Breakthrough Technologies and Emerging Industries: The Role of Entrepreneurial Firms, Incumbents and Intermediaries in Organic and Printed Electronics

A Thesis Submitted to the University of Manchester for the Degree of
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Abstract

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Technological breakthroughs are drivers of structural change and of the economic welfare of nations. However, the evolution from breakthrough technologies to an emerging industry is complex and distributed. It involves interactions and collaborations among heterogeneous actors with varying competencies, competing goals and divergent incentives. Understanding the dynamics underlying the emergence of new industries, though critical, is underresearched. This thesis investigates the dynamics of an emerging industry based on a breakthrough technology – Organic and Printed Electronics (OPE).

OPE is a multidisciplinary field and requires developing and combining competencies across physics, chemistry, and engineering. It requires the expertise of different industries that need to collaborate for innovation. The technology is currently going through a transition, moving from diverse possible technological and market options to become a clearer, smaller number of mainstream selections.

The study aimed at researching this new emerging domain as it emerges, and provides a global overview of the industry, discusses the dynamics at the meso level, investigates the role of intermediaries, and finally focuses on mobilisation of inter-organisational and intra-organisational routines by an entrepreneurial firm as it moves towards commercialisation, discussing in detail how a large incumbent upstream material firm developed the tools and mechanisms to overcome the gale of creative destruction and capture opportunity.

Small entrepreneurial firms are considered as initiators and stimulators of widespread interest in the potential of breakthrough technologies. However, they do face considerable commercialisation challenges owing to their small size, limited financial, human and relational resources and the liability of newness. The findings demonstrate that entrepreneurial firms can be market shapers provided they are product oriented, progressively create an innovation ecosystem and articulate a large repertoire of routines at the intra-organisational and inter-organisational level.

The emergence of new industries is mostly associated with creative destruction and the decline of incumbents. However, there are outliers-the study provides evidence that holistic mechanisms and routines for reconfiguration of capabilities aimed at transformation rather than evolution or substitution can enable an upstream material firm to innovate and capitalise on rising opportunities.

Intermediaries (research and technology organisations (RTO) and industry associations) emerged as enablers for innovation within Organic and Printed Electronics and important loci where inter-organisational routines are developed. RTOs in this fluid phase of technological development provide for the convergence of competing options and are paving the path for commercialisation and scaling up of selected processes. In the case of OPE, the role of the industry association is critical in establishing cognitive and sociopolitical legitimacy, creating expectations, demand articulation, and developing infrastructural knowledge and classification that enable the relevant actors to ascertain their position within the future supply chain.

Declaration

No portion of the work referred to in the thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

Copyright Statement

Abbreviations

TAC - Technical Advisory Council

COPE - Centre for Organic Photonics and Electronics

CPI - Centre for Process Innovation

CSO-Chief Scientific Officer

CTO-Chief Technology Officer

EPFL - École Polytechnique Fédérale De Lausanne

EPSRC - Engineering and Physical Research Council

KTN - Knowledge Transfer Network

LOPEC - Large Area Organic & Printed Electronics Convention

NFC - Near Field Communication

NIST - National Institute of Standards and Technology

OLED - Organic Light Emitting Diodes

OPV - Organic Photovoltaics

OFET - Organic Field Effect Transistors

OTFT - Organic Thin Film Transistor

OE-A - Organic and Printed Electronics Association

OPERA- Organic/Plastic Electronics Research Alliance

PRODI - Manufacturing and Production Equipment and Systems for Polymer and Printed Electronics

RFID - Radio Frequency Identification

RTO - Research and Technology Organisation

SGD - Solvay Global Discovery Program

TSB - Technology Strategy Board

VP-Vice President

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Dedicated To

Asad, Saad, Maaz and Hibah

Chapter 1: Introduction

Emerging technologies are "science-based innovations with the potential to create a new industry or transform an existing one" (Day and Schoemaker, 2000, p.2) and offer something radically new in terms of products, processes and services, thus "altering the competitive landscape" (Garud and Rappa, 1994, p.344). They are also referred to by other terms in the literature such as revolutionary, and enabling (Hilgartner and Lewenstein, 2004; Ávila-Robinson and Miyazaki, 2013). Technological breakthroughs are drivers of structural change (Metcalfe and Gibbons, 1989) and of the economic welfare of nations (Hamilton, 1985). Innovation studies discussing the emergence of new technological and knowledge-based fields like biotechnology and nanotechnology (Darby and Zucker, 2005; Bozeman et al., 2007; Van der Valk et al., 2009) have identified common dynamics which characterise different stages of development: uncertainty; complexity; heterogeneity of actors; distributed nature of knowledge, particularly relevant in the first stage of the industry life cycle; the emergence of a dominant design; and convergence of a broad range of technological and scientific fields at a later stage. Furthermore, breakthrough technologies, though offering high future expectations, are initially low in performance and are challenged by existing incumbent technologies. This therefore necessitates developing them in technological niches where they are nurtured and shielded. Niches, as argued by Geels (2005, p.79), are incubation rooms for radical innovations.

However, the evolution of breakthrough technologies to an emerging industry is complex and distributed. It involves interactions and collaborations among heterogeneous actors with varying competencies, competing goals and divergent incentives (Mina, 2009). Transition from niches to mainstream is thus a dynamic interplay of three processes of articulation of expectation, learning and network (Hoogma, 2002). Understanding the dynamics, underlying the emergence of new industries, though critical (Krafft et al., 2014; Sanderson and Simons, 2014), are mostly left unanswered and underresearched (Giarratana, 2004; Forbes and Kirsch, 2011). "The richness of information that can be collected in the first stages of an industry goes well beyond conventional wisdom of management and industrial studies" (Giarratana, 2004, p.787).

Among the theoretical and empirical challenges that have resulted in this decreased focus are the problems related to identifying the emerging technology before it is mature, and the relative scarcity of data (Forbes and Kirsch, 2011). Some industries fail early and do not experience all the identified stages of industry development such as emergence, growth and dominant design, maturity and decline, resulting in a dearth of systematic research on the emergence of a new population (Aldrich, 1999). According to Tether and Stigliani (2012, p.2), "most industry life cycle studies instead start post-infancy; that is, after the industry has already survived its most vulnerable life stage. But who were these earliest entrants, and how did their behaviours shape the subsequent development of the industry? We know surprisingly little about these questions". One major reason for this limited understanding is the empirical challenges associated with the exploration of ongoing processes for radical technology. Most of the studies have focused on historical and retrospective analysis. Markard and Truffer (2008, p.1166-67) elaborate, "it is demanding because the underlying innovation processes are complex as they typically depend on the co-development of new socio-technical configurations, new market structures, new actors and new institutional settings."

According to Murtha et al. (2001, p.31), "new high-technology industries often bubble under the surface for many years in several countries before they suddenly achieve critical mass and commercialize at global scale in one or more of them". There exists a consensus within the limited but growing literature on industry emergence regarding three periods of industry lifecycle that are characterised as the pre-founding stage, the emergent stage and finally the later stages of growth and maturity (Gustafsson et al., 2015). According to Forbes and Kirsch (2011) industry emergence is a temporal event within an industry lifecycle and it may vary, being a couple of years in some cases and in others extending up to 50 years. They emphasised the required focus for this initial period, that necessitates identifying dynamics beyond the producer firms and extending it to include a variety of other actors such as government authorities, venture capitalists, regulatory bodies and associations.

Emerging industries are characterised by complexity, global competition, fuzzy boundaries, continuously changing landscapes, institutional entrepreneurship, participation of de alio firms and finally emergence of a large number of entrepreneurial firms and start-ups that demand divergence, nonconformity to the norms, creativity, and development of new business models and organisational forms. (Santos and Eisenhardt, 2009; Sine and Lee, 2009; Forbes and Kirsch, 2011; Tether and Stigliani, 2012; Gustafsson et al., 2015).

The management of emerging technologies, owing to their uncertainties, complexities and Schumpeter's vision of the process of creative destruction, is a different game (Day and Schoemaker, 2000). The good practices of managing innovation under a steady state may not be applied in the fluid phase of the technology. It requires building new capabilities and working out of the box. Firms, however, differ in innovativeness and profitability (Dosi et al., 2008). Entrants, compared to incumbents, are considered better equipped to commercialise radical emerging technology owing to their flexibility, small size and limited path dependency (Macher and Richman, 2004). This heterogeneity in organisational capabilities is embedded in organisational processes and routines. Organisational routines, since their popularisation by Nelson and Winter (1982) in evolutionary theory, have been considered vital in understanding organisational behaviour, learning and change (Becker and Lazaric, 2009). They are described as "repositories of organizational capabilities" and knowledge (Winter, 2000; Becker, 2005; Dosi et al., 2008; Nelson, 2009). Routines are multi-actor phenomena and contribute to shared understanding and connection among organisational members (Cohen and Bacdayan, 1994; Feldman and Rafaeli, 2002; Becker, 2004). The collective nature of routines points towards another important attribute associated with routines – distributedness. Routines are carried out by multiple actors distributed across the different business units of the same organisation, thus intra-organisational, or belong to different organisations and are inter-organisational.

1.1 Research Context and Objective

The thesis aims to contribute to the literature on the routine-based view of capabilities at the firm level in the context of the emergence of new industry based on breakthrough technologies. The technology studied in this context is Organic and Printed Electronics (OPE). OPE is considered to be one of the key enabling technologies with a high economic potential and broader societal implications. These visions have been shaping political intervention, coordinated actions and the emergence of hybrid forums and techno-economic networks. At present there are approximately 3,000 organisations active in the field within three competing regions – USA, Europe and Asia – and these include universities, research institutes, and large organisations as well as start-ups (Frost and Sullivan, 2010; IDTechEx, 2011). There is evidence of increased financial support from regional and national government, venture capital, consortia and other organisations.

OPE is a multidisciplinary field and requires developing and combining competencies across physics, chemistry, and engineering. It requires the expertise of different industries that need to collaborate for innovation. The technology is currently going through a transition, moving from diverse possible technological and market options to become a clearer, smaller number of mainstream selections, and this requires developing ecosystems and processes at the macro, meso and micro levels.

The underlying dynamics presented above set the objectives for the thesis and provide the unique opportunity to explore the phenomenon at various levels.

Research Objective 1: How does potentially disruptive and breakthrough technology evolves to become an emerging industry?

- At the macro level, the thesis elaborates on the progressive construction of ecosystem within the two main hubs in Europe – UK and Germany.
- At the meso level, the role of intermediaries for breakthrough technologies and emerging industries is discussed. The study contends that the research and technology organisation (RTO) and industry association are instrumental in the technology's transition from niches to mainstream markets.
- At the micro, firm level, there is the presence of a large number of small and large firms and the space is characterised by interactions, interdependencies and symbiotic relationships. The thesis extends, contributes to and explains in depth the dynamics at the micro level using a routine-based model of the firm (Nelson and Winter, 1982; Cohen and Levinthal, 1990; Lewin et al., 2011). Inter-organisational and intra-organisational routines mobilised by an entrepreneurial, growing firm and a large incumbent upstream firm provide rich and novel insights into the processes at the firm level and in the context of industry emergence.

Routines and capabilities are considered thorny constructs and treated as black boxes (Salvato and Rerup, 2011). The literature on dynamic capabilities discusses routines that form the microfoundations of capabilities (e.g. Elsenhardt and Martin (2000); Teece (2007); Lewin et al., 2011). However, most of the empirical studies were conducted in established industries rather than those in transition, as in the context of this study, and therefore demand investigation.

Research Objective 2: To understand the microfoundation of organisational capabilities and thereby investigate the dynamics of inter-organisational and intra-organisational routines for breakthrough technologies in emerging industries.

1.2 The Research Approach

Owing to the underresearched themes related to emerging industries, organisational routines and newness of the OPE technology, the research has been mainly exploratory and has employed qualitative methods. To identify the revelatory cases and understand the scope of the technology, secondary research, researcher participation in field-configuring events, and discussions with technological and market consultants, government officials and institutional entrepreneurs constituted the initial stages. Primary data was based on interviews mainly conducted face to face with heterogeneous players such as universities, research and technology institutes, centres of excellence, industry associations, academic and non-academic start-ups and large incumbent, mostly upstream, material firms. The fieldwork thus facilitated rich understanding of the dynamics of the technology and provided a rare opportunity to study the breakthrough technology in its emergent phase.

1.3 Structure of the Thesis

The thesis is structured as follows:

Chapter 2 reviews the relevant literature on three central areas: breakthrough technologies and emerging industries; actors and processes in the context of breakthrough technologies and emerging industries whereby the three dominant actors – new technology-based firms, incumbents and intermediaries were discussed; and organisational routines as microfoundation of organisational capabilities.

Chapter 3 elaborates the main research question and a number of sub-questions that guide the research. It discusses the research methodology, provides justification for the single case study design and describes the iterative selection of cases at firm level. It also reflects on the challenges associated with data collection in the context of emerging industries and discusses the data analysis.

Chapter 4 takes the bird's-eye perspective and describes the OPE technology, its characteristics and main applications. It further highlights the importance and disruptive potential of breakthrough technology that acted as the main driver for its selection as an interesting context for the study of emerging industry.

Chapter 5 provides a rich account of the emergence of an ecosystem and agglomeration of heterogeneous actors and institutions in two main European hubs – UK and Germany. It highlight the challenges faced at the current ferment phase and the discourses that proliferate in the space of OPE and sets the scene for the in-depth analysis of cases presented in Chapters 6-8.

Chapter 6 is an in-depth case study of the orchestration of a business ecosystem by an entrepreneurial firm that changed its business model from component provider to integrator. It provides the dynamics of inter-organisational and intra-organisational routines mobilised by the firm to extract value from the ecosystem and develop capabilities related to commercialisation.

Chapter 7 investigates how the large firms are responding to the challenges associated with breakthrough technology. It discusses thoroughly the reconfiguration and transformation of capabilities by a large, upstream incumbent firm that prepares itself to explore the possibilities and opportunities offered by the breakthrough technology and take advantage as and when it arises.

Chapters 8 discuss the meso level activities. Intermediaries are instrumental for the shaping and emergence of the OPE industry. In this chapter, the roles of two main types of intermediary, the research and technology organisation (RTO) and the industry association, are discussed.

Chapter 9 concludes the thesis with a critical review of key findings, reflecting the limitations of the study and discussing its theoretical and empirical contributions.

Chapter 2: Literature Review

2.1 Introduction

The chapter discusses thoroughly the relevant streams of literature that provide the foundation for this study in the context of emerging industries. Section 2.2 introduces the concept of breakthrough technologies and emerging industries and discusses dynamics such as uncertainty, complexity, hype and sailing ship effect associated with breakthrough technologies. It also accounts for theoretical considerations that tend to be important for understanding the transition of technology from protective spaces and emergence of industry. Section 2.3 discusses the role of three major actors: entrepreneurial firms, incumbent large organisations and intermediaries. Sections 2.4 elaborate the distributed nature of knowledge in a domain characterised by uncertainty and complexity, highlighting the need for an alternate form of organising such as an ecosystem. Section 2.5 focuses on the central concept of "organisational routines" that form the backbone of the study. Section 2.6 elaborates on the routine-based model of absorptive capacity that informs the conceptual framework.

2.2 Breakthrough Technologies and Emerging Industries

Stimulating new industries from breakthrough technologies has been identified with the success and economic welfare of nations (Hamilton, 1985; Hung and Chu, 2006) and has the potential to "alter the competitive landscape" (Garud and Rappa, 1994, p.344).

Emerging technologies have the potential to offer something radically new in terms of products, processes and services, and are also referred to by other terms in the literature such as revolutionary, enabling, and breakthrough (Hilgartner and Lewenstein, 2004; Avila-Robinson and Miyazaki, 2011). However, the myriad of conceptual and empirical research has resulted in overlaps, as well as contradictions as to when technology is considered as emerging (Rotolo et al., 2015). Emerging technology can be defined as:

> A radically novel and relatively fast growing technology characterised by a certain degree of coherence persisting over time and with the potential to exert a considerable impact on the socioeconomic domain(s) which is observed in terms of the composition of actors, institutions and patterns of interactions among those, along with the associated knowledge production processes.
>
> Its most prominent impact, however, lies in the future and so in the emergence phase is still somewhat uncertain and ambiguous. (Rotolo et al., 2015, pp.3-4)

The above definition thus points to five important attributes associated with emerging technologies: (1) novel and revolutionary, (2) relatively fast growth, (3) coherence and momentum, (4) pervasiveness and prominent impact and (5) uncertainty and ambiguity. New technologies are also often associated with the emergence of new industries (Adner and Levinthal, 2002). However, the transition from new technology to an emerging industry is complex (Hung and Chu, 2006). The evolution of technology alone is not associated with industry emergence and may require other interacting elements such as government policies, investment climate, new business models, developing value chains, market acceptance and, in a few cases, creating niche markets. According to Day and Schoemaker (2000, p.2), "emerging technologies are science-based innovations with the potential to create a new industry or transform an existing one." Furthermore, "science-based businesses emerge at the intersection of multiple bodies of science" (Pisano, 2006, 2010).

Emerging industries are defined by Porter (1980, p.215) as "newly formed or re-formed industries that have been created by technological innovations, shifts in relative cost relationships, emergence of new consumer needs, or other economic and sociological changes that elevate a new product or service to the level of a potentially viable business opportunity".

Lubik et al. (2012) defined emerging industries as:

> …those where no clear or established value chain currently exists. These can either be those where a new technology exists and there is no clear market and therefore no route to market, or those where a market exists but the introduction of a new technology could rearrange or destroy the existing value chain or industry. (*ibid*., p.11)

Despite the importance of emerging technologies and new industries for economic wellbeing, theoretical and empirical constraints have contributed to a scarcity of research in this domain (Sanderson and Simons, 2014). "The dynamics by which new industries are created, and how these develop over time, represent a crucial issue for understanding the evolutionary patterns of capitalistic economies" (Krafft et al., 2014, p.1663).

According to Tether and Stigliani (2012, p.2), "most industry life cycle studies instead start post-infancy; that is, after the industry has already survived its most vulnerable life stage. But who were these earliest entrants, and how did their behaviours shape the subsequent development of the industry? We know surprisingly little about these questions". One major reason for this limited understanding is empirical challenges associated with the exploration of ongoing processes for radical technology (Gustafsson et al., 2015). Most of the studies have focused on historical and retrospective analysis. According to Gustafsson et al. (2015, p.2), "as a process industry emergence has no boundaries". Markard and Truffer (2008, pp.1166-1167) elaborate, "it is demanding because the underlying innovation processes are complex as they typically depend on the co-development of new socio-technical configurations, new market structures, new actors and new institutional settings."

2.2.1 Dynamics of Breakthrough Technologies

Emerging technologies are characterised by high technological, market and environmental uncertainty, complexity, nonlinearity in their development, long period of gestation, absence of dominant design, initial hype, promises and lofty expectations (Rosenberg, 1995). Extant studies discussing the emergence of new technological and knowledge-based fields such as biotechnology and nanotechnology (Darby and Zucker, 2005; Bozeman et al., 2007; Van der Valk et al., 2009) have identified common dynamics which characterise different stages of technological development. Seminal work by Chen and Van de Ven (1996) and Abernathy and Clark (1985) all point towards similar dynamics within the context of radical technologies in the initial years of the industry life cycle, followed by the emergence of a dominant design and convergence of a broad range of technological and scientific fields in a later stage. Schumpeter (1975, quoted in Van de Ven and Garud, 1989, p.200) highlighted the importance of technological competition for new and emerging technologies that tend to be different from perfect market competition:

> Competition from the new commodity, the new technology, the new sources of supply, the new type of organization (the largest–scale unit of control for instance)—competition which commands a decisive cost or quality advantage and which strikes not at the margins of the profits and outputs of the existing firms but at their foundations and their very lives.

Technological progress within emerging technological fields is mostly attributed to a large number of small entrepreneurial technology-based firms. However, as the technology develops, the domain of innovation shifts from small de novo firms to large established players and the nature of innovation evolves from advancement in scientific and technological fundamentals to commercial applications (Srinivasan, 2008).

Another important aspect of emerging technologies is their novelty, revolutionary character and potential to be disruptive to the existing market and its value network (Rotolo et al., 2015). Radicalness and disruptiveness are two distinct dimensions whereby radicalness is mostly associated with technology while disruptiveness with market, as elaborated by Govindarajan and Kopalle (2006, p.14):

> The radicalness of innovation refers to the extent an innovation is based on substantially new technology relative to the existing practice… the disruptiveness of innovation refers to the extent an emerging customer segment sees value in the time of the introduction… radicalness is a technology based dimension and disruptiveness is market based dimension. (Govindarajan and Kopalle, 2006, p.14)

Products based on disruptive technologies tend to be simpler and cheaper initially, often inferior in terms of performance metrics as valued by mainstream customers, and offer different attributes (new value proposition) which become apparent and valued only once they develop from emerging markets into noticeable market penetration, from niche to mainstream (Christensen, 1997; Govindarajan and Kopalle, 2006). However, moving from research to market for the initially low performing technology may take decades, a process also referred to as "Valley of Death" (Raven and Geels, 2010) and which necessitates the creation of a protected space for "hopeful monstrosities" (Mokyr, 1990, p.291).

