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Technology strategies in converging technology systems: Evidence from printed electronics

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Abstract

Novel technology systems, such as "fiber optics" and "printed electronics," increasingly emerge at the interface of hitherto unrelated technology areas. As such, new technology systems often arise through technology convergence, characterized by integrating technology components and knowledge from different technology systems, resulting in a novel system architecture. This phenomenon is of utmost societal relevancy but simultaneously poses tremendous challenges for firms' technology strategies. Firms must not only cope with unrelated knowledge rooted in hitherto different technologies but also have to decide deliberately how systemic (i.e., complete technology system) versus focused (i.e., single component of the technology system) their engagement in technology development in the converging technology system ought to be. In addition, firms need to decide strategically to what extent to develop specialized or design knowledge. Extant concepts of technology strategy fall short of capturing this complexity inherent in converging technology systems. Therefore, to address how technology strategies co-evolve along with the emergence of new technology systems, this study adds a systems perspective to technology strategy by developing the concept of *technology system coverage*. This novel dimension of technology strategy is formed by the scope (i.e., focused vs. systemic coverage of the technology system) and type of technological knowledge (i.e., specialized or design knowledge). We empirically apply this novel angle of technology strategy to the convergence field of printed electronics. Based on a longitudinal set of 828 patents over 30 years, 74 relevant corporate actors are identified. The underlying taxonomy enables us to reveal four technology strategies and develop five propositions. The results indicate that all firms build design knowledge over time, whereas not all firms build specialized knowledge, no matter what technology strategy is pursued. In sum, this work advances literature by understanding technology strategy in emerging complex technology systems, introducing a systems perspective.

KEYWORDS
complex technology system, technology convergence, technology strategy, technology system coverage

1 | INTRODUCTION

Technology convergence, which builds on the integration of hitherto distant technology systems, presents an increasingly pertinent phenomenon that has huge potential to trigger novel technology-based solutions with strong societal relevancy (Bröring & Leker, 2007; Choi & Valikangas, 2001; Curran et al., 2010; Curran & Leker, 2011; Hacklin, 2008). We are currently witnessing different examples of technology convergence, such as synthetic biology, "nanobioinfotech," or fiber optics, which all emerge at the interface of formerly unrelated technology systems (Kim et al., 2019a; Klarin et al., 2023; Kodama, 1992; Maine et al., 2014; Shmulewitz et al., 2006; Sick & Bröring, 2022). Generally speaking, a technology system consists of different components and an underlying architectural design that links involved components (Henderson & Clark, 1990). In line with prior research, we argue that a converging technology system integrates not only different and formerly unrelated components but also forms a novel architectural design (Henderson & Clark, 1990; Jaspers et al., 2012; Metcalfe, 1995; Staudenmayer et al., 2005).

All the aforementioned examples of technology convergence are built on cross-sectoral research and development (R&D) activities and involve a novel inter-industry architectural design that implicates a co-evolution of components to ensure interoperability with the overall converging technology system (Jaspers et al., 2012). Fiber optics, for example, which presents a well-understood case of a converging technology system, emerges from the fusion of distinct technology systems and thus integrates components stemming from glass, cable, and electronics technologies converging into a novel architectural design (Kodama, 1992). More precisely, this implies that components originating from the technology system of materials, such as flexible glass systems, are merged with those stemming from the field of electronics, such as cable systems. Together, these are forming the novel converging technology system of fiber electronics (Kodama, 1992).

Technology convergences come with inherent complexities, uncertainties, and dynamics, which present firms with significant challenges. Complexity is of structural nature, as converging technology systems are requiring firms to combine knowledge of fundamentally different technological fields, including a multitude of different and novel interfaces (Kapoor & Furr, 2015). In addition, firms are confronted with uncertainties stemming from unknown specifications, lacking industry standards, and time frames (Rotolo et al., 2015; Suárez & Utterback, 1995). Finally, the emergence of converging technology systems is an inherently dynamic phenomenon, which evolves as a highly decentralized process with newly developing components and dominant designs, new actors and network structures, and finally, changing interdependencies

Practitioner points

- Technology convergences create complex technology systems that emerge through recombining and integrating components from previously unrelated technology areas. It is crucial for managers to recognize that these complex technology systems present new challenges impacting their technology strategy.
- Engaging in the development of technology convergence presents managers with the dilemma of whether to prioritize individual components or adopt a comprehensive approach addressing the entire technology system. Accordingly, they need to determine the knowledge base (i.e., degree of design knowledge) to invest in, and establish mechanisms for dynamic adjustment throughout the technology development.
- Another important insight for managers is that all companies that initially engaged in specialized knowledge components have been observed to accumulate design knowledge over time. Thus, our findings emphasize the significance of design knowledge as a facilitator in understanding the interdependencies between components, enabling sustained participation, and potentially allowing for the orchestration of development.
- This study introduces the concept of technology system coverage and its dynamics as a relevant dimension of the technology strategy. It can assist managers in navigating the increasingly complex and uncertain environment surrounding converging technology systems effectively.

between different components (Cho et al., 2015; Staudenmayer et al., 2005; Sukri & Yusoff, 2019).

We argue that the context of converging technology systems poses tremendous challenges for firms seeking to develop technology strategies to position themselves in these emerging yet, often fast-growing sectors. However, it remains unclear how firms shape their technology strategies to approach such an emerging, complex technology system. Especially the scope of the knowledge that firms develop regarding the emerging technology system over time presents a space to uncover. It remains a central strategic question whether firms should focus on their potentially existing position reflected by component knowledge or aim at a broader approach, potentially covering the entire system.

Extant literature so far neglects this systems perspective but rather conceptualizes technology strategy as a plan guiding the development of technological capabilities and knowledge along the classic lines of "timing of entry," "R&D portfolio," or "IP strategy" (Bayus & Agarwal, 2007; Ford, 1988; Schilling & Hill, 1998; Zahra, 1996). However, these concepts fall short of reflecting the particularities of evolving technology systems, for example, how firms can maneuver such a complex system of different components and architectures with changing interfaces (Henderson & Clark, 1990). Moreover, the question arises of how technology strategies can co-evolve with, and adapt to, the dynamics of a converging technology system. As such, to our best knowledge, literature has not dealt with the question of how firms' technology strategies evolve with regard to building relevant knowledge in parallel to the emergence of a new converging technology system. This is striking since the context of complex technology systems triggered by the integration of different technologies seems to be highly relevant beyond the setting of convergence (Jaspers et al., 2012). Especially the idea of digital technology systems, where value creation only materializes if interfaces are well-defined and system designs are understood (Yoo et al., 2012), underscores the need for exploring technology strategy in complex technology systems.

To advance theorizing on technology strategies, this study offers a systems perspective on technology strategy development. The paper, therefore, relates well-established technology strategy approaches (Ford, 1988; Zahra, 1996) to the concept of technology systems and their underlying architectural design (Baldwin et al., 2014; Henderson & Clark, 1990; Metcalfe, 1995) in the topical context of converging technology systems (Kim, Jung, & Hwang, 2019). Drawing on the seminal concepts of architectural innovation (Henderson & Clark, 1990) and systemic innovation (Chesbrough & Teece, 2002), we, thus, develop a novel dimension to technology strategy that considers the systems perspective. In recognizing the different components of a technology system, which stem from different hitherto distinct technology systems and are integrated based on a novel systems architecture, we introduce the concept of *technology system coverage* (TSC). This novel dimension enables deciphering not only the *scope* of a technology strategy but also the *type* of knowledge development pursued. From a knowledge type perspective, firms may target components rich in design knowledge, or focus on specialized components, which require less systems understanding (Baldwin et al., 2014).

Against this backdrop, this paper follows an exploratory theory-building approach (Strauss, 1987) and builds on a longitudinal study on firm-level data, using a comprehensive patent data sample reflecting the converging technology system of printed electronics. Based on a set of 828 patent families comprising a period of 30 years, 74 relevant corporate actors are identified. By seeking to extend our understanding of technology strategy in the context of converging technology systems, this study offers two main contributions to the technology and innovation management literature.

First, by drawing on the literature of inter-industry architectural innovations (Jaspers et al., 2012), more particularly on the complex design of converging technology systems (Baldwin et al., 2014) and the related technological knowledge base (Fleming, 2001; Henderson & Clark, 1990; Yayavaram et al., 2018), we introduce technology systems coverage as a novel dimension of technology strategy. In doing so, we develop an understanding of technology strategies that firms employ to respond to the uncertainties posed by converging technology systems. We explore how firms encounter converging technology systems based on how comprehensively they cover the different technological knowledge bases—that is, the scope of their technological engagement. Moreover, in distinguishing different types of knowledge along their degree of embeddedness in specialized versus design knowledge (Henderson & Clark, 1990; Yayavaram et al., 2018), technology systems coverage adds to the extant conceptualization of technology strategy.

Our second contribution is related to understanding the dynamics of firms' co-evolution with the converging technology system. As we observe technology strategies over the technology life cycle (Ernst, 1997), we are able to empirically identify different development patterns. Thus, our research integrates a dynamic perspective to technology strategy, accounting for the dynamics inherent in evolving technology systems.

By rendering a novel theoretical construct, TSC, and its empirical application to the convergence setting of printed electronics, we offer a taxonomy of technology strategies that enable managers to reflect upon and deliberately configure their technology strategy and related investments in either specialized and/or design knowledge. This seems particularly relevant for contexts of inter-industry architectural innovation (Jaspers et al., 2012), such as technology convergence (Kodama, 1992). But it is also relevant for any field characterized by rapid technological progress that leads to the emergence of complex technology systems (Baldwin et al., 2014). Hence, our taxonomy also informs managers confronted with the emergence of complex technology systems arising from any inter-industry joint value creation, where different actors form novel but complex value propositions (Talmar et al., 2020) emerging from the integration of hitherto distant fields of technological knowledge (Fleming, 2001).

1.1 | Converging technology systems and the related knowledge base

Firms are facing increasingly complex technological environments, which require them to advance their technological knowledge base (Wang & Von Tunzelmann, 2000). This holds especially true in the context of technology convergence, triggering the emergence of novel technology systems (Hacklin et al., 2013). Technology systems, as such, are complex (Baldwin et al., 2014) and comprise a nested hierarchy of design elements (Clark, 1985; Marples, 1961), encompassing a set of different components and an architectural design that defines "the way in which the components [...] are linked together" (Henderson & Clark, 1990, p. 10). As illustrated in Figure 1, all converging technology systems share the peculiarity that their technology components, as well as their architectural design, stem from formerly unrelated technology systems (Giachetti & Dagnino, 2017; Jaspers et al., 2012). This involves the (re-) definition as well as the recombination of different components stemming from any of the incumbent systems and their integration through a new inter-industry architectural design (Baldwin & Clark, 2000; Jaspers et al., 2012). Thus, converging technology systems are characterized by increased levels of uncertainty and ambiguity (Rotolo et al., 2015) as a dominant design only gradually emerges (Suárez & Utterback, 1995).

