legitimacy also play their part in customer acceptance of the products (Low and Abrahamson, 1997). When Inca Digital secured a first customer in a particular region, other sales soon followed as that first customer's competitors recognised the need to also adopt the new technology. Legitimacy has also been aided by competition. In the mid-1990s, Xaar's printhead sales improved when alternative sources of printheads produced by their competitors became available. Through its licensing model, Xaar had created these competitors, which in turn helped develop the market for DoD printheads.

Reducing uncertainty has also been achieved through the leadership of firms within the industry. When in 2001 it was realised that ink development lagged behind that of printhead development, Xaar established an "open ink model", a standard specification for the composition of the inks necessary for operation with Xaar printheads. While this ink model reduced the variety of inks within the inkjet market, it improved the overall quality of DoD printing and ensured the compatibility of inkjet print systems.

7. Conclusions

This paper has investigated the emergence of new industrial activity around commercial inkjet printing. While there was a clear market pull for CIJ in the form of legislation, in contrast, DoD has been a technology searching for applications. The interaction of supply and demand has seen a combination of customer interest and technology potential provide the stimulus for the development of DoD inkjet for

particular applications. However, there have been asynchronies between the supply of reliable and robust print systems and the demand for these products. These asynchronies have arisen for a variety of reasons, including customer conservatism and prior customer investments in incumbent products.

The initial organisational conditions from which DoD inkjet emerged were significant in shaping its later industrial development. CCL incubated the technology, supporting its development through project-based funding, before spinning-out the new venture, Xaar. As a new venture with limited financial resources, Xaar was constrained by how quickly it could develop its printhead technology, with the relatively slow emergence of the DoD industry mirroring this. From these initial system conditions, supply and demand have asynchronously interacted in such a way that industrial growth has occurred. It has previously been identified that market forces, such as profitability (Porter, 1985), consumer preferences and regulatory rules, investment and imitation (Nelson and Winter, 1975), along with costs and prices (Dosi, 1997), combine to create the selection environment. These asynchronies have created opportunities for entrepreneurial activity, which has been realised by those entrepreneurial agents that have been able to adapt to and shape the selection environment.

Demonstrators play a significant role at the intersection of supply and demand, and have been central to convincing customers of the value and performance attributes of the technology and its applications. As a consequence, the emergence of demonstrators reduce technological and market uncertainty. Furthermore, although industrial emergence is not linear, a basic sequential pattern of demonstrator types is apparent at each phase of emergence as technical advances are made and customers' preferences for a specific application are better articulated and understood. There is scope for further detailed research into the role of internal and external demonstrators during industrial emergence.

This study highlights the view of market activity as comprising intersecting industrial ecosystems. Within the DoD inkjet industry there are several distinct industrial ecosystems, comprising a set of different type of firms (printhead developers, product integrators, ink developers), each serving a particular market (e.g. wide format, ceramics, textiles). Not only do these ecosystems intersect with each other but they also intersect with the industry they are attempting to displace, the traditional print industry. As they were already serving these incumbent markets, ink developers have needed to be convinced of the attractiveness of the inkjet technology and future growth of the industry, just as customers have later needed to be. This need to stimulate the development of complementary technologies highlights the platform leadership (Gawer and Cusumano, 2002) that has been necessary on the part of printhead developers.

A final comment relates to the bounding of this study to the Cambridge inkjet cluster. Extending the geographic scope in future studies to include developments made by Xaar's Japanese licensees and competitor Spectra, could provide better insights into where value is created and captured during industrial emergence, along with providing an improved understanding of the roles of knowledge flows and social mobility.

Notes

1. For more detailed descriptions of these inkjet technologies and their applications see Hudd (2009) and Martin and Hutchings (2013).
2. Another account of the emergence of commercial inkjet can be found in Garnsey *et al.* (2010).

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