2.2.1.1 Uncertainty

Uncertainty in radical innovation is around both technology and market. Hilgartner and Lewenstein (2004) refer to emerging technologies as speculative space. In the initial stages, technology is immature and ex ante not much is known about technological feasibility, application and performance, as also suggested by Rosenberg (1995, p.173): "Much of the difficulty… derives from the fact new technologies typically come into the world in a primitive condition." On the market side, uncertainty stems from lack of articulated demand, legitimacy and vision related to future application (Aldrich and Fiol, 1994; Van Lente, 2010). As Rosenberg (1995) stated:

> …new technologies are unrealized potential—building blocks whose eventual impact will depend on what is designed and constructed with them. The shape they ultimately take will be determined by our ability to visualize how they might be applied in new contexts. (*ibid.,* p.181)

Applications of new technologies initially are usually evaluated and interpreted in the context of existing cognitive frames of old technologies, as discussed by the historians of technology, and this limits identification of novel applications ex ante. "Radical inventions may first be interpreted as a small step, and only ex post be identified as major breakthroughs" (Geels, 2005, p.45). Lack of sociopolitical legitimacy especially in the formative years hinders the market adoption and commercialisation of technology as discussed by Kulve (2010) and results in waiting games. In addition to the traditional focus on technological and market uncertainty, Leifer et al. (2001) and more recently O'Connor et al. (2013) talked about organisational and resource uncertainty.

Organisation uncertainty stems from lack of consistency, change in strategic direction during and in-between projects and relationship between the radical project unit and the rest of the organisation. In addition to the above-mentioned uncertainties, radical innovation also faces financial difficulties and funding instability over the period of the project that contribute to resource uncertainty. For Day and Schoemaker (2000), management of emerging technology is not a new game but rather a different one and therefore requires managing differently from other mainstream established technologies.

2.2.1.2 Complexity

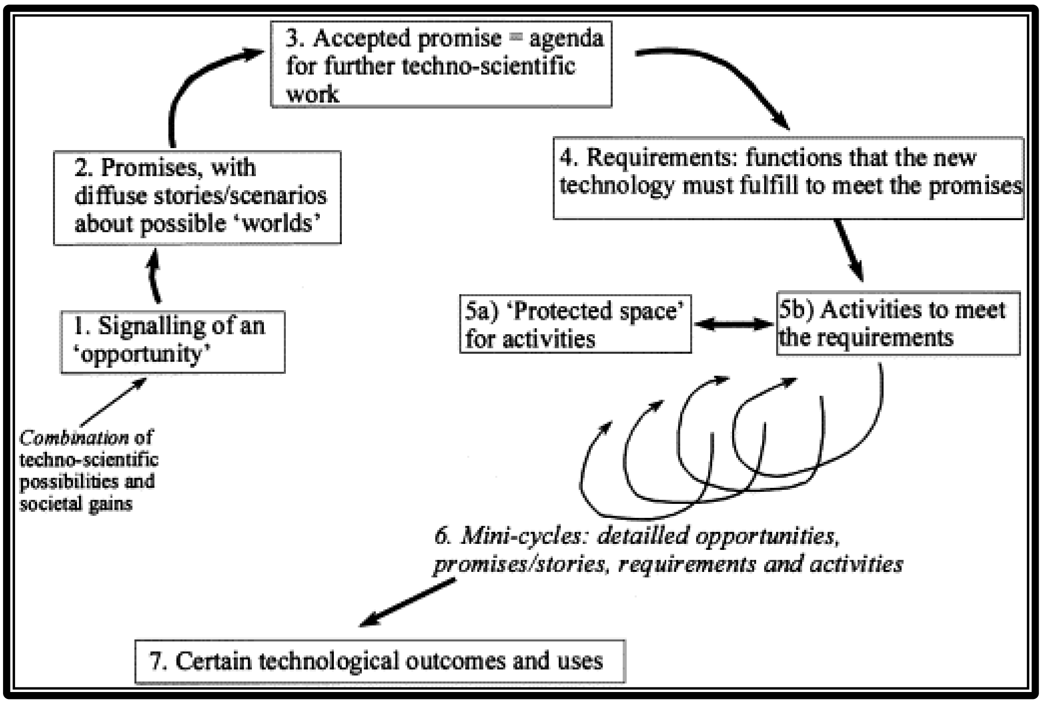
Diversity of technological and knowledge sources contribute towards complexity in the context of high tech sectors. Sources of knowledge and technology tend to be more distributed across firms and industries (Corrocher et al., 2003) and include heterogeneous actors, notably institutions like universities and public research organisations. "The main issue is related to whether new technologies stem from a single idea within a selected and homogeneous set of technological principles, or instead are the result of the convergence of different ideas from different technological fields" (Corrocher et al., 2003, p.3). Hybridisation and technological fusion (Kodama, 1992) are some of the trends prevalent in the emerging technologies, also referred to as general purpose, owing to pervasiveness and potential for application in diverse industries (Bresnahan and Trajtenberg, 1995; Corrocher et al., 2003).

2.2.1.3 Expectation, Hype and Promises for New Technologies

New scientific and technological developments necessitate development of common vision and expectation that bridge disparate communities across boundaries. They can be described as “real time representations of future technological situations and capabilities” (Borup et al., 2006, p.286). Expectations and promises are especially important in the early phase of technology developments as they define roles, build momentum, guide activities, create interest and mobilise resources at macro, meso and micro levels (Van Merkerk and Robinson, 2006). “High rising expectations can even form a crucial impulse for the emergence of new technological or research fields” (Ruef and Markard, 2010, p.318).

Promises are performative. Van Lente (1993) investigated the dynamics of promises (see Figure 2.1) and their role in coordination and building of a technology trajectory. Initial promises are inflated in order to create the necessary hype and attract resources. According to the promise-requirement cycle, when the new opportunity arises, their proponents diffuse various scenarios based on expectations and promises that ultimately translates into requirements, agendas and creation of protected spaces for further development. After initial development work and evaluation of outcomes, new expectations and promises are articulated and the cycle is repeated. “Overall the trajectory moves from requirement-constrained exploration of an option to a focus on exploitation” (Parandian et al., 2012, p.567).

Figure 2-1 Promise-Requirement Cycle

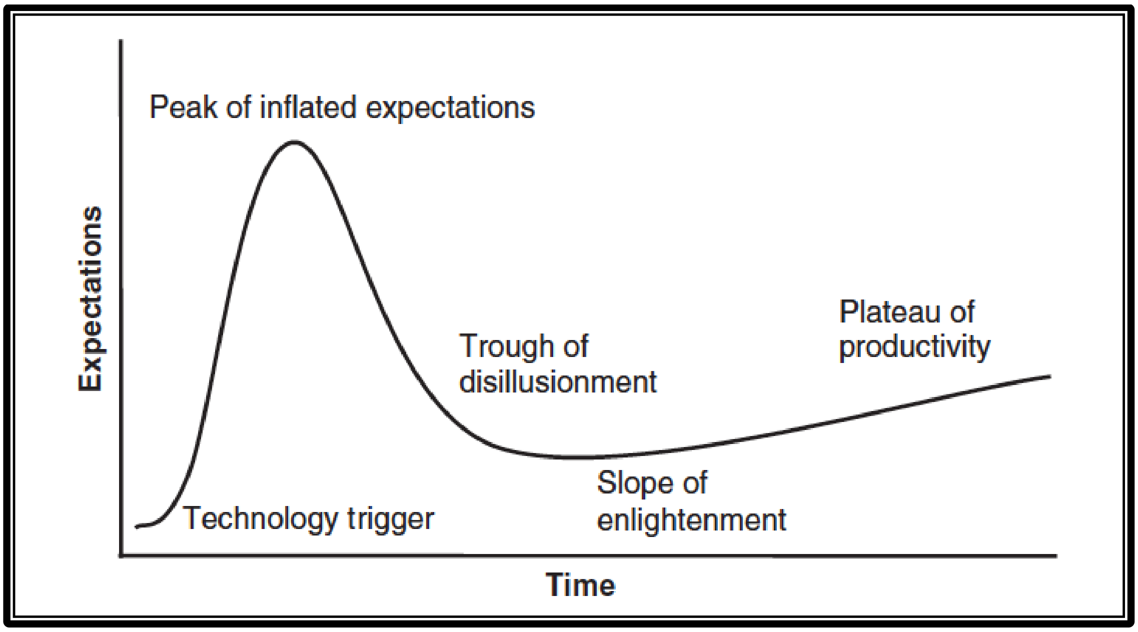


Source: Geels and Smit, 2000

Inflated expectations result in hype (Bakker and Budde, 2012) and are often followed by disappointment. A popular illustration of the hype-disappointment cycle is that by Gartner, a consultancy firm, that maps the dynamics of emerging technologies on a time scale to facilitate investment decisions. Though the shape and length of the hype curve varies as suggested by Van Lente et al. (2013), it consists of four phases as shown in Figure 2.2.

The cycle starts with the "technology breakthrough" that generates media and industry interest. "Inflated expectations" result in heightened momentum, increased mobilisation of resources and many actors joining the bandwagon. The rising upward slope is followed by the "trough of disillusionment", where expectations are not met, as a result of which enthusiasm dies down and many actors leave the field. In fact, as discussed in the literature, unfulfilled promises and failed expectations may be detrimental to the trust of the actors and have a negative effect on the reputation of innovators as well as product (Ruef and Markard, 2010). After the period of disappointment there is a period of gradual improvements and adjustment of expectations.

Figure 2-2 Hype Cycle



Source: Bakker and Budde, 2012

Specific to the dynamics of open promises and inflated expectation (hype) is the concept of waiting games or "technological impasse" (Robinson et al., 2012). Inflated expectations represent a paradoxical situation and create a first mover challenge. In this situation, though the technology potential is accepted, it moves into a trough of disillusionment, as the actors refrain from making efforts or financial commitments and wait for each other to make the first and risky move. Parandian et al. (2012) elaborated on the dual dynamics of open-ended promises or umbrella promises that have a vital role in policy discourse, attracting stakeholders and mobilising resources, but may result in waiting games for the innovation actors such as large customers who may not enter into the promise-requirement cycle and adopt a wait-and-see attitude. Other forms of waiting games are those that have risen in the case of nanomedicine owing to the uncertainty regarding the governance and evolution of regulatory frameworks (D'Silva et al., 2012) and that prominent in hydrogen and fuel cell cars that remained a niche application despite initial hype and promises of high potential (Bakker and Budde, 2012).

2.2.1.4 Sailing Ship Effect

Technological changes create a gale of "creative destruction" thus displacing incumbents with new entrants. However, as discussed by Howells (2002), incumbents actively respond and develop strategies such as exit, switch and "sailing ship effect" in the wake of introduction of new technologies that create a substitution effect.

Established players threatened by new technologies may anticipate forced exit and therefore decide to adopt an exit strategy and leave the market early. In an alternate scenario, threatened firms may decide to participate in the young market as discussed by Cooper and Smith (1992) in their study of eight new industries (ball point pen, CT scanner, electric type writers, microwaves, transistors, electronic watches, electronic calculator and diesel-electric locomotives) and twenty-seven threatened firms.

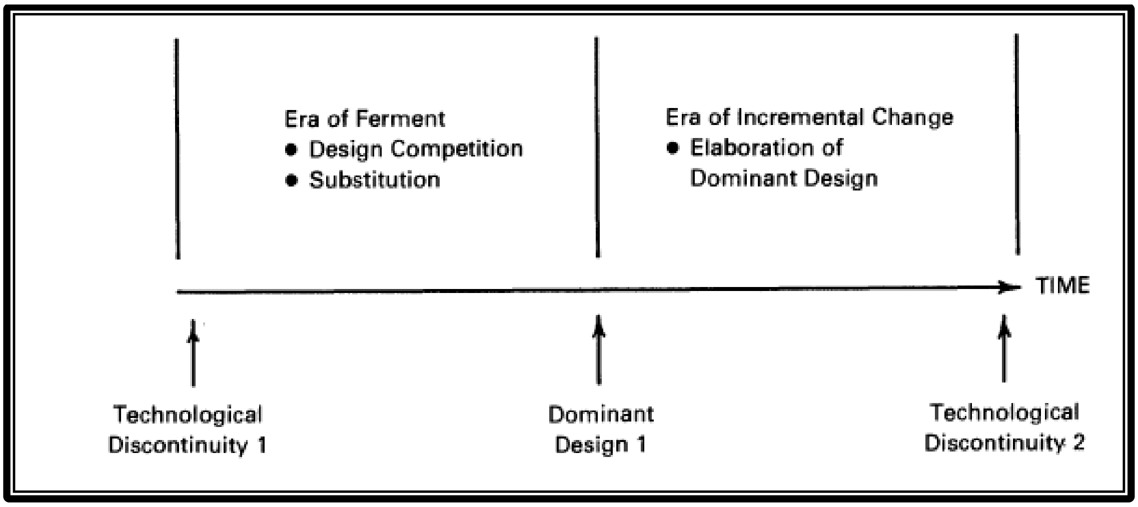
The third response strategy is that of fighting back, where incumbents work harder to improve the performance of their technologies to avoid market loss. This phenomenon is referred to as "sailing ship effect", based on a case study of steam versus sailing ship by Gilfillan (1935). However, Howells (2002) doubts the significance of the sailing ship effect and deliberate acceleration of the effort in existing technology. Snow (2004) provides other explanations for "the last gasp improvements" such as selection effect, that is, applications of new technologies in markets where incumbent technology is inefficient resulting in increase in aggregate efficiency of old technologies in selected market segments and spillover effects from new technology that results in innovation in complementary technologies not available earlier to the incumbents.

2.2.2 Industry Life Cycle Theory and Stages of Industry Emergence

Technological change is an ongoing dynamic journey (Van de Ven et al., 1999). Technological change manifested by discontinuity can be characterised as either competence enhancing or competence destroying. Competence enhancing builds on existing knowledge and skills while competence destroying is normally initiated by new entrants forcing a major shift in skills, processes and competences (Tushman and Anderson, 1986).

Anderson and Tushman's (1990) model of technological change has its roots in evolutionary processes of variation, selection and retention and consists of four phases (Figure 2.3): technological discontinuities, era of ferment, dominant design and era of incremental changes. New technologies, when introduced, are crude. Technological discontinuity thus triggers an era of ferment marked by uncertainty, variation and experimentation that results in rivalry and competition among old and new technologies as well as among variants within the new regime, for example in the case of power generation the competition was not only between AC and DC but also for different frequencies within AC. The era of technical variation and rivalry is followed by selection and emergence of dominant design. Dominant design reduces uncertainty, permits standardisation and results in stability. However, the selection is not driven by technological superiority and other factors such as market demand may impact the selection among the variants as discussed in the classic case of the battle of the Qwerty keyboard (David, 1985). Emergence of dominant design is followed by a period of retention and incremental improvement. During this period the focus is on achieving volumes, decreasing cost, minor improvements and increased differentiation.

Figure 2-3 Technology Cycle



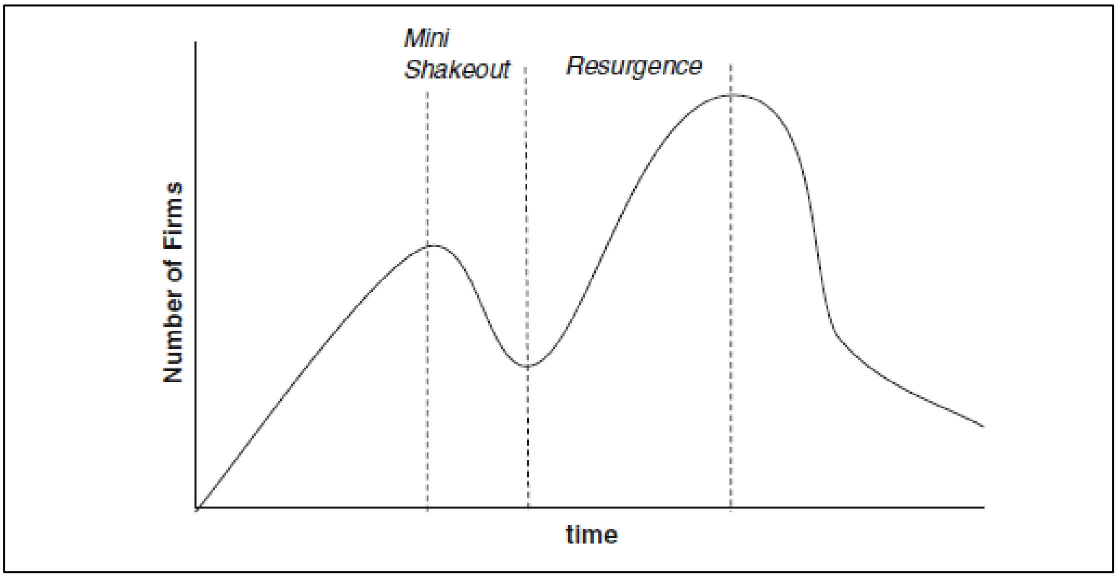
Source: Anderson and Tushman, 1990

The industry life cycle model traces the development of technology and explains the evolution of new industries (Peltoniemi, 2011). However, identifying and defining the phases related to industry emergence poses challenges as the boundaries between different phases are mostly blurred (Gustafsson et al., 2015).

The most prominent contributions under this theme are those by Abernathy and Utterback (1978, 1985) and Klepper (1996). The common theme among these rich strands of literature is the emergence of industry marked by three stages: exploratory with frequent entry of a large number of new firms during the lifecycle; growth and maturity followed by shakeouts;

and the gradual transition from product to process innovation (Klepper, 1997). The proposition and pattern of life cycle theory was evaluated in different industries other than automobiles, such as typewriters, automobile tires, commercial aircraft for trunk carriers, televisions, television picture tubes and penicillin, that provided evidence of common dynamics such as: "output growth tends to decline over time, entry is generally concentrated early, shakeouts are common, early entrants tend to dominate their markets, and product innovation peaks early" (Klepper, 1997, p.168). Recently Agarwal et al. (2014), based on the study of 24 new industries, proposed an alternative model and two additional stages in the widely accepted U shaped life cycle model, suggesting a deviance from the stylised fact (Figure 2.4). They referred to these stages as "mini-shakeout mode" and "resurgence in the number of firms" before final shakeout that mostly occurs after the sales have taken off in industry. Mini shakeout refers to the decline in the number of entrepreneurial firms prior to the growth phase. The drivers for this early exit tend to be different to those of later shakeout and include "unmet expectations" and "strategic importance of emerging industry for the firm".

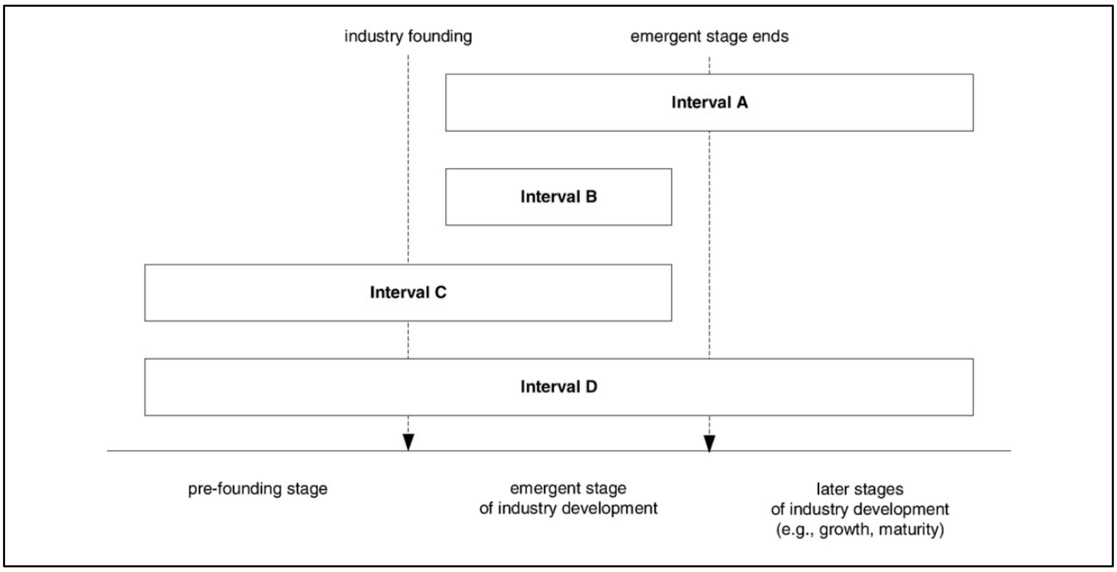
Figure 2-4 Modified Life Cycle



Source: Agarwal et al., 2014

According to Forbes and Kirsch (2011) the period of emergence is a temporal event within an industry lifecycle that varies, being a couple of years in some cases and extending up to 50 years. Figure 2.5 portrays temporal intervals associated with industry emergence. The initial stage is referred to as the pre-founding stage or embryonic stage triggered mostly by scientific and technological advancements. However, there can be other factors such as cultural, regulatory, or demand shock that may challenge the existing technological order (Gustafsson et al., 2015). The initial discontinuity is followed by the entry of a large number of entrepreneurial firms and a range of innovations pursued. The next stage is the emergent stage, also referred to as the co-evolutionary stage and characterised by standardisation, rapid imitation, increase in collaborations and innovation in organisation, product and services. The final stage is that of growth and represents irreversibilities in investments related to technological knowledge and production processes (Gustafsson et al., 2015).