The knowledge base behind any component of a technology system may exhibit different characteristics relative to the type of knowledge required. In particular, we can distinguish between specialized and design knowledge. Some technology components are richer in design knowledge and, thus, contribute directly to the entire system architecture and their interdependencies. Other components are more specific and need to adjust to the overall system architecture and their interdependencies (Baldwin et al., 2014). In the case of fiber optics, for example, the coating of the cable is rather peripherical knowledge (more specialized and less design knowledge), whereas the glass fibers and their composition in the cable is a component rich in design knowledge defining the overall cable architecture.

Following Baldwin et al. (2014), we argue that all components need to incorporate a limited level of design knowledge to ensure systems fit. However, the level of embedded design knowledge may vary significantly in depth. Consequently, we conceptualize technology system as consisting of components that are rather specialized (involve a higher degree of specialized knowledge and limited design knowledge) and those that are rich in

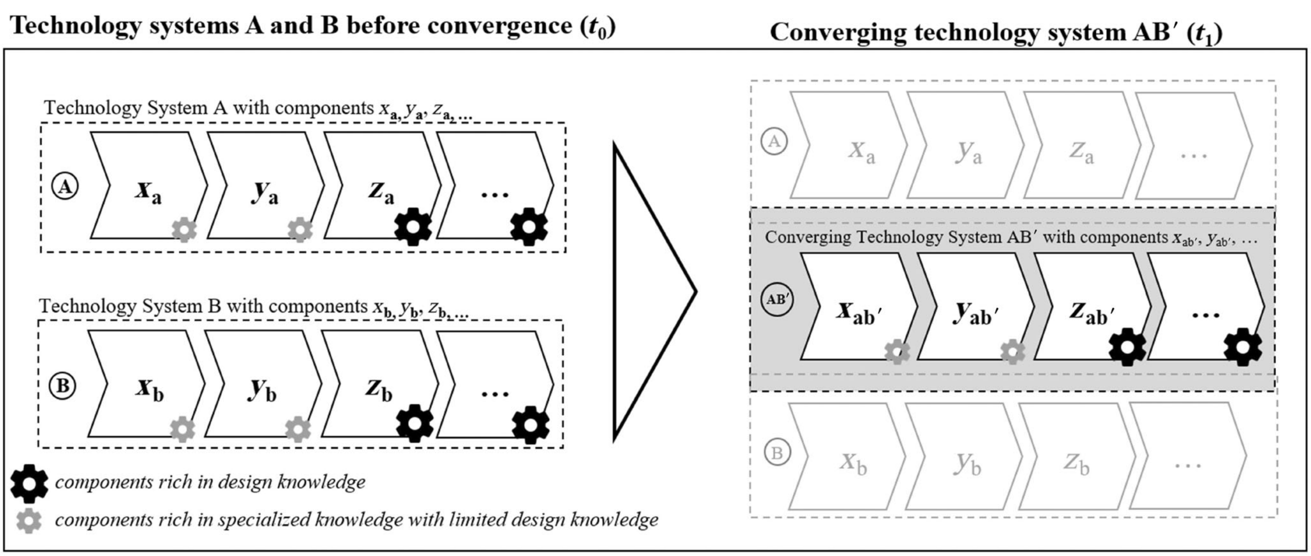

FIGURE 1 The emergence of a converging technology system consisting of components with different knowledge stocks.

design knowledge (compare Figure 1) with a higher impact on the overall systems architecture.

1.2 | Technology strategy in the context of converging technology systems

In a setting of technology convergence, firms need to build the underlying knowledge base to be able to develop a position in the novel technology system (Hacklin et al., 2013). This requires firms to adjust their technology strategy to an evolving competitive environment (Hacklin et al., 2013). More specifically, this includes decisions to align extant competencies with the dynamic technology environment (Sukri & Yusoff, 2019; Zahra & Bogner, 2000). Technology strategy, in its generic sense, encompasses plans and management decisions on resource allocation for the development, maintenance, and use of technology capabilities (Friar & Horwitch, 1985; Zahra, 1996). Ideally, a deliberate technology strategy allows to develop and nurture those technologies that will be crucial for the long-run competitive position of a firm (Schilling & Hill, 1998). Thus, technology strategies provide firms with guidance in determining the attractiveness of technology investment opportunities and may assist in targeted accumulation of knowledge (Ford, 1988; Malerba & Orsenigo, 1996). As such, a technology strategy shapes an important part of firms' competitiveness in settings relying strongly on technological foundations (Bonnet & Yip, 2009; Sukri & Yusoff, 2019; Zahra & George, 2002).

Firms' technology strategies become particularly relevant when facing high environmental turbulence, such as technology convergence, as they determine if and how firms may participate in evolving technology systems (Golder & Tellis, 1993; Hacklin et al., 2013; Zahra, 1996). Here, the extant dimension such as the use of internal and external R&D resources (Hagedoorn & Duysters, 2002; Veugelers, 1997), R&D spending (Zahra, 1996), pioneer versus follower (Lieberman & Montgomery, 1988), balance of technology exploration and exploitation (Clarke et al., 1989; Tushman & O'Reilly, 1996), as well as related IP protection strategies (Drechsler & Natter, 2012), make up multiple dimensions of technology strategy. However, these dimensions may not suffice to capture the uncertainty and complexity of strategy development in the context of converging technology systems. Hence, to advance theorizing regarding technology strategies, we expand existing concepts with a novel dimension that enables to navigate complex technology systems. Accordingly, we conceptualize technology strategies along the following four dimensions and introduce TSC as a central technology strategy dimension, summarized in Table 1 and elaborated below.

1.2.1 | Scope: Focused versus systemic

A central aspect of a technology strategy in the context of convergence concerns the scope of engagement in the emerging technology system. This dimension seems particularly relevant in such a context of high technology dynamics, as technology components merge from previously unrelated technology systems. Firms can seek to develop a single or multiple components of the converging technology system, implying to either remain within their knowledge base or expanding into novel areas. The decision on the scope is informed by the dichotomy of autonomous (focused) and systemic innovation, as introduced by Chesbrough and Teece (2002).

A *focused* scope reflects a technology strategy that directs its development efforts toward a single component of the evolving technology system (e.g., only $x_{a,b}$ in Figure 1). Firms entering a converging technology system with a focused scope may benefit from a very targeted

TABLE 1 Theoretical framework for the extended conceptualization of technology strategy.

Dimension	Characteristics[a]		Conceptually informed by
Technology system coverage			
Scope	Focused	Systemic	Chesbrough and Teece (2002) Taylor and Levitt (2004)
Knowledge base	Specialized	Design	Henderson and Clark (1990) Yayavaram et al. (2018)
Timing	Pioneer	Follower	Lieberman and Montgomery (1988) Golder and Tellis (1993)
Dynamics	Steady	Evolving	Porter (1991) D'Aveni (1994)

[a]Following extant literature, we choose to highlight extreme or dichotomous positions in each dimension to allow for a clear distinction of technology strategy approaches.

R&D activity concentrating on that particular component only (Staudenmayer et al., 2005), potentially remaining in their core knowledge base. In contrast, the converging technology system can be approached more comprehensively by covering more than one component, which we label as *systemic*. Firms following a systemic scope develop knowledge around multiple components (e.g., $y_{a,b}$ and $z_{a,b}$ in Figure 1), which puts them in a position to potentially better understand the entire system, including the interdependencies and linkages between components, and presumably expanding their core knowledge scope (Bröring, 2008; Henderson & Clark, 1990; Taylor & Levitt, 2004).

1.2.2 | Knowledge base: Specialized versus design knowledge

Drawing upon Henderson and Clark (1990) and Yayavaram et al. (2018), we distinguish between different forms of knowledge that firms can build as part of deliberate technology strategies. Accordingly, firms can engage in knowledge development regarding those components of the evolving technology system that are either rich in specialized or rich in design knowledge (see Figure 1). We argue that firms either build *specialized knowledge* needed for specific, rather peripheral components (Baldwin et al., 2014; Yayavaram et al., 2018) and/or build *design knowledge* needed for the overall architectural design.

By understanding technology systems as hierarchical (compare Clarke et al., 1989 or Marples, 1961), we conceptualize design knowledge as relevant for understanding and determining the systems architecture at a higher level. Baldwin et al. (2014) also refer to "core" components in this regard, as components rich in design knowledge determine many subsequent configurations of the system (Henderson & Clark, 1990). The following assumption seems important in this regard: in line with Persoon et al. (2021) and Malerba and Orsenigo (1996), we understand technological knowledge as cumulative, thus a stock of knowledge of the firm that grows over time.

The involvement in a technology system always comes with two decisions: firstly, regarding scope, how many components should be developed: focused versus systemic and, secondly, regarding the knowledge base of a particular component: specialized versus design knowledge (see Figure 1). Thus, the integration of both dimensions leads to the novel construct of technology systems coverage that we conceptualize as a dimension relevant to the development of technology strategy, in particular relevant for firms engaged in emerging complex technology systems (see Table 1).

1.2.3 | Timing: Pioneer versus follower

As technology convergence is an evolving phenomenon—with a novel technology system and dominant design emerging only over time—to ensure a systems fit, the redesign of a component or the entire technology system might be required (Metcalfe, 1995). In this regard, a relevant and well-established dimension of technology strategy concerns the timing of entry (García-Cabrera et al., 2019; Golder & Tellis, 1993; Langerak & Hultink, 2006; Lieberman & Montgomery, 1988; Suárez & Utterback, 1995). However, often this is not a deliberate strategy but rather emerges (Mintzberg & Waters, 1985). Despite the question of whether timing of entry is a deliberate strategic decision or emerges, it seems important to observe and realize the implications of an early entry versus a late following position. In this regard, a pioneering or following position seems particularly relevant with respect to the progression of the system's development. Early participation and, therefore, a positioning as a pioneer enables a firm to build knowledge from the very beginning. This potentially allows for setting a dominant design, which later entrants must follow (Golder & Tellis, 1993).