Figure 2-5 Temporal Intervals for Industry Emergence



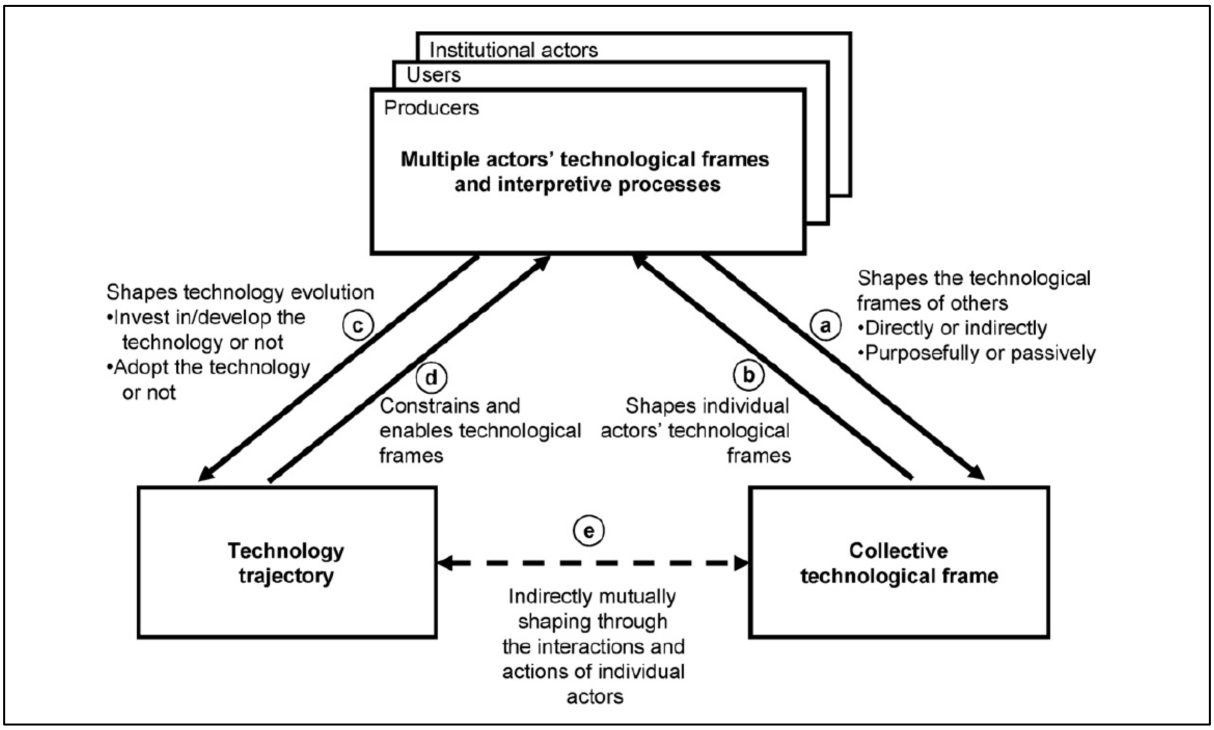
Source: Forbes and Kirsch, 2011

Forbes and Kirsch (2011) emphasised the required theoretical and empirical focus for the period classified as “B” which is nascent as compared to others and there are a few studies, such as that of Eisenhardt and Santos (2009). The interval B focus is on explaining what happens within the period of industry emergence, unlike A, that discusses the entire lifecycle. Intervals C and D discuss the dynamics starting from the historical perspective and pre-founding stages to later stages and maturity. The study within interval B necessitates identifying dynamics beyond the producer firms and extending it to include a variety of other actors such as government authorities, venture capitalists, regulatory bodies and associations.

Apart from scant empirical contribution during the nascent stage and retrospective bias, another limitation of the life cycle model is its neglect of cognitive dimensions and their role in shaping evolution of technology (Kaplan and Tripsas, 2008). Cognitive framework provides additional explanations for technological evolution within the life cycle model in addition to the economic and organisational explanation.

Technological frames of multiple actors, such as producers, users and institutional actors, interpretation of the technology and their interactions, ultimately shape evaluation criteria and finally decisions and outcomes. A technological frame "guides the actor's interpretation of what a technology is and whether it does anything useful" (Kaplan and Tripsas 2008, p.791). It reduces the complexity and uncertainty associated with new technologies ex ante. Both internal and external factors facilitate developing these technological frames (see Figure 2.6).

Figure 2-6 Cognitive Model



Source: Kaplan and Tripsas, 2008

Prior industry affiliations and organisational experiences create shared understanding of the technology and are the typical sources for formation of these technological frames. The technological frames affect the evolution of the technology trajectory. In the ferment stage, the variations are not only stochastic and exogenous; neither can be explained fully by heterogeneous capabilities and resources of participants. The differential framing processes of the divergent actors and their interpretation owing to their idiosyncratic experiences and affiliations impact their technological frames and eventually contribute to a higher degree of technological variation. In addition to that, interactions among producers, users and institutions such as government bodies and associations play an active role in creating a collective technological framework. The actor's technological frame impacts the collective technological frame and in turn itself is influenced and shaped by the collective technological frame.

Cognitive framework emphasises the reduction in cognitive variations along with technological variation in the emergence of dominant design. Collective technological framework provides convergence and results in evolution of technology and finally dominant design. Tight linkages between collective technological frames, producers, users and institutions frame of references eventually solidify and their embeddedness within the industry norms and routines result in inertia that dominate the era of incremental changes.

2.2.3 Emergence and Evolution: Theoretical Considerations

In addition to the life cycle model discussed in the earlier section, there are various diverse and disparate frameworks that discuss emergence of industries (Malerba, 2007; Phaal et al., 2011), namely the technological innovation system (Carlsson et al., 2003), actor-network theory and socio-technical approaches (Callon, 1991), a multilevel perspective on technological transition that builds on the work of Rip, Schot and Kemp's strategic niche management (Kemp et al., 1998), sociological approaches such as social construction of technology (Bijker et al., 1987), socio-cognitive approaches and evolutionary economics (Nelson and Winter, 1982). Though the main focuses of these approaches differ, they share the common notion that technology development involves networks or a seamless web of linkages among heterogeneous actors and the importance of learning processes (Geels, 2005). Owing to the richness of the theoretical framework used to study industry dynamics, the two strands of literature that have contributed to understanding radical innovation transitions and technological transformation – technological systems of innovation (TIS) and technological transition (TT) (Markard and Truffer, 2008) – will be discussed next.

TIS and TT have recently been a central reference in scholarly literature discussing transition to sustainability (Budde et al., 2012). Systems are made of "components, relationships and attributes" (Carlsson et al., 2002, p.234). "Components" refer to both human and non-human actors such as firms, institutes as well as technological artefacts; "relationships" are interactions and provide market and non-market links to connect the components; whereas "attributes" define the properties of components and relationship and characterise the system. The TIS approach (Carlsson and Stanckiewicz, 1991, p.93), having its roots in evolutionary economics, focuses on emergence, diffusion and utilisation of innovation and can be defined as "a network of agents interacting in a specific economic/industrial area under a particular institutional infrastructure or set of infrastructures and involved in the generation, diffusion, and utilisation of technology." The TIS approach, though useful at the system level, is considered a static approach (Geels, 2005) with increased focus on structural components. Furthermore, defining boundaries is complex when it comes to technological systems. Recent propositions have been on delineating boundaries based on functional perspectives and activities rather than on structures (Bergek et al., 2008).

Another approach is that of the multilevel framework of Geels and other Dutch authors for technological transitions. It provides explanation at three levels: niches, regimes and socio-technical landscapes (Figure 2.7). The macro level referred to as socio-technical landscapes refers to the broader context of the society – the political regimes, the cultural trends, the wider external environment that is somewhat hard and changes slowly. The meso level refers to the socio-technical regimes and comprises five regimes: technological, science, market, policy and culture. Within the regimes, "cognitive routines that are shared by the engineers and designers in different companies" (Geels, 2005) provide stability and coordination. At this level, also called "established business fields" by Möller (2010), innovation is mostly incremental along a particular trajectory. The micro level, referred to as technological niches, is considered a major source of radical innovation. "Niches are crucial for Technological Transitions, because they provide the seeds for change" (Geels, 2002, p.1262).

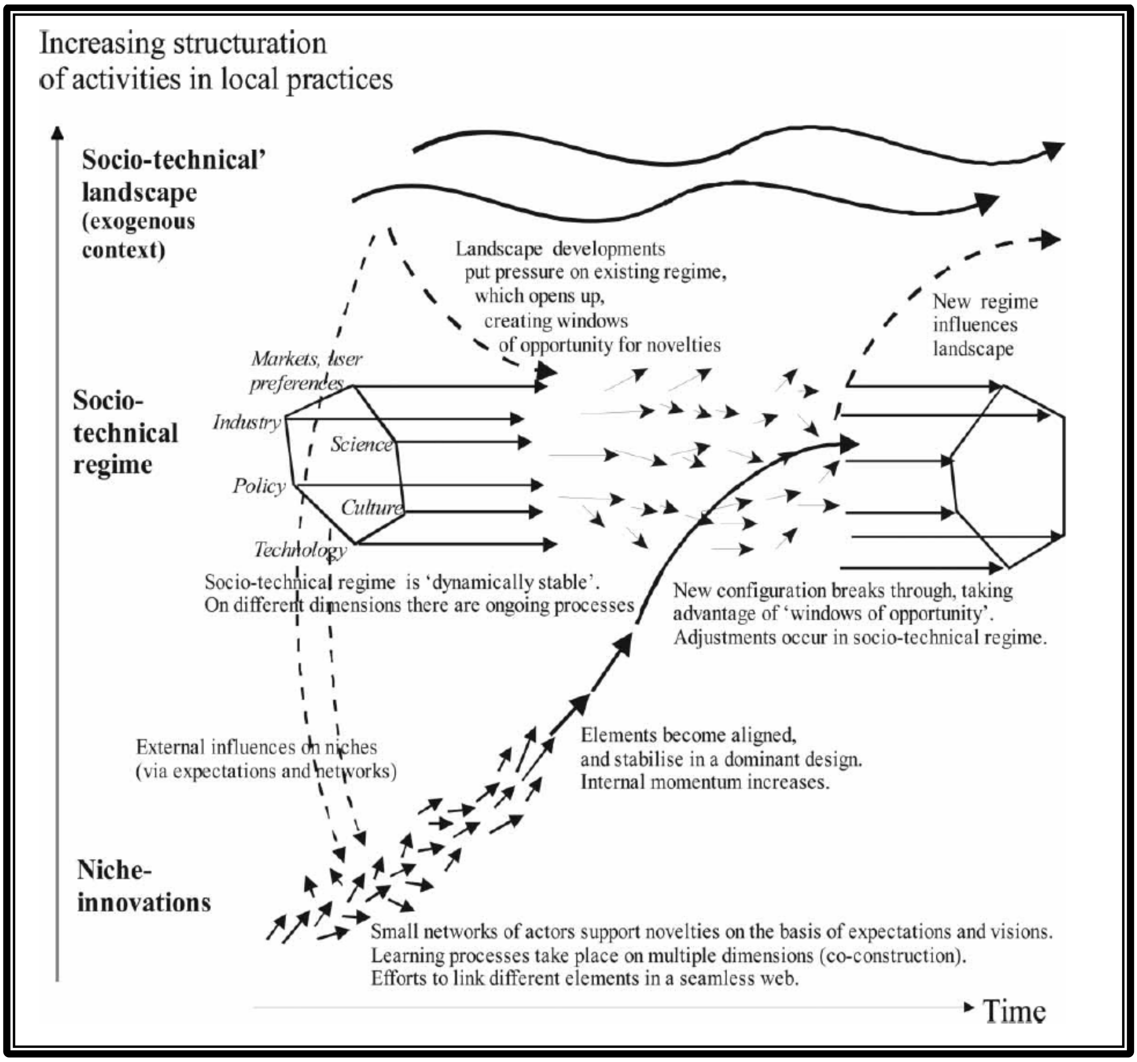
"Niches and Regimes are both sets of rules" (Geels, 2002); however, what differentiates niches from regimes is the level of structuration and stability. Niches are characterised by uncertainty and less stability. In addition to the niches the other factors that are important for technological change as identified by Kemp, Rip and Schot (2001) are the presence of system builders (entrepreneurs), institutional support and existence of capabilities and knowledge in existing regimes.

The main thrust of the multilevel perspective is:

> …that transitions come about through interactions between processes at different levels: (a) niche innovations build up internal momentum, (b) changes at the landscape level create pressure on the regime, (c) destabilisation of the regime creates windows of opportunity for niche innovations. (Schot and Geels, 2008, p.545)

Both the TIS and multilevel framework approaches have been instrumental for understanding technological transition and have inspired a large body of scholarly work and empirical studies. The focus of TT has been mainly on historical and retrospective case studies to explore the dynamics and interactions at micro, meso and macro levels. However, both approaches have been criticised for their limited attention to exploring the strategies at the micro level (Markard and Truffer, 2008; Alkemade et al., 2011; Budde et al., 2012).

Figure 2-7 Technological Transition and Dynamics at Multilevel



Source: Geels, 2002

2.2.3.1 Strategic Niche Management and Role of Niches

Breakthrough technologies are challenged and face strict competition from existing technological regimes that are characterised by established cognitive frameworks, path dependencies and lock-ins (Geels and Raven, 2006). They are referred to as "hopeful monstrosities" (Mokyr, 1990, p.291) and necessitate development of niches to nurture and shield these technologies in their early stages before they are able to compete in the marketplace (Kemp et al., 2001). "These are specific domains for application of a new technology functioning as a test bed, where the new technologies or concepts are (temporarily and selectively) shielded from the pressures of the market and institutions and from the dominant technological regime" (Hoogma, 2002, p.14). Once the technology is developed and survives the selection environment, protection is gradually removed; however, as argued by Raven (2004, p.30), "this does not necessarily mean that the new technology replaces the old one". This planned strategy of niche development, proposed as one of the approaches introduced by the government for managing radical technological changes, is implemented through strategic niche management (SNM) and has its roots in a quasi-evolutionary approach to technical change (Rip, 1992). SNM facilitates interactive and collaborative learning and experimentation among various stakeholders.

Niches, as argued by Geels (2005, p.79), are incubation rooms for radical innovations and are constructed by a group of actors who share expectations and beliefs about the benefits and future prospects of new technology. Articulation of shared vision and convergence of expectations, formation of networks and learning are the processes that tend to be important for development of niches (Hoogma, 2002; Raven, 2005; Hermans et al., 2013). The three mechanisms are interrelated and are a necessary precondition for the formation of niches. Initial expectations and shared vision about the future potential of technology shapes initial experimentation and actors' participation in the early development of technology that initially ranks low in performance.

Expectations play an important role in lobbying, attracting resources from policy makers and creating momentum by attracting other actors, thus expanding the social network. Composition of the network is the second important dynamic within niches. Initial pioneers of the technology are mainly outsiders that support experimentation for radical innovation; however, the outcome of experiments results in enrolling new actors, learning and adaption of expectation. "Niche development requires actors who are willing to invest in maintaining or expanding the niche, even when short-term market value is absent" (Raven, 2005, p.40). The presence of powerful actors, that is, those with adequate resources such as large organisations, on one hand adds value within the network while on the other hand their participation, sometimes motivated via a defensive mechanism, results in slowing down the introduction of radical technology in mainstream markets. Networks support development of (a) dedicated communities of engineers who participate in multi-disciplinary collaborative projects, (b) professional associations and (c) communication spaces and mechanisms that impact learning. Learning in niches may occur at many levels – technology, market, regulation and policy – and facilitates experimenting and transition of technology from niches to a new technological regime (Geels, 2005; Lopolito et al., 2011).

Reviewing the literature on protective space, it could be argued that most of it deals with the emergence of protective space retrospectively. In the context of SNM the focus is on policy measures that enable the convergence and stabilisation of technology. According to Pinkse et al. (2014, p.45), "a disruptive change of systemic technologies thus relies on a significant transformation of the whole network of suppliers, customers, and complementors… companies will not only have to develop new technologies but also need to stimulate the development of a new ecosystem of suppliers and complementors." They discussed the role of both private protection mechanisms such as resource allocation, niche occupation and collaboration-integration as well as public protection levers such as regulation, public–private partnerships, tax incentives and their impact on firm level strategies for introducing disruptive innovation (low emission vehicles – LEV) to the mainstream market. According to them, most of the public protection levers have been targeted towards technology development rather than at the commercialisation stage and "the specific role of these different types of protection levers—private and/or public—has remained unclear" (p.44).

2.3 Actors and Processes in the Context of Breakthrough Technologies and Emerging Industries

Industry emergence is characterised by dynamic patterns of uncertainty, complexity, heterogeneous interaction, co-evolution and adaptation (Phaal et al., 2011; Probert et al., 2013). Literature suggests that both de novo as well as de alio entrants participate in the development of breakthrough technologies (Forbes and Kirsch, 2011; Srinivasan, 2008). In addition to the above mentioned actors, there exists diversity of stakeholders such as policy makers, intermediaries, potential customers, and investors; "…all have an interest in and effect on industrial emergence" (Probert et al., p.782).

Van de Ven and Garud (1989) in their model of industry emergence emphasised the modification of the traditional industry definition and proposed inclusion of three hierarchical subsystems: (1) instrumental subsystems comprising traditional producer firms that engage in R&D and technological innovation; (2) critical resources for the emergence of an industry such as basic scientific R&D, human capital, financial capital and providers of these resource endowments that include universities, venture capitalists and public institutions; and (3) institutional subsystems that legitimise the new industry creation and provide governance, and include actors such as trade associations and standard setting bodies.

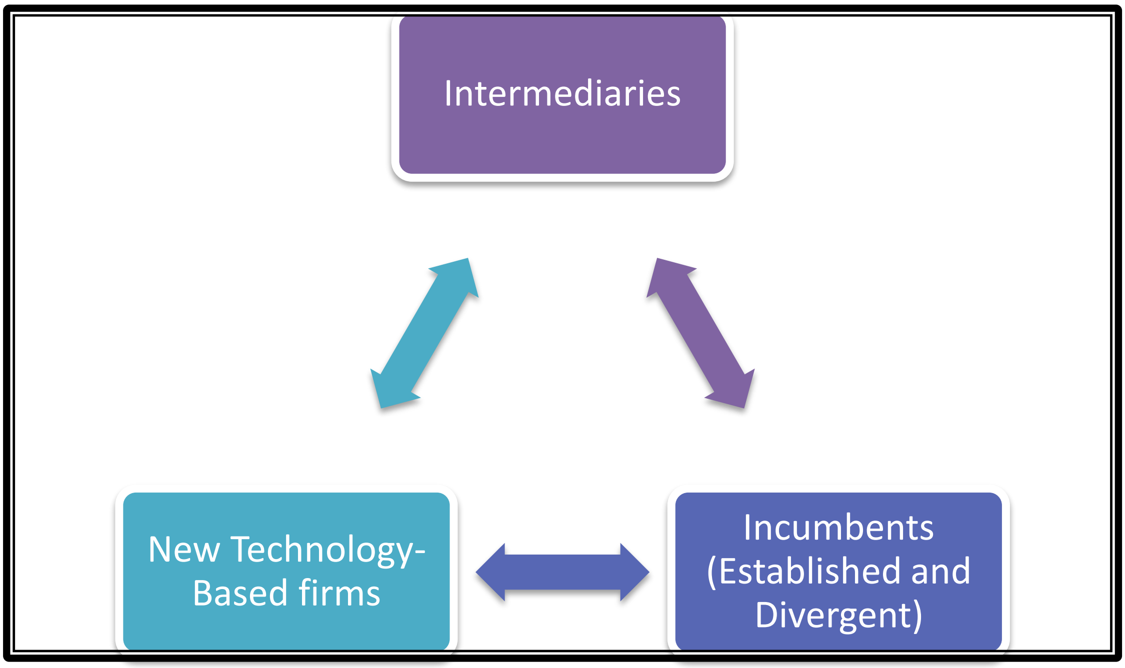
In their cognitive model of industry emergence Kaplan and Tripsas (2008) also emphasised that interactions and interpretations of divergent actors such as producers, users and institutions shape the emergence of a collective technological framework that ultimately affects convergence and evolution of the new industries.

Similarly, Forbes and Kirsch (2011) pointed to the importance of studying the range of individual and organisational actors for exploring the emergence of new industries as well as use of multiple data sources: "…there is a theoretical and empirical basis for the expectation that the sources of data relevant to the study of emerging industries extend considerably beyond those that document the birth, death or behaviour of their producer firms."

In addition to the importance of diversity of actors, Gustafsson et al. (2015) identified the importance of sub-processes such as (1) establishment of a technological basis, (2) emergence of activity networks, (3) market emergence and (4) formation of industry identity, for industry emergence. These processes differ in terms of focus of actors and interactions. For instance, establishment of technological basis depends on processes around standards and technological coalitions. Community building, institutional entrepreneurship and collective action is the main focus of activity networks while cognitive and social legitimacy processes establish industry identity.

Thus new industries "do not emerge in air" and their underpinnings require understanding of the processes and activities of the combination of firms (entrepreneurial and incumbent) as well as emerging institutional structures (Krafft et al., 2014) (see Figure 2.8).

Figure 2-8 Dominant Actors



Source: Author

2.3.1 Role of New Technology-Based Firms

The role of entrepreneurial new technology-based firms (NTBF) in the development of radical or discontinuous innovation or Schumpeter's creative destruction has been discussed in the literature on advancements in industries such as biotechnology and computers (Whitley, 2002). In the context of emerging technologies they are considered as initiators and stimulators for widespread interest in the potential of breakthrough technologies (Acs and Audretsch, 1987). Autio (1997, p.263) referred to them as "bundles of technological resources." However, NTBF face challenges when it comes to commercialising and becoming industry leaders. "While entrepreneurial firms may initiate innovation, the firms that begin commercialising radical or disruptive technologies are not necessarily the ones that profit from them" (Lubik et al., 2013).

However, operationalisation of the term itself is varied and ambiguous such that it refers to "new technology-based firm", "high tech SMEs", "small and medium technology-based firms" and "small technology-based firms" (Storey and Tether, 1998; Cunha et al., 2013).

Based on bibliometric analysis, Cunha et al. (2013) suggest commonality in terms of the importance of technology in the evolution of these firms. The NTBF's role is instrumental for job creation and development of economies (Schumpeter, 1939; Oakey, 2007). Cooper (1971, p.5), the originator of the term, conceptualises it as "a firm that emphasizes research and development or that places major emphasis on exploiting new technical knowledge." In the context of the thesis a broader definition is adopted in line with Butchart (1987) such that it refers to small and medium sized firms operating in high technology environments and contributing towards the emergence of new industry.

Small entrepreneurial firms are considered to have behavioural advantages as compared to their larger counterparts in introduction and diffusion of emerging and disruptive technologies. NTBFs, as argued by Spencer and Kirchhoff (2006, p.151), "are able to approach problems with a clean slate, developing solutions that are not limited by compatibility with existing products," as they do not have a constraining existing customer base, sunk resources or organisational inertia compared to large, established firms.

Rothwell (1984) suggested the existence of complementarities between large and small firms during the evolution of the US semiconductor and CAD industry:

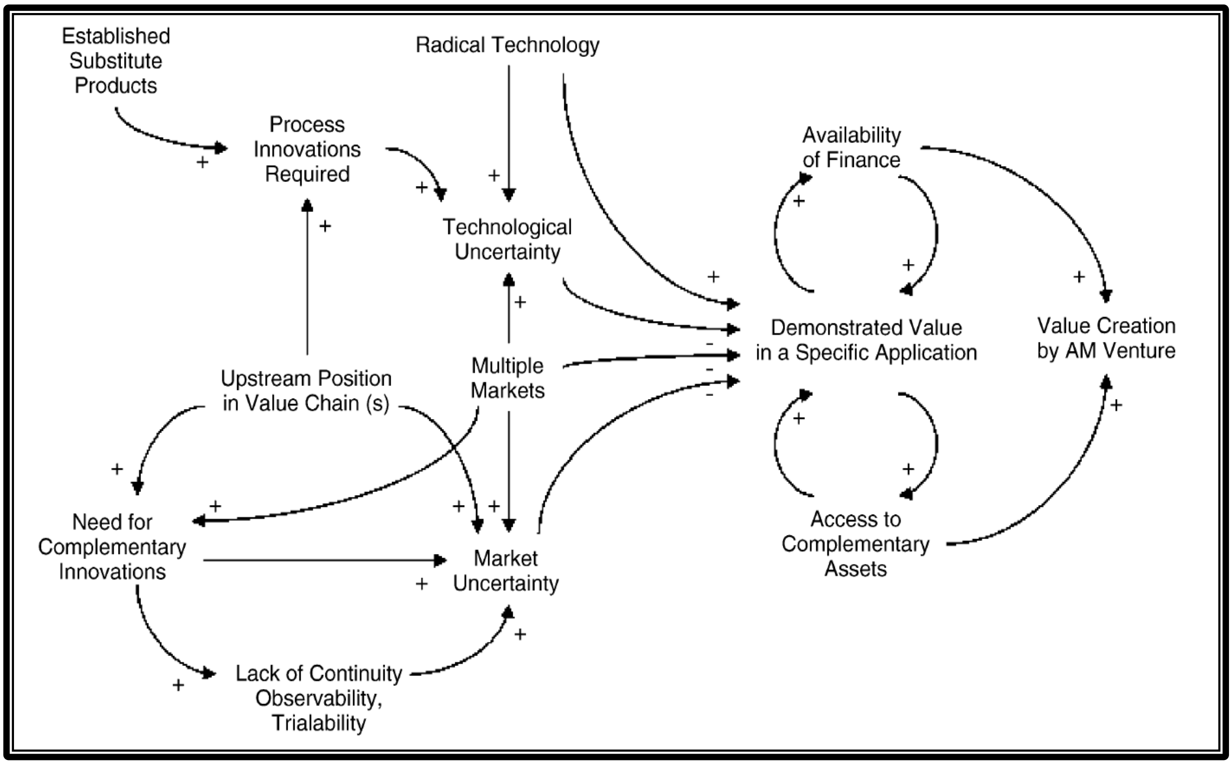
> During the early phases in the evolution of a new industry the behavioral advantages of small scale are crucial; as the industry evolves, technological possibilities become better defined and market needs become increasingly well specified, the advantages of large scale begin to dominate. Comparative advantage shifts to the larger firms. (*ibid*., p.27)

NTBFs are not homogenous. Autio (1997) classified them as science and engineering based. Studies suggest that new ventures originating from academic institutions differ from other non-academic high tech ventures (Zahra et al., 2007; Colombo and Piva, 2008). Colombo and Piva (2012) suggested that the genetic characteristics inherited from founders such as level of education, prior work experience, entrepreneurial knowledge and social capital impact the post entry performance and are a differentiating factor between academic and non-academic start-ups. "It is reasonable to assume that spin-offs' capabilities are linked to the knowledge they inherit from their parents" (Zahra et al., 2007, p.572). Academic spin-offs from universities are considered to be more Schumpetarian, competence destroying and technologically oriented as compared to non-academic start-ups that adopt more of a technology pull approach (Roininen and Ylinenpää, 2009). Due to their technical and scientific endowments academic start-ups are considered to possess comparatively higher potential absorptive capacity than their counterparts (Colombo and Piva, 2012). Zahra et al.

(2007, p.570) proposed that the difference between academic and non-academic start-ups (corporate start-ups) is in their knowledge conversion capability (KCC), defined as "capacity to transform research and scientific discoveries into successful products and goods that are efficiently and quickly commercialized to create value."

High tech ventures face challenges when it comes to commercialisation of technology, such as limited resources (financial, human and relational) and lack of adequate market and product knowledge. They have high failure rates (Song et al., 2008) and suffer from the liability of newness (Stinchcombe and March, 1965). Maine and Garney (2006) identified numerous technological and market challenges associated with entrepreneurial ventures in the advanced material sector as shown in Figure 2.9. The radical nature of the technology, the need for process innovation and the application in multiple markets contribute to high technological uncertainty. The need for complementary innovation and the lack of continuity, observability, trialability and multiple markets contribute to market uncertainty.

Figure 2-9 Challenges for New Ventures



Source: Maine and Garnsey, 2006

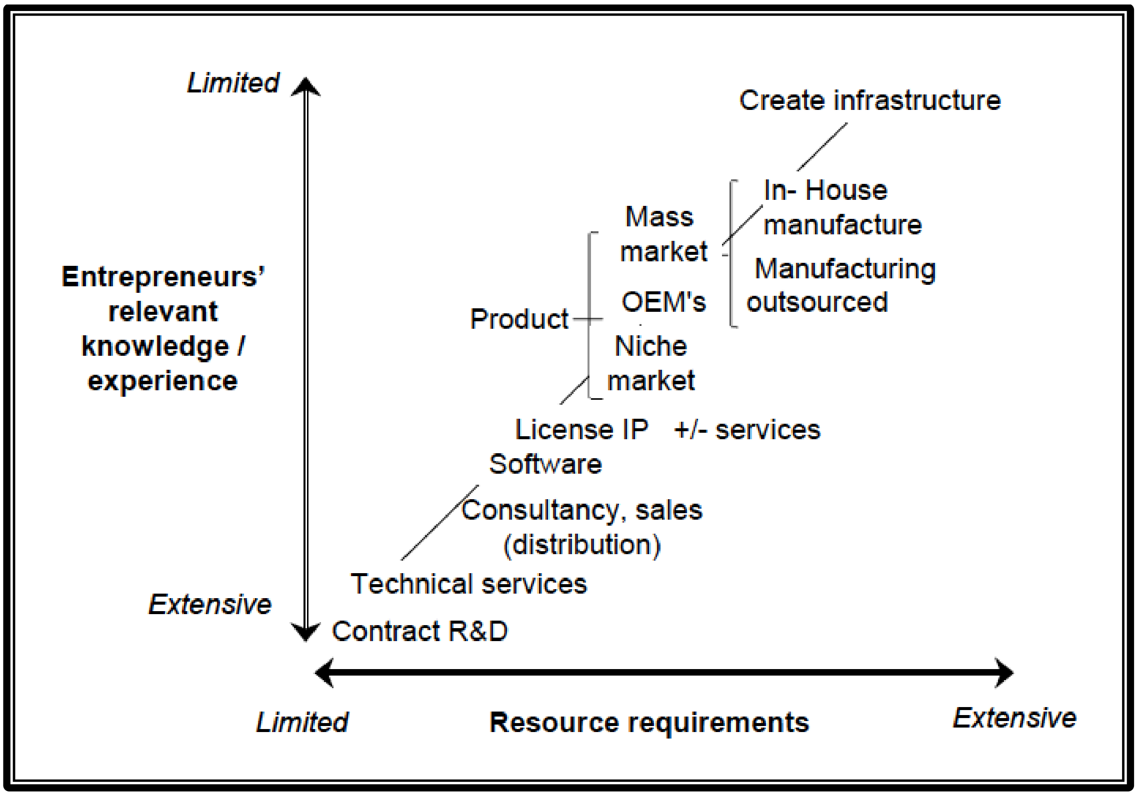
Nascent markets based on emerging technologies, though characterised by uncertainty, offer numerous benefits for entrepreneurial ventures (Santos and Eisenhardt, 2009) and this necessitates understanding the factors that facilitate value creation and growth of new technology ventures and expedite commercialisation. Spencer and Kirchhoff (2006, p.154) emphasised "shifting the focus of study away from how to prevent the failure of large incumbent firms towards how to reduce the barriers to new technology-based firms." Furthermore, as pointed out by Aldrich (1999, p.228), founding a new venture is risky but, for early ventures in the formative years of a new industry, the nature of the challenges is compounded as those are not only related to survival and their embryonic state but the new venture must also legitimise, create new routines, "carve out new markets, raise capital from skeptical sources, [and] recruit untrained employees."

Nieto and Santamaria (2010) in their study on Spanish manufacturing firms found that technological collaborations facilitate bridging the gap between larger and the small and medium sized firms. Absorption of external knowledge and innovation enable young firms to improve their performance and increase chances of their survival (McKelvie et al., 2007). Technical and market knowledge sourcing and in particular collaboration and inter-firm relationships enable SMEs to overcome their human, financial and resource constraints and provide necessary growth opportunities in rapidly changing environments, as discussed in the extant literature (Lechner and Dowling, 2003; Nieto and Santamaria, 2010). "Growth from internal resources only is difficult for most start-ups. Therefore external networks as an alternative model based on inter-organizational activities have been suggested to enable an entrepreneurial growth strategy" (Lechner and Dowling, 2003, p.1).

2.3.1.1 Heterogeneity in Business Models

New technology ventures have to make strategic choices when it comes to adding value and adopting business models (Bhat, 2005; Maine et al., 2012). Druilhe and Garnsey (2004) suggested a diversity and evolution of business models adopted by academic or research-based spin-offs. The range of options (see Figure 2.10) available to the new venture varies from being a consultancy to a development company and, finally, being a product company and developing an infrastructure.

Figure 2-10 Heterogeneity in Business Models



Source: Druilhe and Garnsey, 2004

New ventures may opt for becoming a product company and selling products based on the new technology that requires a decision regarding selecting niche markets, which offer protection and less competition, or selecting multiple markets. Another option is to act as a "development company". This includes selling or licensing the technology and refers to a company "that pulls together initial intellectual property rights (IPR), on which future IPR are built through research and development" (Druilhe and Garnsey, 2004, p.273). A market for technology (Gans and Stern, 1993) is not always a viable option for new ventures as it necessitates developing the technology to an extent where it can be licensed downstream to either manufacturer or customer for scaling.

2.3.1.2 Legitimacy

How do new ventures achieve legitimacy? This strategic question has attracted a lot of interest among scholars that has resulted in a large number of publications – around 30 papers have been produced since 2008. These studies, however, have reviewed legitimatising strategies from different theoretical perspectives such as institutional, cultural, social movement, ecological and impression management, contributing to heterogeneity and fragmentation (Überbacher, 2014). Legitimacy as defined by Suchman (1995, p.574) is a "generalized perception or assumption that the actions of an entity are desirable, proper or appropriate within some socially constructed system of norms, values, beliefs, and definitions." Legitimacy is a resource for new ventures, as argued by Zimmerman and Zeitz (2002), and enables entrepreneurial new ventures to overcome the liability of newness through acquisition of resources such as financial capital and trained and skilled human resources.

Aldrich (1994, 1999) proposed a two-part typology of types of legitimacy – cognitive and sociopolitical – while Suchman (1995) identified three types: pragmatic, moral and cognitive. The cognitive perspective emphasises comprehensibility and taken-for-granted attributes of the new ventures for audiences. It refers to the extent of familiarity of the product or activity for audiences. Sociopolitical or evaluative legitimacy is further composed of moral and regulatory legitimacy and refers to the stakeholder's conformance of new ventures as "appropriate and right" in line with existing cultural value and beliefs and in accordance with government regulations (Aldrich, 1999, p.230). Thus, in contrast to cognitive legitimacy, it is concerned with how to make new ventures and their context more desirable to the audiences.

The ecological perspective (Carroll and Hannan, 1989) associates decreased external legitimacy with high disbanding rates and low founding rates. It considers increased density, that is, a large number of organisations within an established industry, as an indicator of legitimacy, thus suggesting eventual failure for new ventures entering a nascent context (Aldrich and Fiol, 1994; Überbacher, 2014). Building legitimacy in new markets can be extremely challenging (Navis and Glynn, 2010). In the case of new industries devoid of institutional context and with higher uncertainty, entrepreneurs (both new ventures and incumbents) build legitimacy not only at organisational level but also at intra-industry, inter-industry and institutional levels (Aldrich and Fiol, 1994) and for heterogeneous audiences such as investors, alliance partners and government.

The cultural perspective (Aldrich and Fiol, 1994; Lounsbury and Glynn, 2001; Martens et al., 2006) stresses the role of entrepreneurial communication content such as narratives and storytelling for venture legitimisation and acquisition of resources by reducing information asymmetry, establishing identity and communicating intentions (Santos and Eisenhardt, 2009). The perspective is more actor-centred and focuses on the actor's use of narratives and verbal expression to influence stakeholder perception regarding the venture's vision and growth strategies. Legitimacy tends to be even more critical for new technology intensive ventures especially in earlier moments owing to the uncertainty about future prospects and trajectories. Zott and Huy (2007) highlight how frequency and variety in use of symbolic management mechanisms by entrepreneurs help achieve legitimacy and attract resources. Symbolic management tactics find their roots in impression management perspectives and include tactics denoting the entrepreneur's personal credibility and commitment, professional organising through presence of established procedures, organisational achievement via displaying rewards, and the quality of stakeholder relationships.

Other streams of research such as that by Pollock and Gulati (2007) focus on the role of signals, such as affiliation with high status actors and endorsement from third party actors, in reducing information asymmetries and enhancing visibility of new ventures which, in turn, impact sociopolitical legitimacy. For example, affiliation with reputed universities (e.g. in the case of biotechnology), or the presence of eminent scientists or academics on corporate boards, signal normative legitimacy (Zimmerman and Zeitz, 2002; Deeds et al. 2004). Rao et al. (2008) discussed that forming alliances with established partners suggests the potential of the new venture's product and the presence of core capabilities such as marketing and technological competencies. In addition to acquiring legitimacy through external means such as affiliation and alliances, legitimacy can also be developed through other, internal means referred to as historical, scientific, market and locational actions. Historical legitimacy is demonstrated based on past introduction of new products; scientific legitimacy can be communicated by hiring star scientists and academics or establishing board relationships, while recruiting a marketing professional demonstrates the new venture's ability to commercialise and market new products. Location of new ventures in hot spots or clusters is an indication of legitimacy.

In addition to the impact of micro level strategic approaches, such as new ventures' communicative and network strategies that impact legitimacy, evaluative institutions such as government and industry associations that contribute to contextual attributes and build legitimacy at the industry level also influence new ventures' legitimation and decrease their mortality rates (Baum and Oliver, 1991). Petkova et al. (2013) further highlighted the institutional role of mass media in increasing credibility of new ventures. Mass media have the ability to influence the level of attention that new ventures are able to receive from the stakeholders such as venture capitalists. Since media scrutinise and filter information and provide attention to certain selected issues and actors, their coverage therefore increases comprehensibility, perceived value and legitimisation for selected new ventures. “Attracting attention is a precondition for legitimation, as stakeholders need to notice and recognize a new organization as a participant in a given market to consider it as a potential exchange partner” (Petkova et al., 2013, p.867).

Past research has been oriented towards either/or approaches rather than blending both organisational and contextual attributes that may have combined influence on audience judgments (Überbacher, 2014). “The value of technology ventures resides in difficult to understand, intangible and complex scientific and technical capabilities, which are of value only if their emerging industry achieves its promise.” (Deeds et al., 2004, p.10). In practice both macro and micro level influences are important drivers for building legitimacy when the industry is young and emerging. This duality has been emphasised by Suchman (1995, p.577): “…real-world organizations face both strategic operational challenges and institutional constitutive pressures, it is important to incorporate this duality into a larger picture.” Furthermore, Zimmerman and Zeitz (2002) noted that entrepreneurs in new industries are aware of the importance of legitimacy in the growth of business apart from other sources and devise proactive strategies to develop this resource, however detailed empirical work needs to be taken to document such processes.

2.3.2 How Incumbents Cope with Breakthrough Innovations

Extant literature supports the notion that radical, breakthrough, discontinuous innovation cannot be managed in the same way as incremental, sustaining, continuous innovation. According to Laredo et al. (2002, p.48), “The important lesson derived from Abernathy and colleagues of HBS[1] is that the management of incremental innovation takes place on two dimensions (technology and economic) while the management of architectural innovation takes place on three (technology, economic and societal or socio-political).” Thus good practices of managing innovation under a steady state may not be applied in the fluid phase of the technology. It requires building new capabilities and working out of the box, traits mostly associated with new players rather than with incumbents (Bessant et al., 2005). Entrants are

[1] Harvard Business School

considered to be better equipped to commercialise radical emerging technology owing to their flexibility, small size and limited path dependency (Macher and Richman, 2004).

The difficulties faced by incumbents, the "incumbent's curse", in the case of emergence of discontinuous innovation, finds its roots in Schumpeter's process of creative destruction (1950) and has been dealt with extensively within the literature. Several examples and case studies support the argument of incumbent demise, such as the transition from mechanical to quartz movement and its devastating impact on the Swiss watch industry. Tushman and Anderson (1986) discussed that technological innovations result in major evolution that can be classified as either "competence enhancing" or "competence destroying". Competence enhancing enables the leader to gain competitive advantage while competence destroying benefits new entrants as it requires completely new skills, methods and processes. "While liabilities of newness plague new firms confronting competence-enhancing breakthroughs, liabilities of age and tradition constrain existing, successful firms in the face of competence-destroying discontinuities" (Tushman and Anderson, 1986, p.460).