However, when technology systems converge, hitherto unlinked components need to be interlinked with each other, potentially for the very first time or in a novel manner. This involves considerable complexity concerning components outside a firm's core technological knowledge. So, moving first comes with the risk that efforts might be prioritized unfavorably, and a fast-evolving technology bears the difficulty to sustain a durable competitive advantage (Leten et al., 2016; Lieberman & Montgomery, 1988; Suárez & Lanzolla, 2005). Additionally, the investment in early-stage technologies always bears the risk of not meeting the expected return on investment (Porter & Chubin, 1985; Zahra, 1996).

1.2.4 | Dynamics of TSC: Steady versus evolving

Converging technology systems are particularly dynamic and companies potentially need to deepen and broaden their technological knowledge continuously (Yayavaram et al., 2018). Therefore, we argue that firms may seek to adapt their technological knowledge as the technology system evolves (D'Aveni, 1994; Sanchez & Mahoney, 1996). Hence, when examining participation in a technology system, covering dynamics seems to be critical (Thomke et al., 1998). Firms participating in such an environment might continuously be pressured to keep up with these dynamics if they want to sustain their participation (D'Aveni, 1994; Porter, 1991). But the question remains if all firms engage in a dynamic approach or if some rather follow a steady approach. Against this backdrop, we argue that technology strategy can either be *evolving* or *steady*. In contrast to evolving, that is, adapting, we conceptualize steady as not adapting the scope, that is, number of components covered, and knowledge base, that is, specialized or design knowledge.

2 | CONTEXT AND METHOD

2.1 | Research context

To explore technology strategies during the development of complex technology systems, we choose the well-defined convergence field of printed electronics (Bröring, 2010; Cho et al., 2015). It represents an established and rich empirical site to uncover technology strategy development in the context of converging technology systems, as the convergence phenomenon is salient here (Strauss, 1987). The convergence of printed electronics derives from the two formerly distinct technological fields of conventional printing and electronics. Both original fields have long histories of established technological knowledge (Cho et al., 2015; Karvonen et al., 2010; Karvonen et al., 2012).

When the knowledge in conventional printing, for example, printing newspapers, merged with knowledge on electrical properties in inks, the production of printed electronics such as printed microchips, printed electronic circuits, or printed semiconductors was enabled (Cui et al., 2016; Hu et al., 2018; Huang & Zhu, 2019). The main procedural difference in the production of traditional electronics and printed electronics is that the former uses a subtractive procedure, while the latter involves an additive process. This gives printed electronics the advantage of lower production costs while offering increased flexibility and robustness (Cho et al., 2015; Huang & Zhu, 2019). Consequently, this converging technology system is developing fast. It started with the production of printed circuit boards and evolved into areas such as radio-frequency identification (RFID), organic light-emitting diodes (OLED), flexible displays, or flexible photovoltaics (PV) (Hu et al., 2018; Huang & Zhu, 2019).

Applying our simplified model of converging technology systems (introduced in Figure 1) to the printed electronics field, the underlying technology system is built by the integration of four components: substrate, ink, manufacturing device, and electronic application, see Figure 2.

The first component of a typical printed electronics technology system is the *substrate*, which is the surface material onto which the ink is printed. The substrate can be made of various materials and layers, such as flexible polymeric materials, including properties such as being conductive. The second component, *ink*, refers to functional inks, such as semi-conductive, conductive, and insulative pastes. They are printed onto the substrate to produce the circuits (Cui et al., 2016). These first two

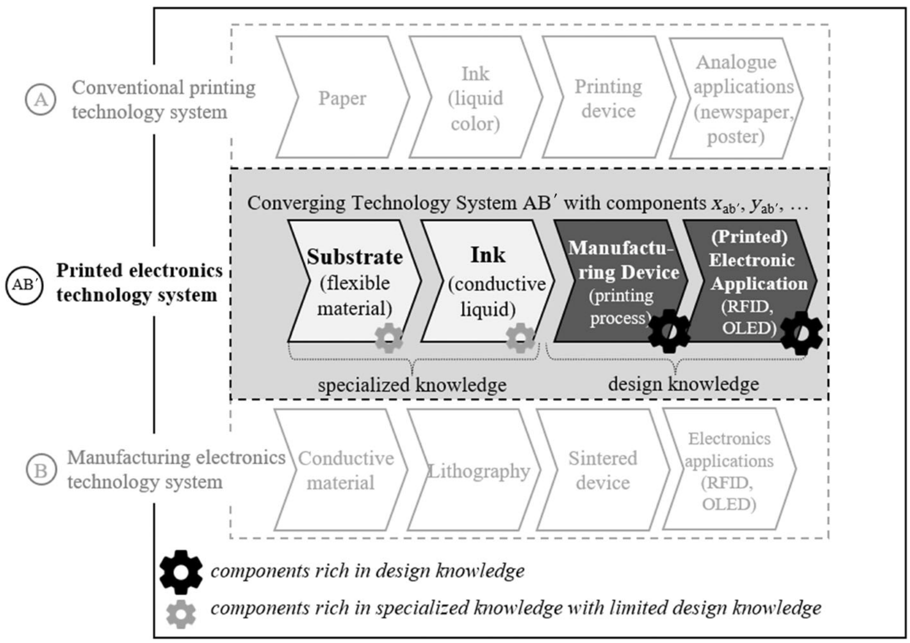

FIGURE 2 Printed electronics converging technology system (based on Cho et al., 2015). OLED, organic light-emitting diodes; RFID, radio-frequency identification.

components derive from material science and need to be integrated into the architectural design of the technology system, originating in the electronics domain. Thus, these components mainly contain specialized knowledge but still need to embed some design knowledge on interface definitions to enable compatibility and systems fit (Baldwin et al., 2014; Henderson & Clark, 1990). For example, ink can be developed primarily remaining within its specialized knowledge base but cannot be developed completely autonomously, as it needs to align with the overall systems architecture. Such design knowledge may entail insights on the needed viscosity of the ink to enable a fit to the manufacturing (printing) device (Cho et al., 2015).

The third component, *manufacturing device*, comprises the printing and patterning processes, that is, the additive manufacturing technique of how to apply layers of inks to a given substrate. This component is rich in design knowledge to enable not only compatibility between the printing materials (ink and substrate) but also ensure that interfaces align with the specific requirements of different electronic applications. The final component, *electronic application*, further adds to previous components by including application-specific design elements of printed electronics, enabling the development of the final printed RFID, OLED, printed (semi-)conductors, printed battery cells, and flexible photovoltaic cells (Cho et al., 2015; Das & Harrop, 2013; Marketsandmarkets, 2021). Developing the printed electronic application resembles a successful synergy of all components of the technology system. As the final component can only be developed through the interoperability of all components, a vast amount of design knowledge is required to master the complexity of the converging technology system.

In contrast to the first two components, manufacturing device and electronic application are both rich in design knowledge and thus have a stronger impact on the overall system architecture (Baldwin et al., 2014). These two components necessitate a more diverse set of knowledge previously rooted in different industries. Although the printed electronics technology system has been developing over several decades, components, as well as their overarching architectural system design, are still evolving: This is also reflected by ongoing development and standardization efforts, yet so far, without reaching a dominant design.

2.2 | Method and data collection

This study seeks to empirically explore patterns of technology strategies during a dynamically evolving technology system. To this end, we analyze an extensive set of actively participating firms in the printed electronics field to capture their different technology strategies. We furthermore investigate how such approaches dynamically change over time, which demands a longitudinal approach covering a substantial part of the emergence of the new technology system. To this end, we use longitudinal patent data, reflecting the development of firm-specific knowledge stocks in the different domains of the evolving technology system.

In high-technology fields, such as printed electronics, intellectual property protection through patents is highly relevant, as it offers a detailed description and protection of new and nontrivial technological developments (Persoon et al., 2021). For this reason, value creation from technological development activities is usually protected through patents (Belderbos et al., 2010). When a dominant design is yet to emerge, protection through patents is essential for firms, as patents allow firms to block potential competitors and signal their activities to the market (Blind et al., 2022). Hence, patents serve as a valid indicator for companies' strategic technological activities in the field and deliver a detailed picture of knowledge stocks developed by firms over time (Andries & Faems, 2013; Blind et al., 2022). Additional benefits of analyzing patents are their highly structured nature and, thus, high comparability, as well as the fact that information, for example, ownership, is validated by skilled patent examiners and available at a detailed level (Ernst, 2003).

To achieve a relevant and comprehensive patent sample, a stepwise approach was applied to define key search terms for printed electronics. First, we selected search terms from seminal scientific publications on printed electronics and added keywords used in relevant industry reports (Das & Harrop, 2013; Marketsandmarkets, 2021). To validate the initial search string, we interviewed four technology domain experts from industries centrally involved in printed electronics. Industry experts were asked to validate, compare, and complement a proposed search string with their endeavors in this field. The final search string comprises keywords referring to the four components. To reach a higher precision, frequently occurring terms that are not related to printed electronics, but misleading to neighboring fields, were excluded (see Table 2 for search string).

The search string was applied to the Derwent World Patents Index (DWPI), which is maintained by Thomson Reuters and offers a collection of over 61 different sources covering over 105 million global patent publications (Clarivate, 2022). To prevent overrepresentation through multicountry filing, this study uses International Patent Documentation (INPADOC) family IDs (World Intellectual Property Organization, 2015). INPADOC families comprise a set of patent documents that relate to

TABLE 2 Applied search string for printed electronics.

CTB=((PRINT* NEAR2 ELECTRO*) OR (PRINT* NEAR2 ELECTRIC*)) AND CTB=((CONDUCT* ADJ INK*) OR (CONDUCT* ADJ SUBSTRAT*) OR (FLEX* ADJ CIRCUIT*) OR (FLEX* ADJ DISPLAY*) OR (PRINT* ADJ SCREEN*) OR (PRINT* ADJ TRANSIST*) OR (OLED*) OR (ORGANIC* ADJ LIGHT* ADJ EMITTING* ADJ DIODE*) OR (RFID) OR (RADIO ADJ FREQUENCY ADJ IDENTIFICATION) OR (SEMICONDUCT*) OR (SEMI ADJ CONDUCT*) OR (SEMI-CONDUCT*) OR (PRINT* ADJ CONDUCT*) OR (LED) OR (LIGHT*EMITTING*DIODE*) OR (PRINT* ADJ PHOTOVOLTAIC) OR (PRINT* ADJ SOLAR* ADJ CELL*) OR (PRINT* ADJ SENSOR*) OR (PRINT* ADJ BATTER*) OR (PRINT* ADJ MEMOR*) OR (FLEX* ADJ SCREEN*) OR (PRINT* ADJ DISPLAY*) OR (PRINT* ADJ SOLAR*) OR (PRINT* NEAR ELECTROLUMIN*) OR (ORGANIC* ADJ PHOTOVOLT*) OR (OPV)) NOT CTB=((IMAG* ADJ FORMAT*) OR (IMAGE-FORM*) OR (ELECTRO* ADJ PHOTOGRA*));

the same technological content over patent offices in multiple jurisdictions (Vicente-Gomila et al., 2017). The use of patent families increases comparability and accuracy (Barbieri et al., 2020; Clarivate, 2018; Persoon et al., 2021) and is, therefore, an appropriate way to analyze strategic behavior (Martinez, 2010; World Intellectual Property Organization, 2015). From now on, and for simplicity, we will refer to "patent," although we use patent families.

The first patent in the field was submitted in 1924, followed by very limited activity over the subsequent decades. A steadily rising trend can be observed only from 1990 onwards. Thus, this date is chosen as the starting point for our analysis. The last year included is 2019 due to a gap of 18 months between patent application and publication in the database.

The sample comprises 3223 patents between 1990 and 2019 (see Figure 3). Each patent is assigned to a company, that is, Derwent's so-called "Ultimate Parent," which refers to the top company in the patent family hierarchy. They have the ultimate and current responsibility for the patent, including the ability to exploit it (Stembridge, n.d.).

We excluded patents that provided incomplete information (i.e., lacking INPADOC family ID, application date, ultimate parent, title, abstract, or claims; comprised around 6% of the sample), and patents filed by universities or research institutions (comprised around 7% of the sample), leaving 2800 patents.

We only included firms with a considerable and sustained interest in the field. Thus, firms not participating intensively in technology development were excluded. For that reason, only patent assignees with an above-average number of patents remained in the sample (average number of patents = 4.5; the threshold for inclusion: min. 5 patents[1]), leaving 1850 patents.

[1]It should be noted that five patents as a threshold might cause the impression of underrepresentation of participation, but our basis remains to rely on patent families. Therefore, the investment made by an organization for five patent families serves as an indicator of sustainable interest in the field.

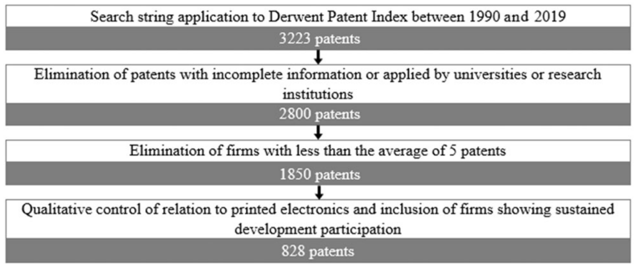

FIGURE 3 Data-cleaning process.

In the next step, a detailed assessment of the patents' relevancy was applied by analyzing the patents based on a textual analysis, which is especially relevant in the context of this convergence due to the similarity of keywords in *printed* electronics and conventional *printer* electronics. Each of the 1850 patents was semantically evaluated based on abstract and claims to secure that only patents pertaining to the printed electronics field were included. Two researchers reviewed the individual patents independently, results were compared, differences discussed, and finally arbitrated. Eight hundred and twenty-eight patents from 74 corporate assignees remained in the final sample for printed electronics.

Lastly, the remaining 828 patents were analyzed semantically to allow a detailed examination of the content and a classification into the four previously identified technology components (Persoon et al., 2021). Analog to the previous step, this was done by building on the independent, qualitative assessment by two researchers. Table 3 offers a list of central reference terms that have been used to assign patents to the components. The list is not complete, as the classification of each of the components includes the identification and understanding of descriptions and synonyms, as well as the understanding of the patent as a whole.

2.3 | Data analysis

In our analysis, we identified 74 firms as relevant actors showing sustained interest in the field. To explore their

TABLE 3 Reference terms used to assign patents to the corresponding component.

Component	Central reference terms	Number of patents
Substrate	Base, pad, plate, sheet, substrate, surface, surface film, surface material	35
Ink	Ink, dye, paste, coating material, liquid material, (semi)conductive traces, (semi)conductive composition, (semi)conductive toner, (semi)conductive film	107
Manufacturing device	Printing process, printing technique, printing patterning, printing method, patterning processes, technique, manufacturing method, manufacturing process, printing system, printing device, methodology	286
Electronic application	Printed RFID, OLED, printed (semi)conductors, printed battery cells, flexible photovoltaic, printed solar panel, printed solar cell, printed connectors, printed display, printed monitor, printed sensor, printed lighting device, printed circuitry, flexible devices, printed wearable	435

Note: A patent could be assigned to two components if the claim was covering the content of two different components. This is the case for 4% of all patents. Abbreviations: OLED, organic light-emitting diodes; RFID, radio-frequency identification.

technology strategy, we measured each firm's scope of engagement and knowledge base, that is, TSC, as well as the timing of entry and the dynamic alteration of the TSC over time (see Table 4 for an overview).

Based on the components (four in the printed electronics case) forming the technology system, participation in technology development is distinguished based on the numerical indicator "technology system coverage". TSC differentiates between a focused and systemic scope of engagement and the integration of knowledge base. A focused approach (engagement in only one technological component) translates into the lowest TSC score of 1. The more systemic a company approaches technology development, that is, the more comprehensively it embraces the technology system, the higher its TSC score (Table 5). To be exact, a systemic approach in two different components but within either specialized knowledge (ink or substrate) or within design knowledge (manufacturing device or electronic application) is labeled as a narrow systemic (TSC = 2). When both, specialized and design knowledge components, are developed, the TSC score increases to 3, "broad systemic," and if all four components are covered, to 4 and "complete systemic."

Firms can extend their TSC and the underlying base of technological knowledge with every additional patent. To analyze and reflect on how a company's TSC changes over time, a dynamic perspective is included in the analysis. To this end, we distinguish between steady (no change in TSC) and evolving (increasing TSC). For that matter, we determine the TSC of each firm twice: in the very first year of their engagement and at the time of their last patent application in printed electronics. Due to the basic assumption of knowledge accumulation (Persoon et al., 2021), a firm's TSC can only increase and not decrease over time.

The assessment of the observed timing of entry is based on Ernst's (1997) model of patenting activity over the technology life cycle. Ernst's generic model distinguishes three stages of patenting activity. At first, a small number of actors initiate the new technology development cycle by increasing patenting activity, followed by a stage of consolidation with declining patenting activity. Both stages can be considered as the early phase in the technology life cycle. This is followed by a maturity stage, which shows a steep increase in patenting activity (Ernst, 1997). This stage, combined with a decline toward the end of the life cycle, can be considered as late phase. Firms to be observed as entering the printed electronics field after the early phase are classified as follower firms.

TABLE 4 Operationalization of technology strategy variables relevant in emerging technology fields.

Dimension	Measure
Technology system coverage (TSC)	
Scope	Number of components • Focused—covering one component • Systemic—covering more than one component
Knowledge base	Type of components • Components rich in specialized knowledge • Components rich in design knowledge
Timing	Timing of entry • Entry in the early phase of technology system emergence • Entry in the late phase of technology system emergence
Dynamics	Change of TSC over time • Steady with constant TSC to deepen knowledge • Evolving with increasing TSC to broaden knowledge

3 | RESULTS

The patenting activity in the converging technology system of printed electronics is visualized in Figure 4. In the early phase between 1990 and 2004, a slow but continuously increasing development can be observed. From 2005 onwards, a strong increase in development activities follows, which in line with Ernst (1997), points to the start of the late phase.

Building on these two conceptually established and empirically observed phases, we classify companies starting their technology development in the early phase, until 2004, as pioneers. Those companies that can be observed to engage in technology development (i.e., reflected by patenting behavior) in the late phase, from 2005, are classified as followers (Golder & Tellis, 1993).

The distribution of patents, as depicted in Figure 5, reveals that components that inherit design knowledge (i.e., manufacturing device and electronic application) lead the technological development in the early phase, while a continuous and substantial development of the specialized components (i.e., ink and substrate) mainly takes place in the late phase. To enable an assessment of the timing strategies (pioneering vs. following) as well as TSC dynamic per firm, Figure 5 renders a mapping of each company's initial and final year of participation. A company's initial TSC is depicted by a blue triangle, while the final TSC is depicted by an orange bubble. The size of the triangle/bubble and the number below depicts the number of firms in this TSC. Overall, 54 out of 74 firms start as pioneers (73%), while only 20 firms pursue a follower strategy (27%). Looking at firms' initial approach to technological system coverage, the majority (91%) of all pioneers and 80% of all followers start with a focused approach (TSC = 1). Thus, only 5 out of the 54 pioneers (9%), and 4 out of the 20 followers (20%), start with a systemic approach (TSC > 1).

Regarding TSC dynamics, a general shift toward more systemic approaches can be observed. The Sankey diagram

TABLE 5 Technology system coverage (TSC) matrix based on components.