However, not all discontinuities are competence destroying or result in incumbents' failures and there may be outliers, as observed in biotechnology where pharmaceutical companies were able to maintain their market position through licensing, forming alliances with new entrants and acquisitions (Gans and Stern, 2000; Hill and Rothaermel, 2003) , a strategy that proved mutually beneficial for both. Large firms were thus able to retain their strategic position and ensure their survival while start-ups were able to get access to their complementary assets (Hill and Rothaermel, 2003; Rothaermel and Thursby, 2007).

The ability of incumbents to cope with these changes depends on the breadth of impact of radical innovation on the upstream and downstream activities of the incumbents, and on gestation period. Methe et al. (1996) suggested that the role of established firms (both incumbents and diversified) is underemphasised and that they are a source of new major innovation, as evident from examples in the telecommunications, medical, semiconductor and liquid crystal industries. They argued that type of change, such as technical or market, is a deciding factor when it comes to determining the source of new innovation (Figure 2.11). When innovation (substitute, complementary or new) requires new knowledge, then major sources of innovation are new firms, while when technical changes require reconfiguration of existing knowledge and routines, then incumbents are incentivised to pursue innovation and are the main player. Tripsas (1997) showed in her study of the typesetting industry the role of specialised complementary assets as a buffering mechanism for the incumbent's survival in the case of competence destroying technical change. Recent theoretical advancements in this direction suggest the role of complementary assets as both pipes and prisms that may impact the investment decision and the technological trajectories pursued (Wu et al., 2013).

According to Chandy and Tellis (1998, p.475), "our review of the decades of research on the effect of size on radical innovation indicates that it has led to little progress in understanding the true drivers of radical product innovation." They pointed towards the importance of attitudinal factors such as willingness to cannibalise in explaining radical innovators' success.

According to Sosa (2009) most of the earlier research has concentrated on loss of technological capabilities and the incumbent's underperformance of R&D. She provides another explanation for the incumbent retaining their position in the drug industry and argues that there are two necessary sets of R&D capabilities – technology specific (non-market specific) and application specific (market specific) – and it is the latter set of capabilities that provides explanation for incumbent survival and competitive advantage in the case of radical innovation. More recently, Lechevalier et al. (2014), in contrast to the established scholarly literature that associates the emergence of new industry with that of new firms (e.g. Audretsch and Thurik, 2004), suggested that "intrapreneurship regime" rather than entrepreneurship regime and incumbents as drivers of radical innovation and industry emergence in the case of the service robot industry in Japan.

Figure 2-11 Influences of Market and Technological Change on Sources of Innovation

Market change	Technical change	
	New knowledge base	Knowledge base reconfiguration
Substitute use	New companies Incumbents (?)	Diversifying entrants Incumbents (?)
Complementary use	New companies	Incumbents Diversifying entrants
New use	New companies	Diversifying entrants
—		+

Source: Methe et al., 1996

Several explanations – economic, organisational and strategic – are offered in the literature for incumbents' inflexibility and delays, such as a preference for continued investing in incremental innovations with certain payoffs rather than continuing development of radical innovation with its higher uncertainty and fear of cannibalising existing sales (Christensen and Rosenbloom, 1995). Other arguments are based on "core rigidities", that is, when existing routines hamper radical innovation (Leonard-Barton, 1992); learning traps (Levinthal and March, 1993) that translate into "*familiarity trap"*, "*maturity trap"* and "*propinquity trap"* (Ahuja and Lampert, 2001); inertia that stems from established routines such as evaluative routines, as suggested by Garud and Rappa (1994) in the development of cochlear implants; culture, processes and structures that limit organisational search in new domains; actors' cognitive framework and interpretative processes (Kaplan and Tripsas, 2008); limited absorptive capacity (Cohen and Levinthal, 1990); and constraints offered by the existing value network of suppliers, customers and investors (Christensen, 1997).

Incumbent and large organisations are characterised by reliability and accountability necessary to develop reproducible organisational structures and processes (Hannan & Freeman, 1984). Paradoxically, the momentum generated through resultant institutionalisation and standardisation contribute to inertia and resistance to change. Inertia theory proposes that both age and size contribute to resistance to change core organisational structures and prevailing routines (Kelly & Amburgey, 1991).

So, how do incumbents counteract inertia? Abernathy and Clark (1985, p.21) concluded that, "while firm may have a dominant orientation, it is likely that the firm will face the task of managing different kinds of innovation at the same time." Tushman and O'Reilly III (1996) proposed "ambidextrous organizations" to counteract "the success syndrome". According to Laredo et al. (2002), "breakthrough innovation (which often represents around a tenth of the R&D portfolio in a large established firm) cannot be managed in the same way as on-going, incremental, sustaining or continuous innovations… which build a gradual accumulation of useful variation." Hill and Rothaermel (2003) proposed a more holistic approach, increased investment in basic R&D and loose coupling between applied and basic units, development of appropriate organisational processes and culture such as legitimising autonomous actions, and structural isolation of units responsible for radical innovation to attenuate inertia and inflexibility. Macher and Richman (2004) discussed three different organisational approaches – "internal venture, joint ventures and acquisitions" – adopted by established organisations (Motorola, IBM and Kodak) in the case of discontinuous innovation to achieve first mover advantages. However, the particular strategy (internal development versus external acquisition) pursued by the organisation among other things was dictated by the time it would require to beat the competition and position within the ferment era of the technology life cycle. If technology is progressing towards the dominant design then the time pressures demand pursuing strategies such as joint venture or acquisitions to acquire the required competency, whereas in the beginning of the cycle, the organisation may be willing to go for internal development.(Table 2.1 summarise the main studies)

Contrary to the dominant stream of literature that focuses on incumbents' strategies in response to an introduction of new technology by new players, Cattani (2006, p.286) focused on preadaptation strategies described as "that part of a firm's technological knowledge base that is accumulated without anticipation of subsequent uses (foresight), but might later prove to be functionally "pre-adapted" (i.e., valuable) for alternative, as yet unknown, applications" for developing radical innovation "fiber optics" by Corning. Pre-adaptation increases knowledge diversity that in a turbulent and uncertain environment can increase the firm's absorptive capacity to identify relevant external technical and market knowledge. Mangematin et al. (2011) identified adoption of pre-adaptation strategies as being instrumental in the case of a large organisation within nanotechnology. They found that in the emergent phase of nanotechnology, investments were to a limited extent by large firms. These large firms adopt pre-adaptation mechanisms, develop diversified knowledge and

Table 2-1 Incumbents' Challenges and Strategies

Author	Year	Research Method	Challenges for incumbents	Approaches for Invention/Discontinuous Innovation
Ahuja and Lampert	2001	Patenting activity in chemical industry	• Familiarity traps • Maturity traps • Nearness traps	• Exploration of novel technologies (new to the organisation) • Experimenting with nascent or emerging technologies • Experimenting with pioneering technologies
Rothaermel	2001	Biopharmaceutical industry. Study of 889 strategic alliances	• Incumbents' survival	• Inter-firm cooperation between incumbents and new entrants through exploitation of complementary assets
Hill and Rothaermel	2003	Conceptual	• Economic Explanation • Organisational Theory Explanation • Strategy Explanation	• Loose coupling between basic and applied research • Use of Real Option Perspective • Legitimisation and Institutionalisation of Autonomous action • History of firm navigating in the turbulence • Establishing a loose coupled standalone division to commercialise innovation
Macher and Richman	2004	Case study (Motorola, IBM, Kodak)	• Commitment to current value network • Established Routines	• Internal Venture • Joint Venture • Acquisition
Cattani	2005	Patent analysis in Fiber Optics	• Prior experience in current domain may act as a constrain	• Preadaptation-Firm prior experience accumulated without anticipation of subsequent uses
Elicia Maine	2008	Case study	• Allocation of Internal R&D resources in a risk averse manner	• Corporate Venturing

Kaplan	2008	Longitudinal data from 71 communication firms in fiber-optics revolution	• CEOs faced great deal of uncertainty in investing in competence destroying innovation.	• Interaction of CEO cognition, organisational capabilities and incentives
Ansari and Krop	2012	Framework development and field illustrations.	• Institutional and Regulatory Environment • Demand Factors • Supply factors • Innovation type and impact on value network • Commercialisation requirements • Incubation time horizon	• Symbiotic relationship with challenger firms • Incumbent firm configuration such as formal organisation of the firm, its culture and formalisation of ambidextrous process • Effectively build and leverage linkages between the innovation and complementary capabilities
Maula, Keil and Zahra	2013	Longitudinal data from largest company in ICT industries	• Top management attention allocation failure owing to their information processing systems and cognitive frame	• Corporate venture capital and heterophilous inter-organisational relationships as a mechanism for directing top management attention
Gerstner, König, Enders and Hambrick	2013	Reaction of established pharmaceutical companies to the emergence of biotechnology (1980-2008)	• Rarity of incumbent firms to respond with aggressive commitments to discontinuous change	• Role of CEO’s narcissism in overcoming inertia and directing top management attention
Wu, Wan and Levinthal	2013	Model development	• Incumbents’ investment decisions and choice of technological trajectory pursued is guided by complementary assets	• Complementary assets act as both pipes and prisms • Firms with low levels of complementary assets follow complement–disrupting technological trajectories while those with existing complementary capabilities may pursue less promising technological trajectories.

hybridise exisitng knowledge with new knowledge by creating small and medium sized subsidiaries with the main focus on patenting rather than publishing.

Incumbents in particular are considered to be at disadvantage when it comes to reconfiguring and adapting themselves in the nebulous stage of industry emergence (Hill & Rothaermel, 2003). Thus there have been two main themes dominant within the literature when it comes to radical innovation, one that focuses on reasons for incumbent failure and another that discusses the dynamics associated with challengers. However, little is known about why few incumbents survive the gale of creative destruction, or their differential responses (Sandström et al., 2009). Further, most of the literature focuses on incumbent performances and only on its survival and that too retrospectively rather than analysing the transition stage or the gestation period, that admittedly tends to be longer and unpredictable (Jiang, Tan and Thursby, 2010; Ansari and Krop, 2012).

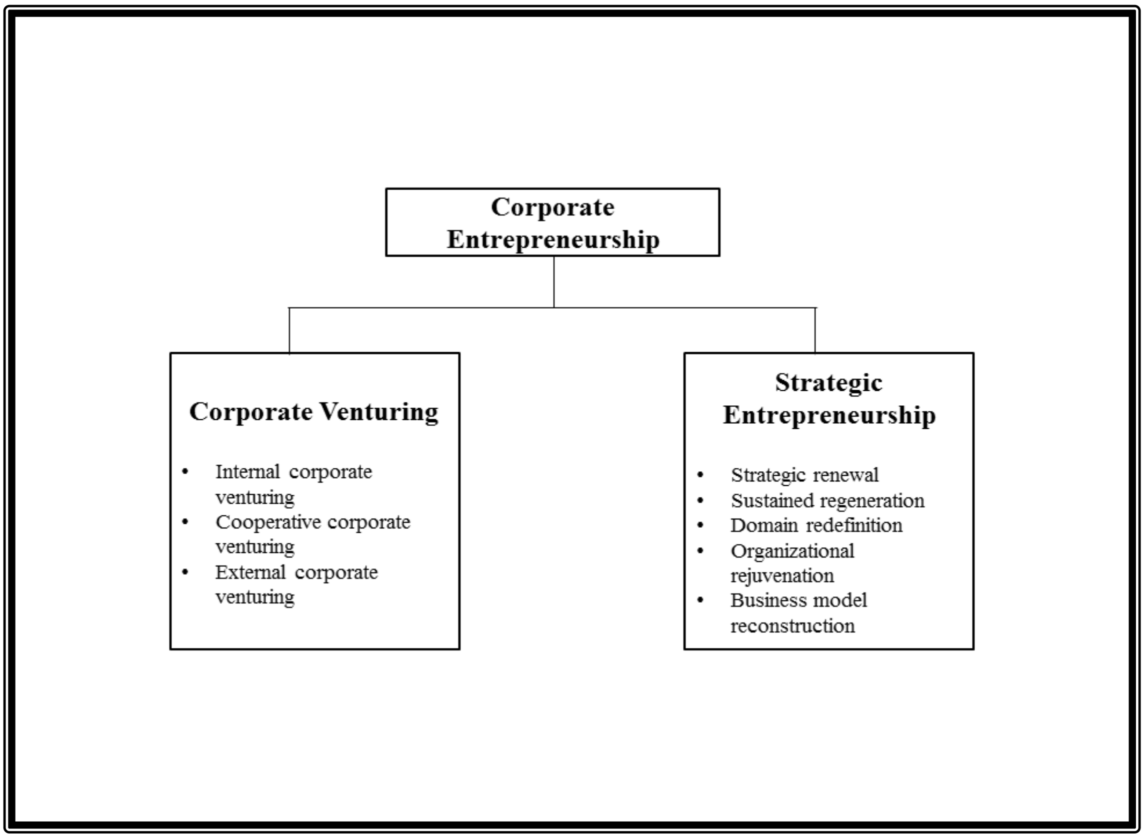
Ansari and Krop (2012) stressed the development of a multilevel framework based on industry settings (institutional environment, complementary markets, demand factors, supply factors, turbulence and rivalry), incumbent firm properties (boundary management, configuration and complimentary capabilities) and challenge (value network, commercialisation requirements and incubation time horizon) to understand incumbents' challenger dynamics.

2.3.2.1 Corporate Venturing

One of the mechanisms through which innovation and entrepreneurship can be introduced in the large venture is through corporate entrepreneurship (Ahuja and Lampert, 2001; Ireland, Kuratko and Morris, 2006). Extant literature suggests fragmentation, inconsistencies and evolution of its definition. (Kuratko and Audretsch, 2009; Narayanan, Yang and Zahra, 2009). Sharma and Chrisman (1999) described it as "the process whereby an individual or a group of individuals, in association with an existing organization, creates a new organization or instigates renewal or innovation within that organization". According to Morris et al. (2008) corporate entrepreneurship can take various forms within an organisation and can be established through modes such as corporate venturing and strategic entrepreneurship (see Figure 2.12). Corporate venturing refers to adding of new businesses or some portion of them via equity investments while strategic entrepreneurship refers to a broader array of entrepreneurial actions taken by a firm to achieve differentiation as compared to industry rivals and maintain competitive advantage. It involves simultaneous exploration of new knowledge as well as exploitation of existing knowledge. Strategic entrepreneurship may not necessarily result in creation of new businesses, however, it represent major changes in strategy, business model, product, services, organisational structure or processes. Thus it can take the form of strategic renewal, sustained regeneration, domain redefinition, organisational rejuvenation and business model reconstruction (Covin and Miles, 1999).

Corporate venturing is of significant strategic advantage in high technology industries that enable incumbents to learn, augment their search, monitor emergence and evolution of new technologies, and develop capabilities in new domains (Schildt et al., 2005; Narayanan et al., 2009). It can be established mainly through internal venturing and external venturing (Keil, 2000). To sharpen the picture further, internal corporate venturing is defined by Sharma and Chrisman (1999, p.19) as "corporate venturing activities that result in the creation of organizational entities that reside within an existing organizational domain" while external corporate venturing activities is defined as "corporate venturing activities that result in the creation of semi-autonomous or autonomous organisational entities that reside outside the existing organisational domain."

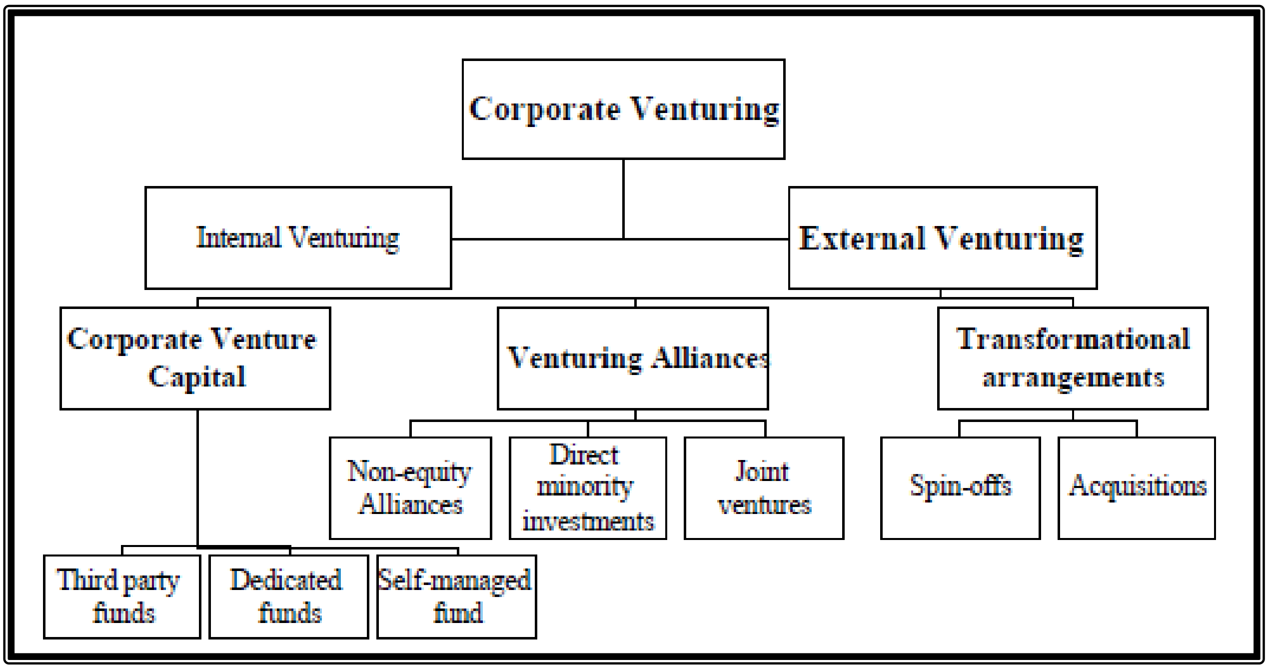
Figure 2-12 Forms of Corporate Entrepreneurship



Source: Morris, Kuratko and Covin, 2008

Keil (2000) further classified external corporate venturing as corporate venture capital, venturing alliances, and transformational arrangements (see Figure 2.13). In the corporate venture capital mode of external venturing, investment is the main mechanism of establishing relationship with independent external firms. However, it may take various forms such as third party, dedicated funds or self-managed funds depending on several factors such as level of involvement by corporation, degree of risk and organisation objectives (financial or strategic). Third party funds are managed by traditional venture capital firms and organisation along with other investors invest in those funds mainly targeting the specific technological domain of interest. In case of dedicated funds, organisation solely set up joint fund with a venture capitalist firm who also manages it. The third option refers to setting up of funds similar to that of a traditional venture capital fund.

Figure 2-13 Modes of External Venturing



Source: Keil, 2000

Venturing alliances represent inter-organisational relationships that are established with the objective of creating or supporting new business activity and include non-equity alliances, direct minority investments and joint ventures. Non-equity alliances can serve as an instrument to monitor the new technological development and involve forming alliances aimed at support or creation of new business. Direct minority investments represent direct investment in the venture firm and seem to have much overlap with corporate venture capital mode. However, whereas the corporate venture capital activities may be driven by both financial and strategic objectives, direct minority investments are mainly focused on developing strategic relationships. Joint ventures involve forming a new organisation and legal entity jointly with an alliance partner.

Acquisitions and spin-offs classified as transformational arrangements are the last form of external venturing activity in Keil's (2000) model. While acquisition is associated with internalising of an external venture, spin-off is related to externalising or diversification of internal ventures. Schildt et al. (2005) suggested a varying impact of different governance modes of external corporate venturing on exploration and exploitation.

After setting the foundation of corporate venturing, the next section will concentrate on looking at the corporate venture capital (CVC) mode. CVC as an important and popular mode of external corporate venturing has been a focus of recent academic debate and discussion owing to its impact in dynamic environments and on breakthrough technologies (Miles and Covin, 2002; Narayanan et al., 2009; Souitaris and Zerbinati, 2014).