TSC	Specialized knowledge	Design knowledge
Focused (TSC = 1)		
One component	Ink or substrate	Manufacturing device or electronic application
Narrow systemic (TSC = 2)		
Two components (either specialized or design knowledge)	Ink and substrate	Manufacturing device and electronic application
Broad systemic (TSC = 3)		
Two or three components (specialized and design knowledge)	Specialized and design knowledge	
Complete systemic (TSC = 4)		
All components covered	Ink and substrate and manufacturing device and electronic application	

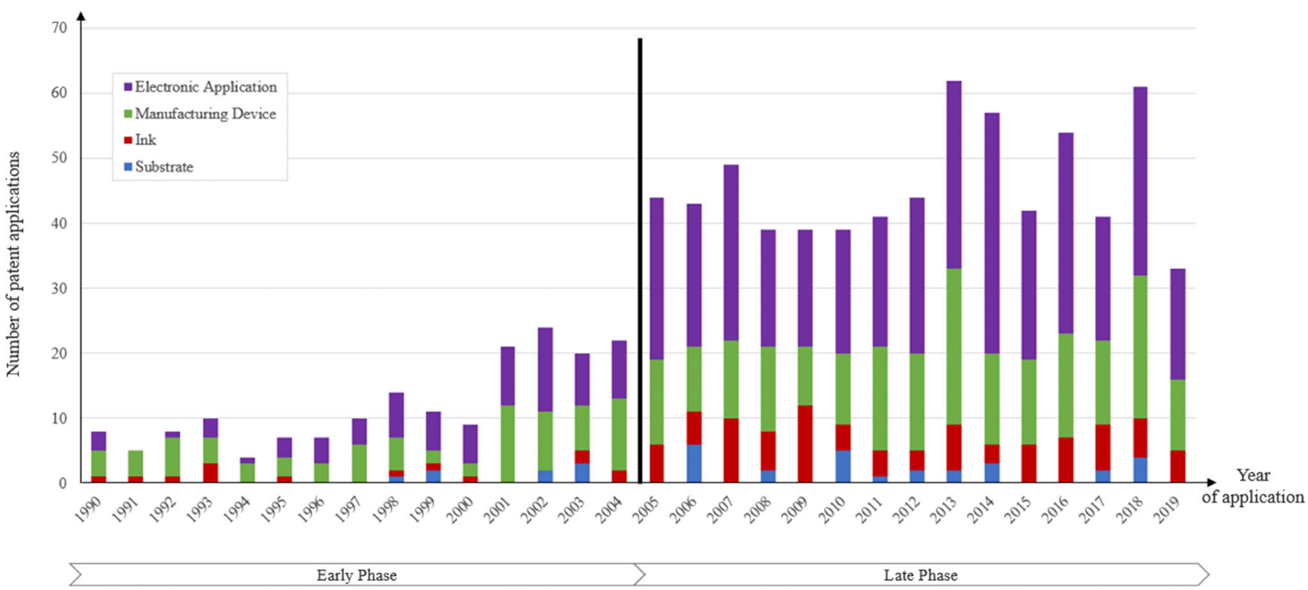

FIGURE 4 Technology system development distinguished by components over time.

in Figure 6 provides insights into the firms' shifts from their initial to their final TSC and allows us to distinguish several streams: while most firms dynamically evolve toward a broader TSC, some remain steady within their initial TSC. In detail, five firms that start with a TSC of 1 remain focused, but the majority starts focused and evolves toward a narrow, broad, or complete systemic TSC. This holds true for 81% of all firms (60 in total). Eight firms start narrow systemic, of which five firms remain narrow systemic, and three firms evolve their TSC to broad systemic. One firm could be observed to start with a broad systemic approach, remaining in this TSC of 3.

In total, 11 firms remain steady in their TSC. This is especially noticeable when we take the timing of entry into perspective—while 11% of all pioneers remain in their initial TSC, 25% of the followers can be observed to remain steady (see Figure 7). The remaining 63 firms evolve to a more systemic stream, of which 48 are pioneers and 15 are followers (see Figure 7).

More detailed insights into the knowledge base inherent in the initial and final TSC are offered in Table 6, illustrating the initial and final TSC per knowledge base with the corresponding number of firms. Firms' final TSC shows that no firm pursues a strategy in specialized knowledge only, neither as a focused nor as a narrow systemic approach. But also, no company could be observed to start narrow systemic in specialized knowledge. Thus, all companies (no matter if focused or systemic) build design knowledge over time.

Looking at firms' final TSC, five firms have remained in the focused approach in the component of the

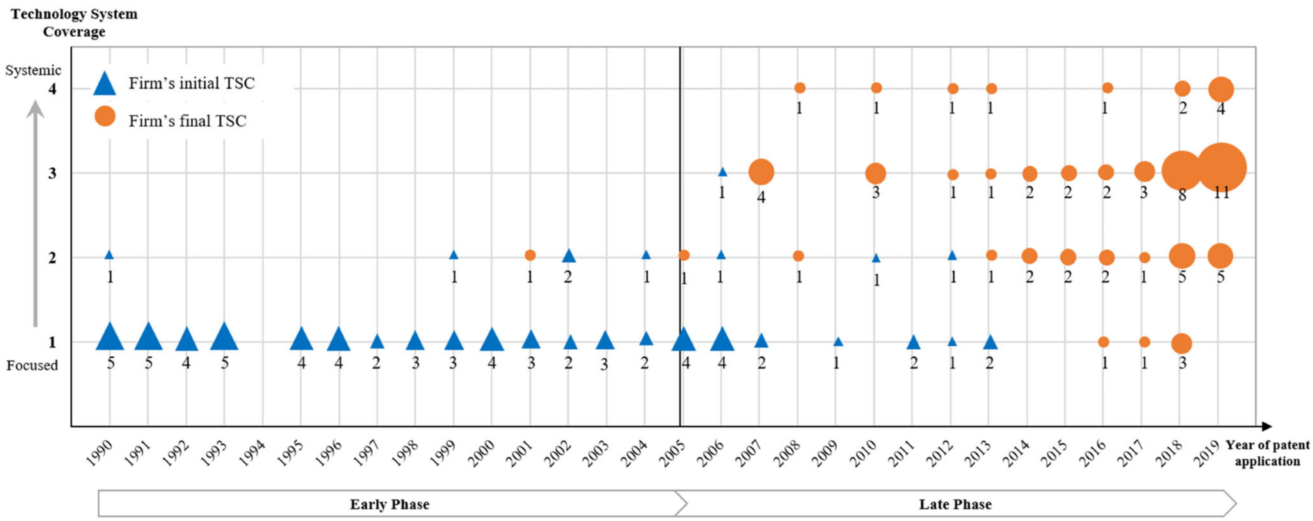

FIGURE 5 Firms' initial and final technology system coverage per year with number of firms below triangle/bubble.

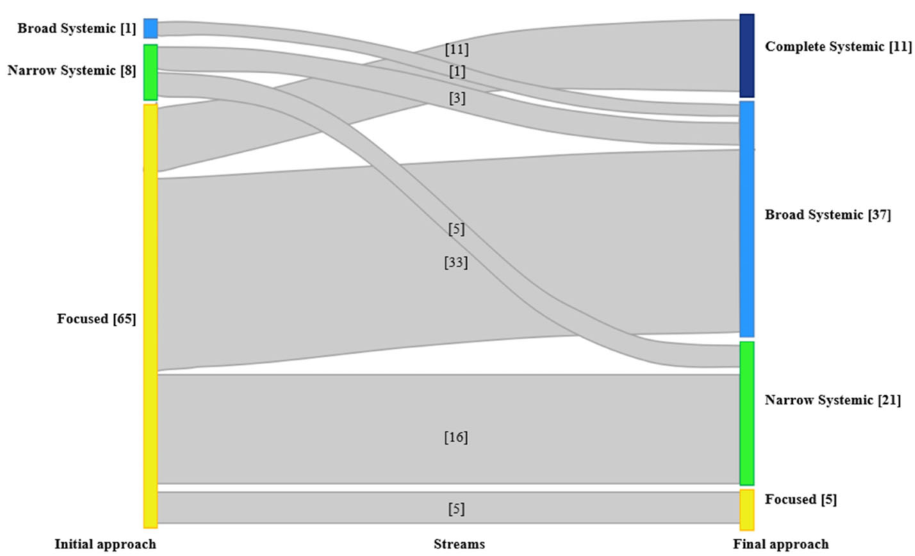

FIGURE 6 Streams of technology system coverage development with number of firms in brackets.

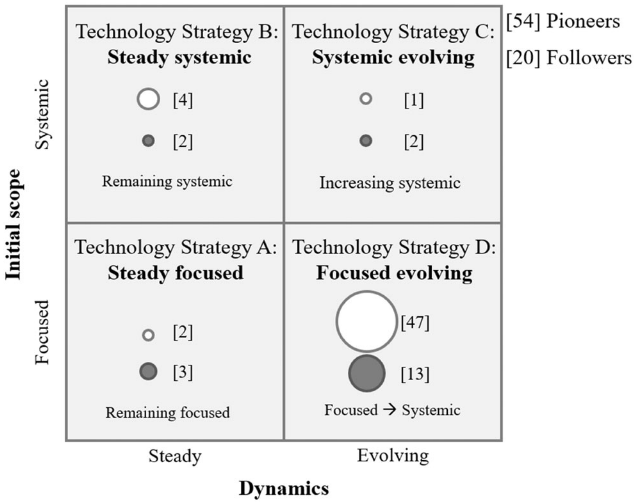

FIGURE 7 Four empirically derived technology strategies.

electronic application, which is rich in design knowledge. These firms are described as steady focused as they remain in the knowledge base of one component throughout the emergence of the technology system. However, 21 companies are narrow systemic in design knowledge (manufacturing device and electronic application) in their final TSC. Five of those firms already started narrow systemic, whereas 16 came from a focused approach in design knowledge. Moreover, firms' final TSC in broad systemic, that is, design and specialized knowledge, resembles 37 firms in total. Out of those, 33 firms initially come from a focused TSC, 3 came from narrow systemic, and 1 remained steady broad systemic. Lastly, 11 firms are classified as complete systemic (TSC = 4) and, thus, have covered all four components in their final TSC. Interestingly, all these firms come from an initially focused approach (compare Figure 6).

4 | DISCUSSION

The underlying technology convergence case of printed electronics is characterized by substantial dynamics, uncertainty, and complexity. As such, the case serves as an insightful example of an emerging complex technology system (Rotolo et al., 2015). By observing the technology strategies that firms adopt to participate in the development of such a converging technology system, our data reveal four different technology strategies (Figure 7): (A) *steady focused*, (B) *steady systemic*, (C) *systemic evolving*, and (D) *focused evolving*. Against the backdrop of the investigated case, this taxonomy enables us to derive propositions for firms aiming at sustained positions in emerging complex technology systems.

Interestingly, our data reveal a general trend of firms aiming for more systemic approaches with increasing maturity of the complex technology system. Thus, the majority of firms, albeit entering the field of printed electronics with a focused approach in just one component, choose to evolve across the scope of the technology system. This indicates that firms expand their initial knowledge domain, which advances Cho et al.'s (2015) study, which found that firms' technology intensification increases, but do not distinguish different types of technological knowledge. Even though late entrants have less time to evolve with the system—simply due to their later participation—this holds true for most pioneers and followers alike. This emphasizes that firms engage dynamically in broader, increasingly systemic knowledge-building activities to ensure alignment with the new evolving technology system. Additionally, those knowledge-building activities might aim at understanding the new architectural design and the evolution of new interfaces (Brusoni et al., 2001; Henderson & Clark, 1990). This corresponds to Brusoni et al. (2001), who argue that firms need to build knowledge bases beyond their factual technology offerings to understand the requirements of the entire system. Furthermore, our finding coincides with Staudenmayer et al. (2005), who argue that increasingly systemic approaches provide firms with relevant maneuvering space in the evolving technology system and potentially with direct and indirect exploitation opportunities for future developments. Moreover, our findings for complex technology systems expand previous literature on strategic behavior in classic product development environments, such as Schilling and Hill (1998), that a more systemic orientation is crucial for most firms to co-evolve with complex technology systems. We therefore suggest our first proposition on the relevance of evolving to a more systemic alignment with the converging technology system:

> **Proposition 1.** *Firms that engage in the development of an emerging complex technology system over time, tend to dynamically expand their scope and knowledge base to embrace more components of the system.*

Companies participating in the development of a complex technology system, expand their initial knowledge to enable a system fit. This involves accumulating knowledge across the scope of the technology system in the long term, which is crucial for sustained participation.