CVC can be viewed as an option building strategy for incumbents in the face of technological discontinuities (Keil, 2000; Narayanan et al., 2009; Van de Vrande and Vanhaverbeke, 2013). Knowledge related to technological discontinuities tends to be fundamentally different from that required for incremental innovation. Managerial cognition in this context often fails to respond to discontinuities in a timely manner. According to Yadav et al. (2007, p.85) the scariest resource is not information but it is actually the "processing capacity to attend to information". Maula, Keil and Zahra (2012), while adopting an attention perspective, suggested the use of heterophilous ties and CVC mechanisms in directing top management attention to discontinuous innovation in an external environment. CVC investments connect the incumbents to a community of venture capitalist firms that provide them with information regarding breakthrough technologies and its evolution and promising new ventures. Apart from acting as radar to the emerging technologies, CVC mechanisms and interaction with start-up ventures also facilitate incumbents in developing cognisant or shared understanding of their capability needs (Keil et al., 2008). Furthermore, the venture capital community have no vested interest in existing technologies and possess a different cognitive framework than that of incumbents for evaluation of new emerging technologies.

2.3.3 Intermediaries

The term intermediary is used in diverse literature such as innovation studies, business studies, science and technology studies and technology policy. Intermediaries have been discussed in the literature using different terms and in different contexts as knowledge brokers (Hargadon, 1998), innovation brokers (Winch and Courtney, 2007), virtual knowledge brokers (Verona et al., 2006), cooperative technical organisations (CTOs) (Rosenkopf and Tushman, 1998), bridging organisations (Sapsed et al., 2007), promissory organisations (Pollock and Williams, 2010) and consultants (Bessant and Rush, 1995). They can be public, private, semi-public, profit or non-profit organisations (Suvinen et al., 2010). The proliferation of terms used has resulted in fragmentation and varied conceptualisation (Howells, 2006; Klerkx and Leeuwis, 2009; Kilelu et al., 2011). Howells (2006, p.720) broadly defined intermediary as "any organization or body that acts as an agent or broker in any aspect of the innovation process between two or more parties.” The performativity perspective conceptualises intermediation as a set of practices for translating knowledge among collective actors. “They not only stand ‘in-between’, but their work, practices, roles, effects and identities also make them ‘in-themselves’ relevant actors to analyse” (Meyer and Kearnes, 2013, p.426). Thus the role of intermediaries is not only limited to passive transfer of knowledge but also includes co-development of innovation, and active shaping of the emergence of new technologies and markets, network facilitation and network governance (Yildiz et al., year not known).

Scholarly literature on intermediation can be distinguished in three different streams as institutions, actors and instruments (Meyer and Kearnes, 2013). Due to the more distributed nature of innovation, the literature on institutions focuses on a range of organisations with intermediary characteristics such as boundary organisations, research councils, industry analysts, research and technology organisations, industry or trade associations, knowledge intensive business services (KIBS) and knowledge transfer offices (Van Lente et al., 2003; Meyer and Kearnes, 2013). The second stream of literature focuses on the intermediary roles played by particular actors such as consultants and analysts, spokespeople or knowledge brokers. In the third stream the focus is on a range of instruments such as business models and standards that facilitate intermediation between science, market and government.

Despite myriads of research on identifying the activities and roles of intermediary organisations, there are few studies discussing their role within the protection space (Hargreaves et al., 2013; Kivimaa, 2014) or for disruptive innovation (Sapsed et al., 2007). According to Pittaway et al. (2004, p.160) “the role of third parties operating within the network infrastructure, such as professional and trade associations, is underresearched.” Innovation intermediaries, especially research and technology organisations that intermediate between research and business communities, position themselves within the innovation gap referred to also as the Valley of Death (Auerswald and Branscomb, 2003) to facilitate transition from invention to innovation (Dalziel, 2010). Similarly, Sapsed et al. (2007) highlighted the role of bridging organisations in overcoming the weakness within the sectoral systems of innovation (SSI) that fail to support disruptive innovation occurring at the boundaries.

The next section will discuss the two important intermediary institutions - research and technology organisation (RTO) and industry association.

2.3.3.1 Research and Technology Organisations (RTOs)

The generation and continuous evolution of new knowledge tend to be extremely important for enabling technology with the potential for competitive advantages and future economic potential. In this regard, academic literatures have focused on external sources of knowledge in general and the importance of universities and public research institutes in particular. However, the extant studies have discussed the role of universities and technology institutes as a whole rather than highlighting the difference that exists among universities, research and technology institutes and public research organisations (Barge-Gil et al., 2011). Furthermore the main focus of the studies has been around discussion of the role of RTOs in various contexts such as national and/or regional (Aström, Eriksson and Arnold, 2008; Barge-Gil and Modrego-Rico, 2008; Loikkanen et al., 2011; Miller, 2014); developing and developed nations (Mazzoleni and Nelson, 2007); heterogeneity of their models (Mina et al., 2009); factors affecting their management and strategies (Barge-Gil et al., 2007), their strength and weakness (Rush et al., 1995); performance indicators (Albors-Garrigos et al., 2010) and challenges encountered (Leitner, 2005).

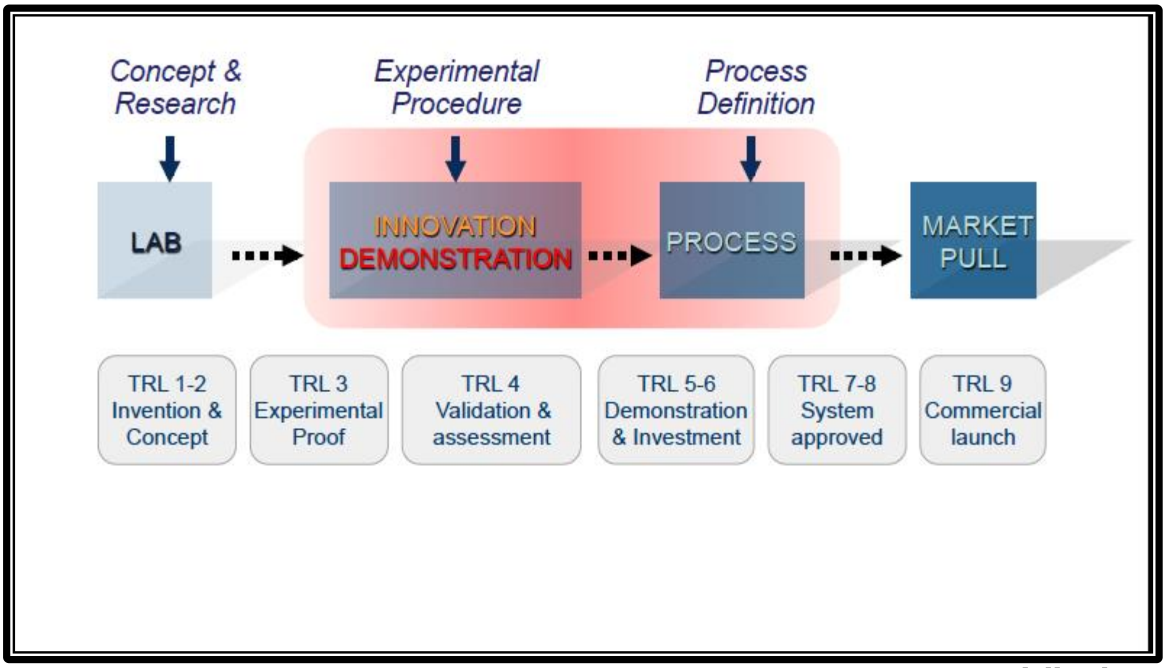
RTOs are defined as "organisations, which as their predominant activity provide research and development, technology and innovation services to enterprises, governments and other clients" (Arnold 2010, p.10). However, they exhibit heterogeneity in terms of their legal status (public, semi-public or private), orientation (national or regional), organisation, mission and output (ranging from basic research to product development and technical services (Leitner, 2005; Leijten, 2007).

RTOs have been identified as one of the main policy intervention tools within the National Innovation System (NIS) and also at regional level as they facilitate development of ecosystem around particular technology or industry sectors and to address market and system failures (Barge-Gil and Modrego-Rico, 2008; Loikkanen et al., 2011). Aström et al. (2008) identified several roles of RTOs within the National Innovation System (NIS) such as mediator of knowledge between university and industry; importer of knowledge via participation in the EU Framework Programme; creator of new in-house knowledge through R&D; and supplier of customised knowledge. In addition to that, they provide infrastructure and impartial testing and certification services.

RTOs maintain close relationship with universities, though their role is considered complementary to that of university as they basically engage in projects that are applied in nature. According to Laredo and Mustar (2004, p.12), both institutions have become essential to the growth of the firms owing to the emergence of "new research collectives." Their role is important both for industrialised and catching up economies (Mazzoleni and Nelson, 2007). From a policy point of view they can also act as orchestrator or as a hub in the innovation ecosystem, as they facilitate knowledge transfer particularly in the context of SMEs that are resource constrained and require external knowledge as well as social capital for their success (Tann et al., 2002; Albors-Garrigós et al., 2010; Albors-Garrigós et al.,2014). Interactions of firms with RTOs can result in internationalisation (Martinez-Gomez et al., 2009) and increased learning, thereby contributing to the absorptive capacity of both the interacting firm as well as the RTO.

RTOs are considered as critical for technological advancement and for crossing the "Valley of Death" – "the situation in which a technology... fails to reach the market because of an inability to advance from the technology's demonstration phase through the commercialization phase" (Frank et al., 1996, p.61). RTOs mostly operate in the technology readiness levels (TRL) 4-7 as shown in Figure 2.14. TRL measures the maturity of technology and is widely used by the US Department of Defense, the Ministry of Defence and NASA. TRL 1-3 refer to basic research, invention and proof of concept and are the levels where universities are mostly involved. TRL 4-7 are for development, technological validation in the lab and demonstration, while TRL 8-9 are for commercial deployment.

Figure 2-14 Technology Readiness Level and Intermediaries



Source: McClelland, 2014

2.3.3.2 Industry Associations / Meta-Organisations

Professional associations or spanning organisations facilitate creation of collaboration networks between firms, universities and government (Rosenkopf and Tushman, 1994; Swan and Newell, 1995). Collaborative networks tend to be important for learning, innovation and diffusion of knowledge especially in the context of emerging technologies where the space is still developing and the value chain is fragmented. New industries face immense competition in their early years from established industries. Extant literature suggests formation of new industries is a social and political process and creating an industry association in the early years helps achieve cognitive and sociopolitical legitimacy among stakeholders (Aldrich and Fiol, 1994; Rao, 2002). Constitutive legitimacy, that is, the process through which "new industries is understood and taken for granted by consumers, investors and potential employees", can be achieved through many parallel processes such as evangelism, advertising, demonstrations and claim making (Rao, 2002, 2004). Despite their importance, they are underresearched and have been somewhat neglected until recently (Esparza et al., 2013; Reveley and Ville, 2010). Watkins et al. (2015) emphasised the importance of the role of intermediaries such as industry associations as institutions in the context of the National Innovation System for developing and catching up countries.

"Industry associations (IAs) can be defined as business interest organisations that represent their members' political and economic preferences" (Aldrich and Staber, 1988). Ahrne and Brunsson (2008) refer to them as 'meta-organisations' – organisations of organisations. For Greenwood et al. (2002) they provide arenas for interaction "whereby members of a community represent themselves to others." Barnett (2013, p.214) defined them more explicitly as "organizations through which a group of interdependent firms, typically in the same industry, pool their resources and coordinate their efforts so that they may "speak with one voice" on matters of shared interest." Aldrich (1999) refers to them as "minimalist organizations" as they operate on low overheads and are initially founded by an "industry champion."

Industry associations are meta-organisations that facilitate inter-organisational bridging among their diverse members. According to Geels (2005, p.65) they are "important for cognitive stabilization, for example articulation of problem agendas, standard setting." In addition to providing a common platform for discussion and networking, the members join an association to achieve legitimacy, shared identity, development of common language and lobbying.

> TAs do not simply represent interests of members but often select and redefine them in a way which renders possible their collective representations. These representations of interest may assume the forms of more or less binding recommendations and de facto obligatory sets of rules, defining acceptable ways of business behavior - a kind of code of business ethics. (Lane and Bachmann, 1997, p.239)

There are various mechanisms adopted by industrial/professional associations to facilitate the innovation process and enhance industry stability. Among the formal practices are newsletters, publication of journals, organising seminars, conferences and workshops, etc. Trade fairs and conferences, also referred to as field-configuring events and discussed in the next section, encourage informal collaboration among boundary spanning individuals from diverse organisations, foster a climate of trust and facilitate dissemination of knowledge via a network of weak ties (Newell and Swan, 1995).

New technologies often require staged introduction, for example through dramatic announcements to persuade investors and potential customers and create necessary technology pull, as discussed by Lampel (2001). *Field-configuring events* such as conferences and tradeshows provide such opportunities because they represent:

> …settings where people from diverse social organizations assemble temporarily, with the conscious, collective intent to construct an organizational field. These events are microcosms of nascent technologies, industries, and markets. They are places where business cards are exchanged, networks are constructed, reputations are advanced, deals are struck, and standards are set. (Meyer et al., 2005, p.467)

The role of field-configuring events has recently received much attention in the scholarly literature as evident from a special issue in the Journal of Management Studies (2008) and a recent call in the Industry and Innovation Journal (2013). These events play an important role in path creation, shaping the trajectories of the technologies, markets and industries (Lampel and Meyer, 2008).

They can rightly be called arenas, which may be organised temporarily on a one time basis or periodically to enable social exchanges, discuss future developments, identify trends, limitations and crucial issues and reward accomplishments. "They can become crucibles from which new technologies, industries, and markets emerge" (Lampel and Meyer, 2008, p.1026). They are not the only source of updated information, but may serve as venues that impact selection of technological paradigms or preferences of one approach over another (Garud, 2008). Intensity of interactions across boundaries may result in an unanticipated emergence of outcomes. "They make it possible for streams of events to intersect, amplifying certain dynamics while dampening others" (Garud, 2008, p.1084). "Dramaturgical events" (Lampel, 2001), through persuasion, create a bandwagon process and facilitate sense making, convergence and closure that is not achieved by field actors using factual information.

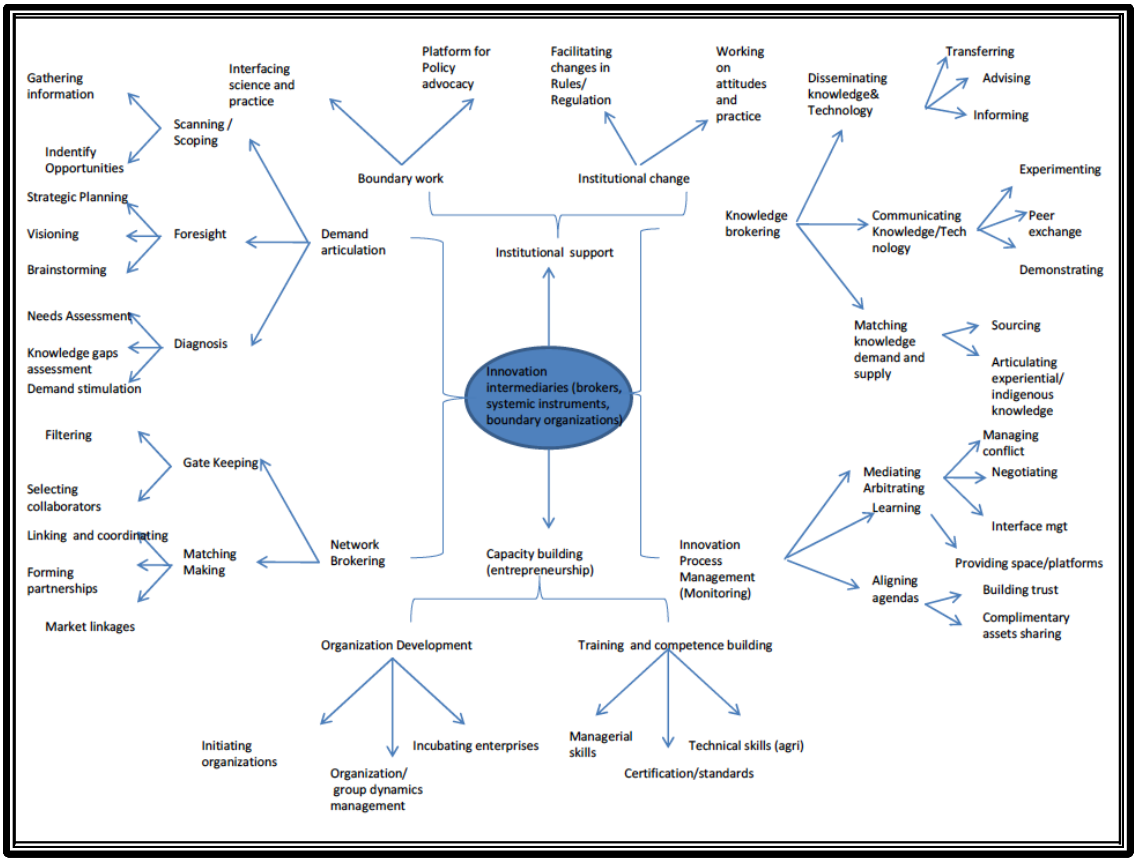
2.3.3.3 Roles of Intermediaries for Emerging Industries

The role of brokerage in the context of intermediary organisations has received much attention in scholarly literature. Kilelu et al. (2011) distinguished six broad intermediary functions: such as demand articulation, knowledge brokering, network brokering, capacity building, innovation process management and institutional support (Figure 2.15). The next section discusses intermediaries' roles such as demand articulation, network orchestration, communication and learning and mobilising expectations identified as important for breakthrough technologies.

Collingridge's dilemma (1980) provides a rationale for intervention at early or fluid stages of technology development. The era of ferment is characterised by high uncertainties regarding technological options, the possible applications and related demand. Once the stabilisation is reached and uncertainties are reduced, actors and stakeholders are more certain about the possibilities and directions. However, at later stages intervention is difficult. This points towards the importance of *demand articulation* that includes identifying problems or requirements at the embryonic stages of technology development by employing all the relevant stakeholders (Boon et al., 2008; Boon et al., 2011). It can be defined as:

> …an iterative, inherently creative process in which stakeholders try to unravel preferences for and address what they perceive as important characteristics of an emerging innovation. Demand articulation takes place when thoughts of stakeholders, in terms of content and position (in favour or against), are made explicit, in such a way that it prompts other actors to (re-)act. (Boon et al., 2008, p.645)

Figure 2-15 Intermediary Functions



Source: Kilelu et al., 2011

Uncertainty, complexity and dynamism are some of the characteristics of emerging technologies that inhibit network formation. “Despite limited knowledge of each other's ways of working, firms must share information, make non-retrievable investments and engage in intense collaboration, often before trust has been developed" (Story et al., 2011, p.954). Batterink et al. (2010) proposed that in this context intermediaries provide necessary *network orchestration* for SMEs that is "scanning, scoping, filtering and matchmaking of sources of complementary assets such as knowledge, materials and funding" (*ibid.,* 2010, p.52) and align their interests with frequent interaction and communication. New networks are instrumental for niches and since intermediaries maintain a heterogeneous and divergent network they provide necessary bridging of weak ties and structural holes that enable innovation and learning.

Intermediaries facilitate *coordination and communication* between two different worlds, that is, research and industry. Frequent interactions within the network develop trust, enable knowledge mobility and enhance learning (Batterink et al., 2010). Kivimaa (2014, p.1373) identified the role of intermediaries for both first and second order learning mechanisms within the niches. Some of the practices identified include: "knowledge gathering, processing, generation and combination, prototyping and pilot testing, creating conditions for learning by doing and using and evaluation."

Expectations, as discussed in earlier sections, are instrumental for mobilising resources, enrolling actors and shaping the market for new technologies. However, "not all expectations influence technologies in the same way," as suggested by Pollock and Williams (2010, p.530). They elaborated on the activities undertaken by promissory organisations- industry analyst not only in creating expectations but also in making them performative. These include intervention aimed at identification of technological markets and important players referred to as "infrastructure knowledge"; signposts or predictions about the current and future state of the industry; and vendor ranking and assessment of the potential of suppliers within a particular sector. Intermediaries facilitate "convergence and alignment of expectations" within a network, an important process within the niche (Hoogma, 2000; Raven, 2004). Caniels and Romijan (2008, p.615) elaborated "the importance of developing a common core view about where the participating actors are going with each other and with the technology. Actors' strategies, expectations, beliefs, practices, outlooks, perceptions and views must go in the same direction and become more specific and consistent."

Knowledge in the context of emerging industries, as discussed earlier, is highly distributed and therefore requires different organisational forms and capabilities. The next section will discuss the literature that informs the capability development of the actors in the emerging context.

2.4 New Organisational Forms - Ecosystems

Internal processes and generation of knowledge are important determinants of firm performance, in the context of high technology where the knowledge tends to be more complex, diverse and distributed. Crossing the valley of death increasingly depends on external knowledge and collaborative relationships with heterogeneous partners. Most of the organisations do not have the ability to mobilise internally the diverse portfolio of knowledge required for innovation and therefore rely on coordination mechanisms that range from pure market mediated interactions to strategic alliances to access the external knowledge and capability they do not possess internally.

"A distinguishing feature of the competitive performance of firms is their differential ability to manage the external collaborative relationships required by modern innovation conditions" (Coombs and Metcalfe, 2000, p.209). They further add, "Knowledge is not in general in the atmosphere, despite its non-rival nature. It has to be searched for and acquired through positive steps" (*ibid*., p.222)

Coombs and Metcalfe (2000) identified three main factors that contribute to the rationale for distributed sources of innovation such as increased *technology diversity*, that is, companies have to "know more"; blurring of industrial boundaries as evident from Kodama's (1992) proposition of technology fusion. Furthermore, increased *systemic complexity*, specialisation and complementarity associated with recent technological advancement make it increasingly difficult for a single firm to develop capabilities required to manage them.

Understanding of an innovation as an interactive and distributed process is not new. It builds on and has been informed by other works such as "system of innovation" literature and Callon's (1984) "actor network" approaches (Coombs et al., 2003). The success of Japanese firms in the 1980s highlighted a more parallel approach to innovation, marked a shift towards a distributed form of innovation, and increased emphasis on networks, strong external vertical and horizontal linkages with customers and suppliers, in addition to integration with internal cross-functional teams of R&D, marketing and manufacturing. Rothwell (1992) proposed a fifth generation *model* of innovation, an evolution from the earlier sequential technology push and demand pull models of the 1960s and 1970s and Kline-Rosenberg's (1986) chain-linked model. Dougherty and Dunne (2011, p.1214) pointed towards the challenges associated with organising ecologies of complex innovation: "…it concerns how to foster the necessary collaborations among so many diverse organizations over such a long period under such ambiguity."

In the context of rapidly developing fields such as biotechnology, the locus of innovation is in networks (ecosystem) as knowledge is widely distributed and not the domain of a single organisation (Arora and Gambardella, 1990; Powell et al., 1996). Knowledge, not being readily available, cannot be bought in the market. Innovation success in turn largely depends on the intensity and number of inter-organisational collaborations. Jacobides et al. (2006) suggested moving from a dyad level of analysis to architectures while Gulati et al. (2012) pointed towards the emergence of the meta-organisation. Powell et al. (1996) further stressed that these inter-organisational collaborations should not be viewed as on-off market transactions nor are they aimed to fill the internal knowledge gap only, but they are a source of continuous learning. Membership in the network is a conduit to gain access to novel knowledge outside the organisation's boundaries.

Lubik and Garnsey (2014) highlighted the importance of and rationale for the use of the ecosystem perspective for studying new ventures in science-based industries:

> This perspective makes it clear value generation is a distributed process that involves co-innovation from other value-adding participants in the venture's environment. Moreover ecosystem analysis can accommodate the influence of policy makers, regulators and standards setters, who do not usually appear in standard value chain analysis nor in the industrial structure approach to the firm's business environment. (*ibid*., pp.315-316)

The construct 'ecosystem' was proposed by Moore who suggested it as a third form of organising in addition to market and hierarchies; it has its roots in complexity and chaos theory (Lengnick-Hall and Wolff, 1999; Gueguen et al., 2006). The idea of business ecosystem motivates the contributors with divergent interests that there exists an opportunity space that cannot be explored individually but requires collective action and convergence of vision.

> Members of an ideal business ecosystem are motivated to work together to advantage the community. Their focus is on working with others to develop and expand existing and new markets in which both their present capabilities as well as future contributions may have full play. (Moore, 2006, p.32)

> Business ecosystems are communities of customers, suppliers, lead producers, and other stakeholders—interacting with one another to produce goods and services. We should also include in the business ecosystem those who provide financing, as well as relevant trade associations, standards bodies, labor unions, governmental and quasi governmental institutions, and other interested parties. (Moore, 1998, p.168)

Business ecosystem consists of interdependent heterogeneous actors bounded by either cooperative or competitive relationship who depend on each other for their survival and success (Iansiti and Levien, 2002). The key defining characteristics of ecosystem are value creation, coordination mechanisms and symbiotic partnerships (Thomas and Autio, 2012). An ecosystem not only provides radical opportunities for all its participants but also enables timely exploitation thus creating value for its partners. Co-specialisation (bilateral dependencies) provides required interfaces among participants and ensures distribution of roles and division of labour (Jacobides et al., 2006) whereas complementarities ensure symbiosis.

Another distinguishing feature of ecosystems is that they are not limited to particular industries and thus difficult to confine by traditional supply chain boundaries (Moore, 1993). Adner advocated the boundaries of an ecosystem to be related to value proposition and structure of an interdependencies and defined ecosystem as ‘the collaborative arrangements through which firms combine their individual offerings into a coherent, customer-facing solution’ (2006, p.99). The boundaries, rather than being product centric, are more fuzzy and aim towards designing unique, customer centric value proposition by combining interrelated technologies and competencies (Basole, 2009; Autio and Thomas, 2014). Organisations that are part of a particular ecosystem may also belong to other networks and ecosystems at the same time. Loose coupling tends to be the important success feature of a successful business ecosystem such as that of eBay (Iansiti and Levin, 2002). Having a vision of system level goals and absence of formal authority further differentiates ecosystem design (Gulati et al., 2012).

Iansiti and Levien (2004) established that the idea of business ecosystem is analogous to that of biological ecosystems owing to the presence of heterogeneous structure and different roles such as keystones, dominators, landlords and niches that impact the overall health of an ecosystem. As with any biological system, the dynamics within an innovation ecosystem are complex and constantly in flux. The relationships among ecosystem partners can range from “complete interdependency to predatory practices” (Zahra and Nambisan, 2011, p.9). The presence of a keystone, also referred to as hub firm, adds to the stability and coordination of the system (Gulati et al., 2012). Hub firms orchestrate the ecosystem and are responsible for shaping and evolution of the ecosystem, maintaining its momentum through compelling future value proposition, thus binding heterogeneous ecosystem partners and also attracting customers. Furthermore, they are able to balance both value creation and value capture that differentiate them from dominators. Dominators represent traditional vertically integrated firms as they control entire value chain processes, eliminating diversity, while dominators that focus on both value creation and capture, landlords, concentrate on capturing maximum value from the ecosystem for themselves, thus impacting the overall stability of an ecosystem. Niches form the mass of the ecosystem and are located at the "fringes of ecosystem" (Iansiti and Levien, 2004, p.125). Niches add to robustness and bring diversity to the entire ecosystem through specialisation. Their focus is on providing complementarities and leveraging to the platform created by keystones and other niche players. These roles, however, are not static and evolve with the ecosystem, that is, the niche in one domain may be the keystone in another.

In addition to the varying roles that firms may take, an ecosystem also differs in terms of its structure and organisation, shared goals and processes for knowledge sharing and appropriation that are in turn shaped by strategic thinking and entrepreneurial activities of organisations. Sawhney and Nambisan (2007) classified the innovation ecosystem into four different models: Orchestra, Creative Bazaar, Jam Central and MOD stations, based on the dimensions of structure of the innovation space (defined / emergent) and network leadership.

However, a question arises when reviewing the fragmented but growing literature on ecosystem (business, innovation, technological): how is it differentiated from other constructs such as innovation networks? Ecosystems can be considered a type of network. But what differentiates them is the rich analogy with a biological ecosystem characterised by distributed nature of knowledge, interdependencies, shared fate, symbiosis and leveraging of relationship. According to Autio and Thomas (2014), inclusion of the broad range of stakeholders, especially customers and complementors, rather than focusing on the production side alone, adds value to the use of the metaphor.

2.4.1 Significance of Ecosystem Perspectives for Emerging Technologies

Powell and Sandholtz (2012, p.95), while discussing the emergence of the first generation of biotechnology firms, emphasised that, “In a nascent field, uncertainty and controversy surround what a firm should look like and what elements it should contain”. Success within an emerging technology landscape therefore does not depend on organisations’ innovative activity alone but on a co-evolutionary and interdependent set of heterogeneous actors/players within the space who provide the required symbiotic, commensalist as well as competitive interdependencies, as is discussed by Eisenhardt and Galunic (2000) in the case of a multi-business unit. The importance of building an ecosystem / collaborative networks / value networks varies across industries and tends to be critical for emerging technologies that are being protected in niches owing to higher market and technological uncertainty, dynamism, the complexity and distributed nature of knowledge and increased interdependence with complementors (Moore, 1996; Parise and Casher, 2003; Rosenkopf and Schilling, 2007; Rong et al., 2013). According to Autio and Thomas (2012, p.204), “the attractiveness of this rather loose and versatile metaphor rests on its ability to evoke and highlight interdependencies between organizations and to provide a fresh way to think about specialization, co-evolution and co-creation of value.”

Furthermore, challenges within the emerging ecosystems that are around new and emerging technologies tend to be different than those around stable or incremental technologies (Möller, 2007). In such contexts, developing a traditional execution focus strategy based on core competencies, customer insights and pacing the competitors is necessary but not sufficient, as it does not help in spotting blind spots that organisations often fell prey to and ultimately results in failed innovation. The great innovation efforts, despite being excellently executed, failed, such as Sony’s failure in the e-reader market and Michelin’s run-flat tire PAX system (Adner, 2012). “The goal is no longer to lock out entire vertical stacks with proprietary advantage, but to be the best in chosen area of specialization” according to Iansiti and Levien (2004, p.23).

These relationships tend to differ from the traditional supply chain or value chain inter-organisational arrangements that focus on existing markets, linear models rather than nurturing new markets and co-creation of value (Peppard and Rylander, 2006; Rong et al., 2013). Efficiency as well as flexibility both are sources of value in ecosystems. The firms’

R&D in an ecosystem focuses on increased specialisation rather than building portfolios, and decreased market capitalisation, as is evident in the semiconductor industry with the presence of fabless firms.

2.4.2 Risks in Ecosystem

Participation in an ecosystem, as the literature proposes, offers several advantages such as reciprocal commitments from other members, shared vision, distributed cost and common fate. It further enables the players to direct their efforts towards continuous innovation and establishing markets for their offerings rather than working on independent paths surrounded by uncertainty (Moore, 2006). However, formation of ecosystems is not without risks and disadvantages, as evident from the failure of high definition television (HDTV) penetration in the market and organisations struggling to get value out of their alliance portfolios (Parise and Casher, 2003; Adner, 2006). The challenges now do not reside solely within the focal firm, but progress is also constrained by complement uncertainty (Adner and Kapoor, 2010). Furthermore, challenges within the emerging ecosystems that are around new and emerging technologies tend to be different than those around stable or incremental technologies (Möller, 2007). Based on the roles and position of actors within the ecosystems, Adner (2012) identified three types of risk: (1) execution risk, (2) co-innovation risk and (3) adoption risk. Execution risk refers to developing and evaluating one's focal technology and therefore is more operational and internal to the focal firm. Co-innovation risk arises owing to the interdependencies and points to the requirements for development of other necessary technologies by ecosystem partners for the focal firm offer to be successful. Adoption risk arises depending on how far or upstream the focal firm's innovation is from the end consumers and whether innovation necessitates adoption by many intermediaries situated between the focal firm and consumers. Thus the challenges faced by the focal firm cannot be solely defined based on their level of magnitude but also depend on location, that is whether they are more upstream and at the level of component or more downstream at the complement level.

According to Kapoor and Lee (2013, p.275), "firm's ability to create value from a new technology will depend, in part, on the accompanying changes by complementors in the ecosystem who may need to undertake new investments and adapt their activities in order for the new technology to be successfully commercialized". The integrator challenges do not reside only within the firm, related to technological barriers offered by components, but technological innovations are also constrained by complement uncertainty (Adner and Kapoor, 2010). Thus the challenges faced by the focal firm cannot be solely defined based on their level of magnitude but also depend on location, that is whether they are more upstream and at the level of component or more downstream at the complement level. Adoption risk arises depending on how far or upstream the focal firm's innovation is from the end consumers and whether innovation necessitates adoption by many intermediaries situated between the focal firm and consumers.

While the discussion on business ecosystems is populated around success stories of large hub firms like Walmart, Microsoft and Apple that act as a platform provider and thus provide niche opportunities for new ventures and small companies, however, scant attention has been given to the emergence and creation of ecosystems (Autio and Thomas, 2012) and still less to those orchestrated by small firms and in a nascent market, with the exception of work done by Santos and Eisenhardt (2009) and Walrave et al. (2013).

Having discussed the new organisational forms such as ecosystem, the next section will discuss the organisational routines and routine-based model of capability development.

2.5 Organisational Routines

Scholarly work on routines could be broadly bifurcated into two dominant camps focused on using either "capabilities lens" or "practice lens" as concluded by Parmigiani and Howard-Grenville (2011) in their literature review on routines. The former has its roots in organisational economics, treats routines as black box and focuses on firm level outcomes and performances while the latter, rooted in organisational theory, focuses on investigating the dynamics of a particular routine, the role of actors and artefacts in shaping routines, and explores the "how" aspects of routine rather than focusing on "what" and "why". Empirical studies within the capabilities perspective have studied routines as (1) microfoundation of capabilities (the focus of the thesis), (2) genes that contribute to stability, inertia and stickiness and (3) as repository of organisational memory and learning. The dominant themes of empirical investigation within the practice camp are on the embeddedness of routines and role of both actors and non-human actors (artefacts) in performance of the routines.

However, despite the differences in approaches and methods employed in both perspectives, the two approaches are complementary and there are commonalities such as: importance of the role of individuals; knowledge tacitness; routines as source of both stability and change; and idiosyncratic organisational and industry context.

2.5.1 Foundation of Routines

Foundation of routines, also referred to as standard procedures or simple rules, can be traced back to the Carnegie School and the work of March and Simon (1958) and, since their popularisation by Nelson and Winter (1982) in evolutionary theory, have been considered vital in understanding organisational behaviour, learning and organisational change (Becker and Lazaric, 2009). They are described as "repositories of organizational capabilities" and knowledge (Winter, 2000; Becker et al., 2005; Dosi et al., 2008; Nelson, 2009). Knowledge of routines is the heart of understanding behaviour (Nelson and Winter, 1982, p.128). Hoeve and Nieuwenhuis (2006) have emphasised the importance of routines in explaining innovative behaviour of organisations at different levels and have modelled organisations as composed of interlocking routines wherein the change in routines leads to innovation. In addition to management, innovation and strategy, other areas where the concept of routines has gained popularity include accounting (Burns and Scapens, 2008), political science (McKeown, 2008) and manufacturing (Tranfield and Smith, 1998). However, despite their importance and realised potential, routines are conceptualised in widely different ways in extant literature (see Table 2.2), contributing to limited empirical investigation (Cohen et al., 1996; Becker, 2004; Becker and Zirpoli, 2008; Hodgson, 2008). Nelson (2009, p.11) refers to routines as technologies, "a productive technique for doing something and involves both physical technology that is apparatus, procedures as well as social technology, complex human interactions". Organisational routines can be complex, incorporating both aspects, and simple, based on only a single dimension. Becker and Zirpoli (2008) identified three prominent definitions associated with routines in the extant literature as "behaviour or collective recurrent pattern, rule or standard operating procedures or as disposition and stored behavioural capacity".

Table 2-2 Definition of Routines

Author	Definition
Pentland and Rueter (1994)	An organisational routine is not a single pattern but, rather, a set of possible patterns—enabled and constrained by a variety of organisational, social, physical, and cognitive structures—from which organisational members enact particular performance.
Cohen and Bacdayan (1994)	Patterned sequence of learned behavior involving multiple actors who are linked by relations of communication and/or authority.
Cohen et al. (1996)	Executable capability for some repeated performance in some context that has been learned by an organisation in response to selective pressure.
Feldman and Pentland (2003)	An organisational routine is a repetitive, recognisable pattern of interdependent actions, involving multiple actors.
Vromen (2006)	Recurrent intra-organisation, multi-person interaction displayed in specific artificially created physical environments
Dosi et al. (2008)	Routines are used in contexts where nobody can explain what they are… "the way things are done around here". Routines are the building blocks of capabilities with a repetitive and context dependent nature, although they are not the only building blocks of capabilities.
Hodgson (2008)	Routines are organisational dispositions to energise conditional patterns of behaviour within an organised group of individuals, involving sequential responses to cues.
Nelson (2009)	Routine is a collection of actions in appropriate sequence that gets the job done, sometimes with closely specified inputs, and machinery designed to process those inputs in a particular way. Routine is an activity involving a number of people and groups coordinated by particular patterns of cooperative action, with often many aspects under explicit management direction.
Parmigiani and Howard-Grenville (2011)	Repetitive patterns of interdependent organisational actions.

2.5.2 Routines as Collective Recurrent Pattern

An important characteristic of routines discussed extensively in the literature is their collective and recurrent nature (Nelson and Winter, 1982; Becker, 2004). "Routines are collective, recurrent activity patterns: they describe what is done by whom and why" (Hoeve and Niewenhuis, 2006, p.7). The recurring pattern of routine results in reducing uncertainty and complexity, increased control, improving efficiency by providing ready solutions and enabling the decision makers and organisation to cope with the problem of bounded rationality (Knudsen, 2008). However, this recurrence has also been argued to result in competency traps (Becker, 2004; Knudsen, 2008), reduced reflexivity (Howard-Grenville, 2005) and provision of use of suboptimal solutions as a result of positive feedback. According to Pentland and Hærem (2015), the role of repetition is necessary for defining routines, even if it is rare. "The existence of a plan, a guideline, a written procedure, or any such artifact is neither necessary nor sufficient to define an organizational routine" (ibid., p.467).

Routines are multi-actor phenomena and contribute to shared understanding and connection among organisational members (Cohen and Bacdayan, 1994; Feldman and Rafaeli, 2002; Becker, 2004). However, as pointed out by Pentland and Hærem (2015), the same set of actors or awareness of each other's role is not a necessary condition for performance of routine. The collective nature of the routines points towards another important attribute associated with routines and that is distributedness. Thus, routines are carried out by multiple actors (human and non-human) distributed across the different business units of the same organisation, thus intra-organisational, or they belong to different organisations and are inter-organisational (Pentland, 2004). Inter-organisational routines are defined by Zollo et al. (2002, p.701) as "stable patterns of interaction among two firms developed and refined in the course of repeated collaborations". The distributed nature of the routine and its multi-actor characteristics, however, contributes to complexity associated with understanding routines (Cohen and Bacdayan, 1994).

Routines are context dependent (Becker, 2004). Hodgson (2008, 2009) has referred to routine as organisational, analogous to individual habits and not equal to the simple aggregation of individual members' properties. "Just as the human body has a life in addition to its constituent cells, the organization thus have a life in addition to its members" (Hodgson, 2008, p.22). This distinction has also been made in the literature by Dosi et al. (2008), Cohen et al. (1996), Becker (2004), Hoeve and Nieuwenhuis (2006) and Knudsen (2008), thus emphasising the collective and contextual nature of routines. The contextual nature of the routines makes them sticky and poses limitation to the transfer of routines (Szulanski, 1996; Becker, 2004). According to Howard-Grenville (2005), the degree to which routine is embedded into another structure results in inflexibility and persistence of routine.

2.5.3 Routines as Behavioural Dispositions

Nelson and Winter (1982) referred to routines as organisational genes thus indicating their longevity. However, Hodgson (2008) argued that this analogy of routines, though useful, results in conceptualising routines as both behaviour and disposition that is both cause and effect. Routines can be conceptualised at two layers, one that is observable and another that exists as latent potential and generative (Pentland et al., 2010). Thus routines as dispositions are not behaviour but stored capacity or tendencies to act when triggered by suitable stimuli (Becker, 2005; Hodgson, 2008). This characteristic of routines is useful to explain its regeneration and replication (Birnholtz et al., 2007) and resonates with Dewey’s concept of habit (Cohen, 2007).

Referring to routines as capacities suggests that they are stored within individuals as procedural memories. Cohen and Bacdayan (1994) provide the distinction between procedural and declarative memory. Procedural memory refers to the component that stores individual skills, is less subject to decay and is difficult to transfer, while declarative memory relates to facts. The skills stored in an individual’s procedural memory thus contribute to routine automaticity, tacitness and its reproduction within or outside the organisational context as also demonstrated by Birnholtz et al. (2007) in the case of Camp Polar Grove. The increased experience of the routines results in promoting a stable pattern of action within the routines.

2.5.4 Duality of Routines: Routines as a Source of Stability and Endogenous Change

Conceptualisation of routines embodies the paradox of (n) ever changing world (Cohen, 2007). On one hand the routines connotation refers to something that is rigid and invariant over the period of time, mundane in content and therefore not of much significance, mindless, performed without deliberation and explicitly stored (Levinthal and Rerup, 2006). For instance, Schulz (2008) focused on the variety of mechanisms for routine stabilisation and its path dependency such as habitualisation, institutionalisation, formalisation, coercion, and calculation. For him, “not only do routines repeat, the steps within routines repeat as well” (*ibid*., p.237).