4.1 | Steady focused technology strategy

A small share of firms resists the dynamics of the systemic evolution and follows a steady focused strategy by

TABLE 6 Firms' dynamic development from initial to final technology system coverage (TSC).

TSC	Initial TSC				Final TSC			
	Specialized knowledge		**Design knowledge**		**Specialized knowledge**		**Design knowledge**	
Focused (TSC = 1)	Ink 12 (8 pioneers 4 followers)	Substrate 2 (1 pioneer 1 follower)	Manufacturing device 24 (21 pioneers 3 followers)	Electronic application 27 (19 pioneers 8 followers)	Ink 0	Substrate 0	Manufacturing device 0	Electronic application 5
Narrow systemic (TSC = 2) (within same knowledge base)	Ink and substrate 0		Manufacturing device and electronic application 8 (5 pioneers 3 followers)		Ink and substrate 0		Manufacturing device and electronic application 21	
Broad systemic (TSC = 3)	Specialized and design knowledge 1 (1 follower)				Specialized and design knowledge 37			
Complete systemic (TSC = 4)	All components 0				All components 11			

engaging in a single technology component of the converging system throughout their entire engagement. These firms abstain from building knowledge stocks across the converging technology system and appear to find a sustained position, nonetheless. While the environment of the converging technology system around them is changing, these firms seize the opportunity to exploit their focused knowledge position and concentrate their efforts to potentially become an expert in one component.

This observed strategy seems to contradict the findings of previous studies such as Baldwin and Clark (2000) and Staudenmayer et al. (2005), who argue that component and system level knowledge need to be aligned. When following a focused strategy, especially early on in technology system development, a higher risk of misattributed efforts would be expected. Moreover, in such dynamic environments, a focused strategy is expected to bring high risks as relevance, industry standards, and interface specifications are not yet defined in the dynamics and uncertainties of the emerging technology system (Rotolo et al., 2015; Staudenmayer et al., 2005; Suárez & Utterback, 1995). Such contrasting views in literature in comparison to our observation may be resolved by distinguishing the underlying knowledge base of the components. Our analysis enables the differentiation between different knowledge bases (see Table 5), and the results indicate that firms that participate in the converging technology system with a steady focused technology strategy mitigate the underlying risks by targeting a component that is rich in design knowledge, that is, electronic application—and not in any of the specialized components, that is, ink or substrate (see the upper right corner in Table 6). One explanation is that electronic application, as a component, boasts interfaces to all other components, those of specialized and of design knowledge. While firms that build knowledge stocks in this central component may have a focused scope, an understanding of intersections and compatibilities is nevertheless maintained (Baldwin et al., 2014). Thus, we suggest the second proposition for the condition under which firms are enabled to a steady focused strategy and may become a component expert, possibly even directing the overarching development of the technology system from their focused perspective:

> **Proposition 2.** *Firms that engage in the development of an emerging complex technology system within a single component and refrain from expanding their scope and their knowledge base tend to focus on a component that is rich in design knowledge.*

4.2 | Steady systemic technology strategy

Another counter trend to the dynamics of an emerging complex technology system is the steady systemic technology strategy, which is characterized by a more comprehensive but steady approach, that is, targeting multiple components, potentially from different knowledge bases. In the printed electronic case, this is empirically evidenced by multiple firms participating in the technology development with components in manufacturing device and electronic application, that is, multiple components in design knowledge, and one firm starting with these two components and additionally in substrate, that is, components in design and specialized knowledge (see Table A1 in the Appendix for detailed references).

Suárez and Utterback (1995) found that flexibility comes at high costs when investments have been approached systemically. This is due to the underlying risk of a directional change during the emergence of a dominant design (Grodal et al., 2015; Suárez et al., 2015; Suárez & Utterback, 1995). These findings can be supported in converging technology systems when looking at firms that develop knowledge in components embedding specialized knowledge only: there is no evidence of firms in a steady systemic technology strategy that remains in specialized knowledge only. But when we are looking at firms that participate in components rich in design knowledge, the steady systemic technology strategy offers a potentially successful path. Thus, in line with findings in the steady focused technology strategy, evidence from this study suggests that a steady systemic technology strategy is only viable when components rich in design knowledge are integrated. To be precise, investing in components embedding specialized knowledge only, does not seem to offer sufficient coverage of interdependencies, thus, does not ensure a fit between various components. Nonetheless, if firms initially engage in the development of a converging technology system by investing in multiple components rich in design knowledge, a steady systemic strategy is a viable path for engaging in a converging technology system. This aligns well with Wang and Von Tunzelmann's (2000) study on complexity, suggesting that a steady approach toward a technology system is only achievable if the complexity inherent in the approached components is adequate and allows an overall understanding of the system. Thus, the development of the more complex design knowledge seems to be needed to follow a steady systemic technology strategy, as it allows maneuvering the complexity and interdependencies of the complex technology system. If a firm's knowledge base lies in specialized knowledge components only, the option to remain in a steady systemic technology strategy does not seem to be viable, similar to the findings of Grodal et al. (2015) that highlight the importance of co-evolution of firms' understanding with the emerging industry. Therefore, firms that rely solely on components reflecting specialized knowledge may be at risk of being disrupted if they do not continuously innovate and evolve with the emergence of the complex technology system. Thus, our third proposition suggests:

> **Proposition 3.** *Firms that engage in the development of an emerging complex technology system with a steady systemic technology strategy tend to cover components rich in design knowledge.*

4.3 | Systemic evolving technology strategy

The first dynamic technology strategy regards firms that start with multiple components, for example, in manufacturing device and electronic application, and expand their scope and knowledge base over time, for example, to also include ink. We identify these firms as pursuing a systemic evolving technology strategy. While this approach is adopted by the smallest group of firms in our sample, all of them seem to follow the same pattern: they start with multiple components embedding design knowledge and expand to components embedding specialized knowledge. When firms participate in the development of the converging technology system with a broader scope, design knowledge appears to be a crucial starting point to further co-evolve with the overarching technology system. Building specialized knowledge stocks then appears to be an opportunity in subsequent development stages.

Starting with design knowledge in a converging technology system may be crucial for firms to take advantage of the cumulativeness of a technology, which refers to the structure of knowledge and how different knowledge bases build on each other (Persoon et al., 2021). This approach might enable firms to later branch out to specialized knowledge bases and, thus, participate in the development of the technology system with a broader knowledge scope. But starting from multiple specialized components in a converging technology system does not seem to offer an ideal approach. Baldwin et al.'s (2014) study on software releases supports this notion by suggesting that an understanding of the design of the technology system enables coupling at the component level. In summary, our fourth proposition suggests that the sequence of knowledge accumulation in a complex technology system should start with design knowledge, followed by specialized knowledge bases in subsequent development stages:

> **Proposition 4.** *Firms that engage in the development of an emerging complex technology system with multiple components rich in design knowledge can, in later stages, expand further by building additional knowledge stocks in components rich in specialized knowledge.*

4.4 | Focused evolving technology strategy

The focused evolving strategy refers to firms that initially start with a focused approach, by entering the development of the converging technology system with a single technology component and over time, reaching a more comprehensive knowledge scope. This dynamic technology strategy enables the opportunity to align and, thus, co-evolve the firm's knowledge scope with ongoing developments in the technology system. This technology strategy is adopted by the majority of firms in our sample. The benefit of this technology strategy may be that through the co-evolution with the converging technology system, participation and influence are increased and aligned with maturing interfaces and emerging dominant designs, which in turn, might enable orchestration (Grodal et al., 2015).

From their initial focused approach, we can distinguish between three different complexities that the firms develop to: narrow systemic, broad systemic, and complete systemic. Looking at the different levels of knowledge complexity that firms build over time, the largest share of firms develop to a broad systemic approach, covering both knowledge bases but not covering all four technology components (see Figure 6).

An interesting finding here is regarding the knowledge base: while a share of firms only expands within design knowledge, no firm can be observed to start and remain in only specialized components, that is, ink or substrate (see Figure 7). Instead, all firms that start in components embedding specialized knowledge, over time, build knowledge bases in design knowledge, too. It appears that investing in components rich in design knowledge enables firms to position themselves in the converging technology system, taking architectural design challenges into account (Jaspers et al., 2012). For the investigated printed electronic case, this means, for example, that material suppliers cannot only produce conductive ink for the manufacturing process of printed electronics without an understanding of the complex design requirements of the converged printed electronics application and/or process itself. This highlights the need for firms that invest in components rich in specialized knowledge, to also build design knowledge in order to meet the demands of a dynamically evolving technology system and allow for compatibility.

In line with prior research, we argue that in highly dynamic environments, as characterized by converging technology system, specialized knowledge alone is not sufficient—contrarily, building additional knowledge across design knowledge bases seems critical (Fleming, 2001; Fleming & Sorenson, 2001; Galunic & Rodan, 1998; Henderson & Clark, 1990; Wang & Von Tunzelmann, 2000). Rotolo et al. (2015) find that emerging technology systems inherit uncertainty and dynamics, which, according to our findings, can be overcome by firms if they co-evolute their technology strategy with the development of the technology system.

The observations made in the focused evolving technology strategy underline again the importance of design knowledge, which embeds an understanding of system structure, intersection, and possible interdependencies (Baldwin & Clark, 2000; Grodal et al., 2015; Jaspers et al., 2012). The importance of design knowledge for every firm, no matter the initial knowledge base, is reflected in the following proposition:

> **Proposition 5.** *Firms that start engaging in the development of an emerging complex technology system with a focused approach and then expand, tend to additionally develop design knowledge to allow co-evolution with the converging technology system.*

Building a sustained position in the evolving technology system, potentially acting as a system integrator, is in contrast to theory, not necessarily bound to the firm's timing of engagement (Bayus & Agarwal, 2007; Lee et al., 2000). However, while the focused evolving strategy is prominent in our sample regardless of timing of entry, followers have a slightly higher tendency to follow alternative technology strategies to the focused evolving approach. Those firms that we observe to enter late appear to have a higher tendency to start systemic compared to pioneers. This can potentially be extended with a finding observed by García-Cabrera et al. (2019), who conclude that followers tend to have a higher technological competence. This also aligns with the early findings of Lieberman and Montgomery (1988), who argue in their seminal work on first-mover advantages that pioneers need more capacity to protect their position against aggressive followers—this shows in our case through a strong majority of pioneers expanding their investments in depth and breadth over time. Figure 8 summarizes the five propositions on technology strategy, integrating system coverage, relevant knowledge stocks, and strategy evolvement.

5 | CONCLUSION

This study explores technology strategies in converging technology systems based on the conceptualization of TSC. To the best of our knowledge, this is the first attempt to account for the complexities inherent in converging technology systems and offering an operational approach to strategically master associated challenges. More precisely, TSC draws on the scope, distinguishing between a focused and a systemic approach; and the underlying knowledge base, distinguishing between components rich in design or specialized knowledge. The conceptualization of TSC adds a novel dimension to technology strategy in the realm of complex, uncertain, and dynamic characteristics of emerging technology systems. Based hereon, the study identifies four central technology strategies that differ regarding their technology systems coverage and their dynamics. The results indicate that all firms build design knowledge over time, whereas it is

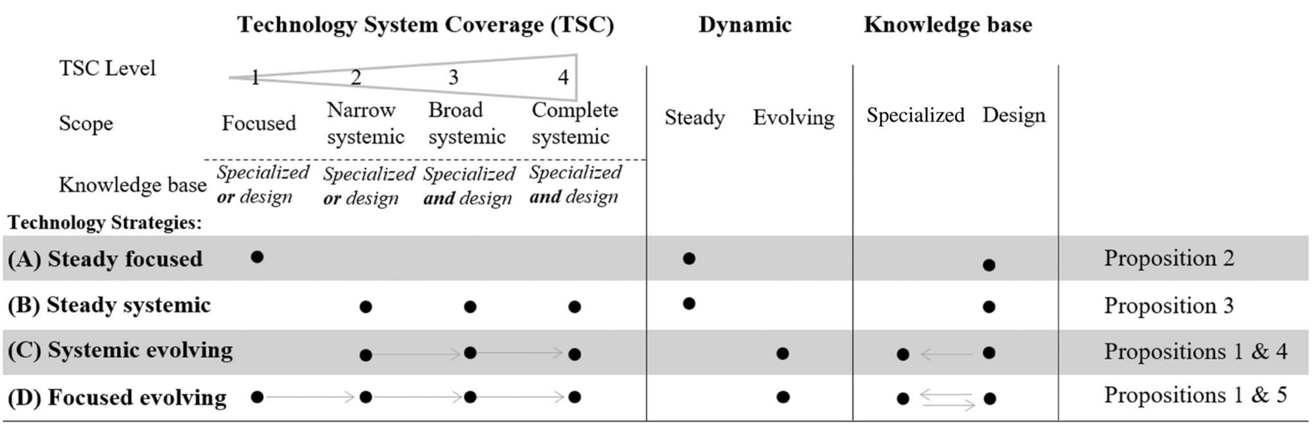

FIGURE 8 Empirically informed technology strategies and propositions.

remarkable that not all firms build specialized knowledge, no matter what technology strategy is pursued.

This study provides a valuable contribution to the previous understanding of technology strategies, which are yet lacking a systems perspective: In their foundational article on technology strategy, Zahra (1996) conceptualized a company's technology strategy based on six dimensions: timing of entry, number of products, internal/external R&D source, R&D spending, portfolio of applied/basic R&D projects, and use of patenting. We expand their notion by offering TSC as an additional dimension of technology strategy. While Zahra (1996) focuses on the competitive environment, TSC as a strategy dimension allows additional insights into a firm's co-evolution with the emerging technology system.

Moreover, this study advances Schilling and Hill's (1998) process view of the new product development process by shedding light on the connection and co-evolution between a firm's technology strategy to the development of complex emerging technology systems. In particular, our findings highlight the importance for firms to adjust their knowledge base and the importance of design knowledge as an enabler to understanding interdependencies between components and potentially allowing orchestration of the development.

We also expand the approach of Cho et al. (2015), who assign each firm to a single technology component based on their industry classification, while we offer a more fine-grained perspective by assigning each patent to a single technology component. While Cho et al. (2015) rely on collaborative network activities to emphasize the increase in technological intensity, our study offers a more intricate view on the co-evolution of firms participating in emerging technology systems. This enables a better understanding of how firms expand their internal knowledge base and scope when participating in an emerging complex technology system. Our findings based on the two knowledge bases, design and specialized, and the relevance of their sequencing, further advance the findings of Persoon et al. (2021), who emphasize the importance of technological cumulativeness.

The results of this study lead to several practical implications. The findings enable managers to become aware of the complexity inherent in converging technology systems. In particular, we suggest a structuring as follows: First, to structure a complex technology system into components and their emerging development; second, to build an understanding of to what extent components and involved knowledge bases might originate from another hitherto distant technology system; and third, to monitor interdependencies between components and the technology system's underlying architectural design. Moreover, by disentangling underlying interdependencies, firms can identify bottlenecks and competence gaps in a timely manner. Overall, TSC and its dynamics as a relevant technology strategy dimension may support firms in developing their technology strategies in the increasingly complex and uncertain environment surrounding emerging technology systems.

5.1 | Limitations and future research

Despite the significance of our findings, it is important to consider them in light of several limitations. This study refers to patents as indicator of firms' development and knowledge-building activities in a converging technology system. While the search string has been carefully put together based on previous studies and validated by industry experts, interviews with these industry experts additionally suggested that a patent search string needs to balance capturing all relevant patents and keeping noise at a manageable level. Thus, said interviews indicated that aiming for completeness is not realistic in a technology landscaping approach, similar to our underlying study, due to the nature of patents, which are often written with the intention not to be found. Therefore, a risk remains that not every patent relevant to the field could be represented in this study. To mitigate this risk, we truncated search terms and selected patent families instead of individual patents as a basis, whereby we increase the probability of inclusion and securing a comprehensive sample.

Another limitation regarding patents relates to completeness. Even though patenting is widespread in the electronics industry, it might not cover all technology development activities, as not every invention is patented in the first place. Patents thus provide a robust albeit not entirely complete reflection on technology strategies. Moreover, patents do not capture the entirety of companies' knowledge-building approaches. To this end, firms' technology portfolios beyond patents in printed electronics might add further insights. Future research could triangulate patent data by capturing in-licensing (Motohashi, 2008), mergers and acquisition data (Rennings et al., 2022), or technology collaborations, as well as additional publications on firms' technology strategies, such as annual reports.

Moreover, the findings regarding key players in the systemic evolving technology strategy may be somewhat limited by the consequence of small number statistics. As our database contains only firms that present a long-term interest in the field through continuous participation, this causes a relatively small sample size of 74 key players in the field. Consequently, the systemic evolving technology strategy has only been observed in three key players. Even though these three players show the same pattern of evolution, we suggest interpreting this specific technology strategy with caution. Further studies in other complex technology systems, possibly with a larger sample, could be undertaken to further explore the technology strategies and propositions uncovered here.

Another point that should be noted is that the underlying sample focuses on firms actively participating in the converging technology system and does not include companies that resist participation and those that withdraw from sustained participation. Future research efforts could address this point and extend the sample beyond active participants, for example, to explore ineffective technology strategies and potential reasons for their ineffectiveness. We would also like to draw the readers' attention to the fact that the underlying assumption of knowledge accumulation does not necessarily imply that firms are continuously active in these knowledge areas and, on a similar note, the sample is not able to account for strategic reorientation. We suggest integrating this in future studies, for example, by using additional patent-based measures such as patent newness or citations.

Scope and knowledge base as foundations of TSC, in combination with dynamics, seem especially relevant for developing deliberate technology strategies in the context of complex technology systems. However, future research could reflect the identified technology strategies against Mintzberg and Waters' (1985) view on the nature of strategy in general: not all strategies are ex-ante consciously intended, some also simply emerge as a pattern.

For scholars rooted in convergence research, the four technology strategies in this paper may serve as a starting point to investigate how company dynamics impact industry dynamics. Future research might therefore explore which industry background and competence profiles, in connection to specialized versus design knowledge, allow the orchestration of converging technology systems and how this affects the overall industry structure.

Lastly, it would be highly desirable if further research included the novel dimension of TSC amongst other dimensions of technology strategy. This would not only validate the novel construct but also help to understand how it relates to other dimensions. To further increase generalizability, a replication of our analyses in other high-technology sectors involving complex technology systems seems insightful.

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CONFLICT OF INTEREST STATEMENT

The authors have no conflict of interest to declare.

ETHICS STATEMENT

The authors have read and agreed to the Committee on Publication Ethics (COPE) international standards for authors.

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APPENDIX A.

TABLE A1 Overview of companies and their technology strategies.

Company name	Timing	Initial year	Initial component	Initial TSC	Initial knowledge base	Final year	Final components (accum.)	Final TSC	Final knowledge base	Technology strategy
3M CO	Pioneer	1990	Ink	1	Specialized	2010	Substrate/Ink/MD/EA	4	Both	Focused evolving
AMS AG	Pioneer	2003	EA	1	Design	2018	Ink/MD/EA	3	Both	Focused evolving
APPLE INC.	Pioneer	2012	MD/EA	2	Design	2019	MD/EA	2	Design	Steady systemic
ASE TECHNOLOGY HOLDING CO. LTD.	Pioneer	2000	EA	1	Design	2018	MD/EA	2	Design	Focused evolving
AVERY DENNISON CORP.	Pioneer	1997	EA	1	Design	2016	EA	1	Design	Steady focused
BASF SE	Pioneer	1991	Ink	1	Specialized	2018	Ink/MD	3	Both	Focused evolving
BLUE SPARK TECHNOLOGIES INC.	Follower	2005	EA	1	Design	2017	EA	1	Design	Steady focused
BOE TECHNOLOGY GROUP LTD.	Pioneer	1993	EA	1	Design	2019	Substrate/MD/EA	3	Both	Focused evolving
BOEING CO. (THE)	Follower	2004	MD/EA	2	Design	2019	MD/EA	2	Design	Steady systemic
BORGWARNER INC.	Pioneer	1992	MD	1	Design	2005	MD/EA	2	Design	Focused evolving
BOSCH (ROBERT) GMBH	Pioneer	2002	EA	1	Design	2014	MD/EA	2	Design	Focused evolving
BROTHER INDUSTRIES LTD.	Pioneer	1998	EA	1	Design	2015	MD/EA	2	Design	Focused evolving
CANON INC.	Pioneer	1999	Ink	1	Specialized	2018	Substrate/Ink/MD/EA	4	Both	Focused evolving
COMPAGNIE DE SAINT-GOBAIN	Follower	2000	EA	1	Design	2019	Substrate/MD/EA	3	Both	Focused evolving
CORNING INC.	Pioneer	2013	MD	1	Design	2017	Substrate/MD/EA	3	Both	Focused evolving

TABLE A1 (Continued)

Company name	Timing	Initial year	Initial component	Initial TSC	Initial knowledge base	Final year	Final components (accum.)	Final TSC	Final knowledge base	Technology strategy
DIC CORPORATION	Pioneer	2006	Ink	1	Specialized	2019	Ink/MD/EA	3	Both	Focused evolving
DOW CHEMICAL CO.	Pioneer	1993	MD	1	Design	2010	Substrate/MD	3	Both	Focused evolving
DUPONT DE NEMOURS INC.	Pioneer	1998	Substrate	1	Specialized	2019	Substrate/Ink/MD/EA	4	Both	Focused evolving
EASTMAN KODAK COMPANY	Pioneer	1991	MD	1	Design	2018	Substrate/Ink/MD/EA	4	Both	Focused evolving
FUJI FILM HOLDINGS CORP.	Follower	1992	EA	1	Design	2015	Ink/MD/EA	3	Both	Focused evolving
GENERAL ELECTRIC COMPANY	Pioneer	2002	MD	1	Design	2018	Ink/MD/EA	3	Both	Focused evolving
GLOBAL FOUNDRIES INC.	Pioneer	1996	MD	1	Design	2013	MD/EA	2	Design	Focused evolving
GULA CONSULTING LLC	Follower	2005	MD	1	Design	2010	Ink/MD/EA	3	Both	Focused evolving
HENKEL KGAA	Pioneer	1993	Ink	1	Specialized	2015	Ink/MD	3	Both	Focused evolving
HITACHI LTD.	Pioneer	1992	Ink	1	Specialized	2007	Ink/MD/EA	3	Both	Focused evolving
HON HAI PRECISION INDUSTRY CO. LTD.	Pioneer	2000	EA	1	Design	2019	Ink/MD/EA	3	Both	Focused evolving
HONEYWELL INTERNATIONAL INC.	Pioneer	1999	EA	1	Design	2018	MD/EA	2	Design	Focused evolving
HP INC.	Pioneer	1990	EA	1	Design	2019	Ink/MD/EA	3	Both	Focused evolving
HSIO TECHNOLOGIES LLC	Follower	2011	EA	1	Design	2018	EA	1	Design	Steady focused
ILLINOIS TOOL WORKS INC.	Follower	2006	Substrate	1	Specialized	2018	Substrate/MD/EA	3	Both	Focused evolving
INFINEON TECHNOLOGIES AG	Pioneer	2001	MD	1	Design	2019	MD/EA	2	Design	Focused evolving

(Continues)

TABLE A1 (Continued)

Company name	Timing	Initial year	Initial component	Initial TSC	Initial knowledge base	Final year	Final components (accum.)	Final TSC	Final knowledge base	Technology strategy
INGREDION INC.	Follower	2000	Ink	1	Specialized	2016	Ink/MD/EA	3	Both	Focused evolving
INTEL CORPORATION	Follower	2001	MD	1	Design	2019	Ink/MD/EA	3	Both	Focused evolving
INTERNATIONAL BUSINESS MACHINES CORP.	Pioneer	1990	MD	1	Design	2013	Substrate/Ink/MD/EA	4	Both	Focused evolving
JOHNSON ELECTRIC HOLDINGS LTD.	Pioneer	1993	EA	1	Design	2018	EA	1	Design	Steady focused
KOCH INDUSTRIES INC.	Pioneer	1995	MD	1	Design	2019	MD/EA	2	Design	Focused evolving
KONINKLIJKE PHILIPS N.V.	Pioneer	1997	MD	1	Design	2012	Ink/MD/EA	3	Both	Focused evolving
KYOCERA CORP.	Pioneer	1995	Ink	1	Specialized	2016	Ink/MD/EA	3	Both	Focused evolving
LG DISPLAY CO. LTD./LG CHEM LTD.	Follower	2003	EA	1	Design	2019	Ink/MD/EA	3	Both	Focused evolving
MERCK KGAA	Pioneer	2006	MD / EA	2	Design	2017	Ink/MD/EA	3	Both	Systemic evolving
MICRON TECHNOLOGY INC.	Pioneer	1992	MD	1	Design	2010	Ink/MD/EA	3	Both	Focused evolving
MITSUBISHI ELECTRIC CORP.	Pioneer	1990	MD / EA	2	Design	2016	MD/EA	2	Design	Steady systemic
MOTOROLA SOLUTIONS INC.	Pioneer	1991	MD	1	Design	2008	Substrate/Ink/MD/EA	4	Both	Focused evolving
NEC CORP.	Pioneer	1993	MD	1	Design	2014	Substrate/MD/EA	3	Both	Focused evolving
NOKIA CORPORATION	Pioneer	1996	EA	1	Design	2019	MD/EA	2	Design	Focused evolving
OKI ELECTRIC INDUSTRY CO. LTD.	Pioneer	1995	EA	1	Design	2001	MD/EA	2	Design	Focused evolving
PANASONIC CORPORATION	Pioneer	1990	MD	1	Design	2016	Substrate/Ink/MD/EA	4	Both	Focused evolving
PARELEC INC.	Pioneer	1999	MD	1	Design	2007	Ink/MD	3	Both	Focused evolving

TABLE A1 (Continued)

Company name	Timing	Initial year	Initial component	Initial TSC	Initial knowledge base	Final year	Final components (accum.)	Final TSC	Final knowledge base	Technology strategy
PARKER HANNIFIN CORP.	Follower	1998	EA	1	Design	2018	Ink/MD/EA	3	Both	Focused evolving
POLARIS INDUSTRIES INC.	Pioneer	2002	MD / EA	2	Design	2007	Substrate/MD/EA	3	Both	Systemic evolving
PRECURSOR ENERGETICS INC.	Pioneer	2010	MD / EA	2	Design	2014	Ink/MD/EA	3	Both	Systemic evolving
QUALCOMM INC.	Pioneer	2004	MD	1	Design	2014	MD/EA	2	Design	Focused evolving
RENESAS ELECTRONIC CORPORATION	Pioneer	2001	EA	1	Design	2016	MD/EA	2	Design	Focused evolving
ROHM CO. LTD.	Pioneer	1995	EA	1	Design	2015	MD/EA	2	Design	Focused evolving
SAMSUNG ELECTRO MECHANICS CO. LTD./ SAMSUNG ELECTRONICS CO. LTD.	Pioneer	1996	MD	1	Design	2019	Substrate/Ink/MD/EA	4	Both	Focused evolving
SAUDI ARABIAN OIL COMPANY (SAUDI ARAMCO)	Follower	2003	Ink	1	Specialized	2018	Ink/MD/EA	3	Both	Focused evolving
SEIKO EPSON CORPORATION	Pioneer	2002	MD / EA	2	Design	2008	MD/EA	2	Design	Steady systemic
SEMICONDUCTOR ENERGY LABORATORY CO. LTD.	Follower	2004	EA	1	Design	2018	MD/EA	2	Design	Focused evolving
SHIN-ETSU CHEMICAL CO. LTD.	Pioneer	1990	MD	1	Design	2018	Ink/MD/EA	3	Both	Focused evolving
SONY CORP.	Follower	2006	EA	1	Design	2012	Substrate/Ink/MD/EA	4	Both	Focused evolving
STMICROELECTRONICS	Follower	2012	EA	1	Design	2018	EA	1	Design	Steady focused
SUMITOMO CHEMICAL CO. LTD.	Pioneer	2006	Ink	1	Specialized	2017	Ink/MD/EA	3	Both	Focused evolving
TACTOTEK OY	Pioneer	2011	EA	1	Design	2019	Ink/MD/EA	3	Both	Focused evolving

(Continues)

TABLE A1 (Continued)

Company name	Timing	Initial year	Initial component	Initial TSC	Initial knowledge base	Final year	Final components (accum.)	Final TSC	Final knowledge base	Technology strategy
TAIWAN SEMICONDUCTOR MANUFACTURING CO.	Pioneer	2007	Ink	1	Specialized	2018	Ink/MD/EA	3	Both	Focused evolving
TCL CORP.	Follower	2013	EA	1	Design	2019	Ink/MD/EA	3	Both	Focused evolving
TDK CORPORATION	Pioneer	1999	MD / EA	2	Design	2018	MD/EA	2	Design	Steady systemic
TEXAS INSTRUMENTS INC.	Pioneer	1996	MD	1	Design	2018	MD/EA	2	Design	Focused evolving
THIN FILM ELECTRONICS ASA	Follower	2005	EA	1	Design	2019	Ink/MD/EA	3	Both	Focused evolving
TOSHIBA CORP.	Pioneer	1991	MD	1	Design	2017	MD/EA	2	Design	Focused evolving
UNIMICRON TECHNOLOGY CORP.	Follower	2006	Substrate/ MD/EA	3	Both	2013	Substrate/MD/EA	3	Both	Steady systemic
VORBECK MATERIALS CORP.	Follower	2009	Ink	1	Specialized	2019	Substrate/Ink/MD/ EA	4	Both	Focused evolving
X DISPLAY CO. TECHNOLOGY LTD.	Follower	2007	EA	1	Design	2019	Substrate/MD/EA	3	Both	Focused evolving
XEROX CORP.	Pioneer	1991	MD	1	Design	2019	Substrate/Ink/MD/ EA	4	Both	Focused evolving
ZHUHAI SEINE TECHNOLOGY CO. LTD.	Pioneer	2005	MD	1	Design	2007	Ink/MD	3	Both	Focused evolving

Abbreviations: EA, electronic application; MD, manufacturing device; TSC, technology system coverage.