On the other hand other perspectives describe routines as dynamic and a source of continuous change (Feldman, 2000; Feldman and Pentland, 2003; Howard-Grenville, 2005; Feldman and Rerup, 2011). The debate around routines as mindful or mindless representations has been a dominant dividing theme within the literature (Becker, 2004; Pentland et al., 2011). Pentland and Rueter (1994) have used the analogy of grammar and referred to routines as effortful accomplishments rather than mindless or automatic behaviour. “Organizational routines are not only effortful but also emergent accomplishments. They are often work in progress rather than finished products” (Feldman, 2000, p.613). Feldman and Pentland (2003) emphasised the importance of both structure and agency and described organisational routines as consisting of a “mutually constitutive” ostensive and performative aspect. This line of work was able to bridge together earlier two distinct conceptualisations of routines as behavioural regularities and cognitive regularities (Salvato and Rerup, 2011). The ostensive aspect refers to the narrative, abstract notion of routine that guides organisational actors’ cognition while the performative aspect refers to enactment, improvisation and those behavioural aspects of routines that result owing to the actual performance of routines by specific people in a specific context. Furthermore, improvisation is translated into a variety of performances as organisational members not only choose different elements from their repertoire but also change the repertoire (Feldman and Pentland, 2003). This perspective of routines has been a contributing factor towards identifying routines as a source of organisational learning and innovation.

According to Pentland and Hærem (2015), the tendency to concentrate on one side of duality has contributed to theoretical debates in routine literature around: latent-expressed; potential-actual; ostensive-performative; and deep structure-surface structure. Recent work has emphasised combining both the perspective of mindfulness and mindlessness and considering them as duality and mutually constitutive rather than as dualism and mutually exclusive (Farjoun 2010, Turner and Rindova, 2012). Levinthal and Rerup (2006) suggested strong complementarities between two concepts whereby a degree of less mindful processes enable mindfulness and appropriate response in novel and uncertain situations and sustain mindfulness across time and space.

In addition to the above mentioned focus on the generative nature of the organisational routines and their endogenous adaptation and change, the recent scholarly literature has emphasised the role of bounded rational actors and their experiences in shaping the performances of routines (Salvato, 2009; Salvato and Rerup, 2011; Turner and Fern, 2012). Routines are distributed in time and space across organisation and therefore necessitate investigation at multilevel (Salvato and Rerup, 2011). For example, Salvato (2009) demonstrated the connection between the mundane daily activities of individuals and their role in the evolution of an organisation's new product development capability. Turner and Fern (2012) extended further contribution in this direction to incorporate responsiveness of individual level performance experience to contextual changes. The increased experiences of actors promote overall stability of the routine performances within the context but at the same time also augment their capacity for the adaptation of routines in response to changing contextual constraints. The experience in routine performance over the period of time enables and shapes variations in the future sequence of actions from those of past patterns employed by actors. These debates thus contribute to the microfoundation debates and the increasing role of actors and contextual conditions in routine performances (Salvato and Rerup, 2011).

2.5.5 Sociomateriality of Routines

Furthermore, the practice-based perspective of routines emphasises sociomateriality of routines and the role of artefacts in making routines performative (Pentland and Feldman, 2005). Routines are rarely carried out by humans alone as emphasised by Pentland et al. (2012) but are carried out by sociomaterial ensembles of non-human actants that may be enabling and constraining. Bundling of routines and interaction further contributes to their role in innovation. This has resulted in a recent focus on non-human actors and other intermediaries such as standard operating procedures (SOPs) in routine evolution, adaptation and emergence (D'Adderio, 2008; Bapuji et al., 2012). In this conceptualisation, artefacts act as more than tools, "they extend work, increase interactions, increase visibility of knowledge actions" (D'Adderio, 2008, p.774).

According to Schulz (2008), artefacts such as checklists, flow charts, and tools keep routines on track as they guide subsequent actions. Artefacts thus provide standardisation of tasks, however, they may be used for reorganisation and producing desired variations in response to environmental changes (Turner and Rindova, 2012). Actants may either act as intermediaries or as mediators and their engaging practices thus contribute to the generative power of routines (Sele and Grand, 2016).

2.5.6 Routines as Truce

The idea of routines as truce helps in combining both cognitive and motivational dimensions (Becker, 2004) to ensure its smooth functioning and recurrence. Organisations are made of individuals with varying and divergent interests that result in intra-organisational conflicts (Coriat and Dosi, 1998). Routine as a truce indicates “stable accommodation” between the formal requirements as laid down in the job description and the motivation of organisational members (Nelson and Winter, 1982, p.108). However, as argued by Nelson and Winter (1982, p.111), the terms of governance or truce in routines are not necessarily explicit or manifested only through rules and regulations but are subtle and defined by “shared tradition” among members. Thus the notion of truce further implies that organisational adaptations that seem trivial or logical might be difficult to implement as this would risk overt conflict and breaking of the truce (Zbaracki and Bergen, 2010).

2.6 Routines as Microfoundations of Organisational Capabilities

Firms differ in innovativeness and profitability (Dosi et al., 2008) and this heterogeneity in organisational capabilities is embedded in organisational processes and routines and thus provides for selection and competition (Jacobides and Winter, 2012). “Knowledge is conceived as know-how embedded in the organization’s activities, as opposed to passive, library-like stocks that are stored in the heads of participants” (Dosi et al., 2008, p.1176). Routines are considered as building blocks for organisational capabilities and a source of heterogeneity in firms’ performance (Nelson and Winter, 1982; Teece et al., 1997; Abell et al., 2008; Lewin et al., 2011). For Grant (1991), capability of an organisation is a set of interacting and coordinating routines that may exist at different levels and for different purposes.

Capabilities can be further bifurcated as standard or operational that refers to those that are needed to perform the functional activities and dynamic or higher level (Collis, 1994). Zollo and Winter (2002) linked organisational dynamic capabilities with the evolution of operational routines and learning mechanisms and defined organisational capability as a "learned and stable pattern of collective activity through which the organization systematically generates and modifies its operating routines in pursuit of improved effectiveness" (*ibid*., p.340). This conceptualisation of routines highlights that routines can vary in complexity, from being simple to a high level meta-routine. Furthermore they evolve and change over a period of time based on internal and external processes of variation, selection and retention.

According to Winter (2013, p.122), "Routines and capabilities" offers a helpful cognitive frame and a near-natural theoretical language for discussing organisational goings-on; there is accordingly a lot to be learned by applying it to one's personal encounters with the "real world" and the real people who inhabit it.

Microfoundations are the subject of a key emerging and ongoing debate and have received substantial attention by scholars for understanding firm level heterogeneity, strategies and capabilities that requires exploring micro level explanatory mechanisms such as routines, individual level cognition and managerial level competencies (Abell et al., 2008; Salvato and Rerup, 2011; Felin et al., 2012; Foss et al., 2012; Molina-Azorín, 2014; Helfat and Peteraf, 2015). Felin and Foss (2005) argued that most of the earlier work on routines and capabilities has focused on collective dimensions and higher level routines compromising the individual aspect and hence the microfoundation leading to ambiguities in conceptual literature. Salvato and Rerup (2011, p.469) proposed considering routines and capabilities as "assemblage of heterogeneous parts rather than collective entities". For Felin et al. (2012, p.1352), a strong motivation for unpacking routines and capabilities in microfoundational terms is that "this will advance our understanding of what drives differences in the behaviour and performance of firms". However, according to Winter (2013) the criticisms on seminal work on routines and the recently advocated microfoundation approach point towards methodological reductionism and individualism. He stressed the importance of investigating the origin question and considering not only how the individual level habit and trait aggregate into organisational capabilities but also industrial architectures that shape feedback mechanisms and evolution of capabilities (Jacobides and Winter, 2012; Winter, 2012).

2.6.1 Routine-Based Model of Absorptive Capacity

Organisational routines have been linked in the literature to absorptive capacity (Pentland et al, 2012). Absorptive capacity is defined as "ability of firms to recognize the value of new external information, assimilate it and apply it to commercial ends" (Cohen and Levinthal 1990, p.128); it tends to be path dependent and cumulative and depends on the firm's prior knowledge and therefore can be bought or integrated readily via mergers and acquisitions, hiring new personnel, or through consulting services. Firms differ in their ability to develop "Absorptive Capacity" (AC) as highlighted in the seminal article by Cohen and Levinthal (1989, 1990). "Heterogeneity in the level of absorptive capacity translates into differences in the benefits from otherwise similar stocks of external knowledge both because the firm can identify more of them and because it can exploit them more efficiently" (Escribano et al. 2009, p.98).

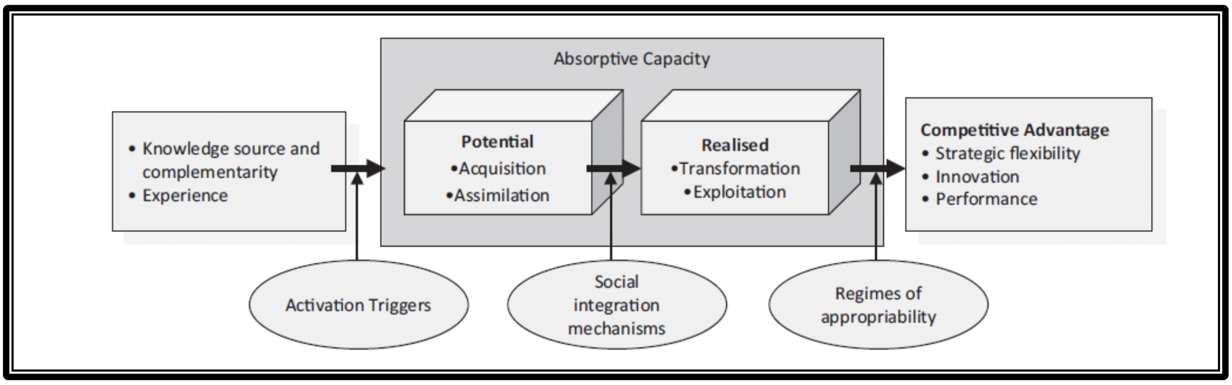
AC for Cohen and Levinthal (1990) is an organisational phenomenon that being dependent on an individual's cognition is simply not equal to the sum of the absorptive capacity of the individuals. Intensity of efforts, diversity of knowledge structures, developing internal mechanisms and interfaces such as communication systems between external environment and organisation and also within subunits are critical sources for developing AC.

The importance of AC is evident from growing use and research interest in relation to diverse phenomena such as innovation (Murovec and Prodan, 2009), intra-organisational knowledge transfer (Szulanski, 1996), inter-organisational learning (Lane and Lubatkin, 1998), knowledge creation (Matusik and Heeley, 2005), new product development (Stock et al., 2001), and international joint ventures (Lane et al., 2001; Mahnke, Pedersen and Venzin, 2005). The organisations with a higher level of AC tend to be more innovative and proactive (Cohen and Levinthal, 1990; Lewin and Massini, 2003). AC impact expectation formation results in predicting the future technological advances in an uncertain environment (Cohen and Levinthal, 1990). If firms do not invest in AC early on they may not be able to identify new and emerging opportunities or invest in developing AC in subsequent periods. AC acts a funnel and results in an expanding knowledge spiral as absorptive capacity leads to learning that leads to more AC (Van den Bosch et al., 1999).

Zahra and George (2002) have reconceptualised AC as a firm's dynamic capability, enhancing competitive advantage and enabling evolution and change. They suggested that

AC consist of two components, Potential and Realised (see Figure 2.16), and defined it as a "set of organizational routines and processes by which firms acquire, assimilate, transform and exploit knowledge to produce a dynamic organizational capability" (2002, p.186). Acquisition and assimilation constitute Potential AC while transformation and exploitation form the Realised AC component. Acquisition refers to the firm's ability to identify and acquire external knowledge; assimilation is the process that enables the firm to interpret and understand the acquired external information; transformation emphasises recombination of external acquired knowledge and that lying within firm boundaries and finally exploitation is associated with the application of knowledge to create new products and services. The theoretical frameworks also contribute to the understanding of the antecedents such as knowledge sources, complementarities and experiences as well as other moderating variables of activation triggers, social integration mechanisms and regimes of appropriability that impact the four components and, finally, competitive advantage.

Figure 2-16 Zahra and George's Absorptive Capacity Model



Source: Zahra and George, 2002

This conceptualisation instigated a new wave of research and moved AC from being very statically defined and empirically treated as a black box measured in R&D perspective only, to being considered as dynamic capability. A number of studies have built on Zahra and George's (2002) concept of potential and realised absorptive capacity. Jansen, Van Den Bosch and Volberda (2005) developed the scale for measuring potential and realised absorptive capacity and explored the varying impact of organisational antecedents such as combinative capabilities in addition to the prior related knowledge on dimensions of AC, thus further contributing to the understanding of the construct. Todorova and Durisin (2007) further refined the model proposed by Zahra and George. They emphasised recognising the value of external knowledge rather than acquisition, as valuing tends to be biased and hampered by cognitive capabilities of managers and the focus of stakeholders on current demands. They further argued that transformation is an alternative to assimilation rather than a process that follows it and proposed feedback loops that will facilitate and capture dynamic orientation of the construct.

Lane et al. (2006) emphasised the learning process perspective of the absorptive capacity dimension that has been neglected in previous studies and proposed the definition of the construct as: "Absorptive Capacity is a firm's ability to utilize external held knowledge through three sequential processes: (1) recognizing and understanding potentially valuable knowledge outside the firms through exploratory learning, (2) assimilating valuable knowledge through transformative learning, and (3) using the assimilated knowledge to create new knowledge and commercial outputs through exploitative learning" (2006, p.856).

In addition to the above mentioned studies whereby the main focus is on the cognitive dimensions and absolute AC at the level of the firm, other dominant streams have focused on the relational aspects and relative AC. Lane and Lubatkin (1998) have reconceptualised absorptive capacity at the dyad level and identified three characteristics that are important for inter-organisational learning: similarity between teachers and student firms' knowledge bases, organisational structure, compensation policies and dominant logic. Dyer and Singh (1998) argued that firms' competitive advantage is based on relational rents embedded in firms' knowledge sharing routines and processes. Lane et al. (2001) further refined the construct and developed the AC model in the context of international joint ventures (IJV). They identified inter-organisational trust in addition to relative AC to impact the first component of AC – ability to understand foreign partners' knowledge while certain structure and processes such as IJV flexibility and adaptability, management support and training influence the assimilation of knowledge. Strategic context and training contribute to the application of external knowledge and performance of IJV.

Despite its importance and diverse use, the operationalisation of AC is still ambiguous and does not fully capture the richness and multidimensionality of the construct. (Zahra and George, 2002; Jansen et al., 2005, Matusik and Heeley, 2005; Easterby-Smith et al., 2008;

Lim, 2009; Volberda et al., 2010; Lewin et al., 2011; Patterson and Ambrosini, 2015). The ambiguity not only surrounds conceptualisation, number of dimensions and definition, but development of a scale to measure AC poses additional challenges (Flatten et al., 2011; Jimenez-Barrionuevo et al., 2011). According to Lane et al. (2006), the diverse use of the AC construct has resulted in its reification. In their review of the literature on absorptive capacity, they analysed 289 papers from 14 journals to assess how the construct has been utilised and identified only four papers that have extended the understanding and refined the construct of the absorptive capacity, but these attempts have also not been integrated. AC is ambiguous, complex, context dependent and difficult to observe (Lim, 2009) and the use of deductive rather than inductive lines of reasoning has been another limiting factor in the development and advancement of theoretical understanding. Furthermore, it has been measured by proxy measures such as R&D spending, patents (Ahuja and Katila, 2001), the presence of highly educated people, investment in training and education (Huang and Rice, 2009), larger infrastructure (number of labs), investment in scientific and technical training, and type and number of collaborations (Mangematin and Nesta, 1999; Escribano et al, 2009). The use of these static and single measures has contributed to conflicting definitions and dimensions that constitute AC (Flatten et al., 2011).

Volberda et al. (2010) developed an integrative model, based on the bibliometric analysis, to address the research gaps. They suggested antecedents at individual, organisational and inter-organisational level need further attention. They found that multidimensionality of the construct has not been fully explored in the follow-up articles and much emphasis has been on themes of exploration and assimilation of knowledge rather than on application, which is underrepresented. Robertson et al. (2012) also share these views that the knowledge-based view of AC does not provide adequate explanation in the incremental process innovation context where the knowledge is tacit, distributed and embodied in artefacts. They identified accessive, adaptive and integrative capacities as important drivers for mobilisation of knowledge.

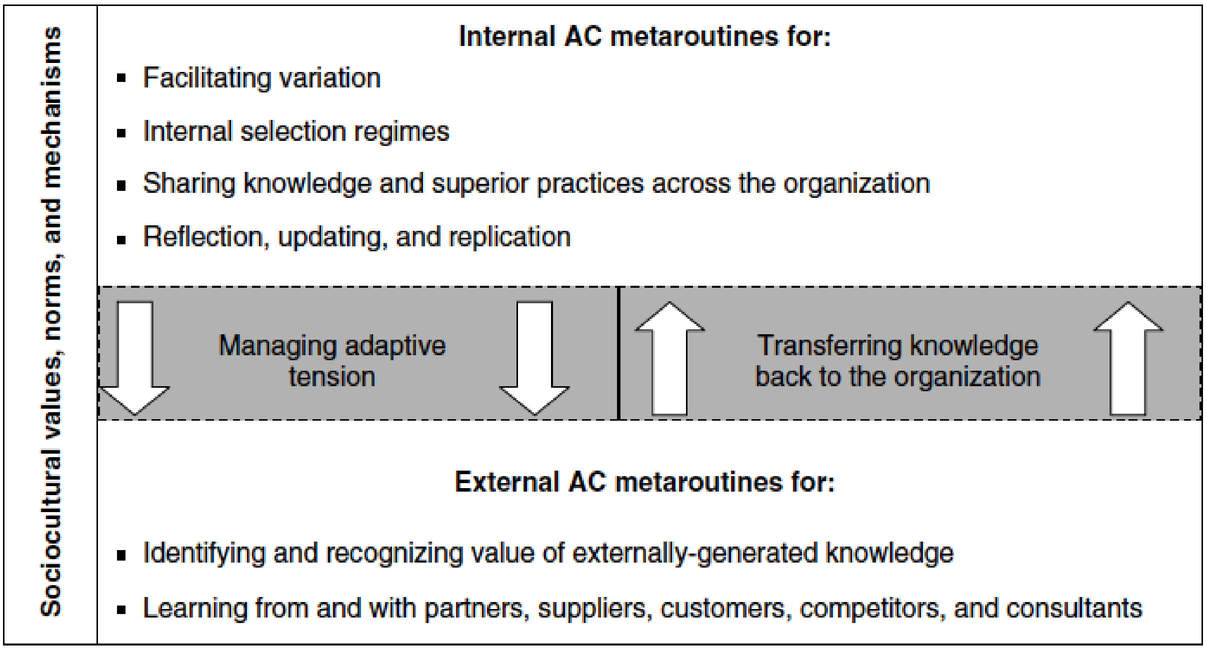
Furthermore, Volberda et al. (2010) stressed the importance of understanding of microfoundations to fully utilise the potential of the construct. Foss et al. (2011, p.982) argued, “Most of the research on absorptive capacity focuses on knowledge related antecedents to absorptive capacity (e.g. R&D investments), and very little examines how absorptive capacity relates to organizational practices.” Their study identified the role of inward and outward looking organisational practices for sourcing external knowledge, especially that from customers and users.

To address these shortcomings in the extant literature of AC, there has been emerging stream of research to advance understanding of the processes and microfoundations of the construct such as that by Lewin et al. (2011), Ebers and Maurer (2014), Marabelli and Newell (2014) and Patterson and Ambrosini (2015).

Lewin et al. (2011) proposed a routine-based model of absorptive capacity (AC) and provided a taxonomy of AC routines, decomposing the construct into internal and external meta-routines: routines for transferring knowledge back to the organisation and for managing adaptive tensions (see Figure 2.17). These meta-routines tend to be abstract and are expressed and empirically measured by more observable practised routines that are idiosyncratic to the firm. The different configurations of internal and external practised routines implemented and developed by organisations and the extent of complementarities between and among them, as well as the moderating effect of socio-enabling mechanisms, are a source of variety among innovators and imitators and affect their innovative performance.

This hierarchical configuration of practised routines and meta-routines can be traced back to Nelson and Winter's (1982) evolutionary theory whereby practised routines are operational at the lower level, idiosyncratic to the firm and more observable whereas meta-routines are higher level and are more theoretical. This aspect also bears similarities to Feldman and Pentland's (2003) work on ostensive and performative aspects of routines.

Figure 2-17 Routine-Based Model of Absorptive Capacity



Source: Lewin et al., 2011

The literature on dynamic capabilities has also used the notion of hierarchies of capabilities. Some notable contributions in this regard have been the work of Collis (1994), Winter (2003), Danneels (2008) and Ambrosini et al. (2009). Collis (1994) suggested four categories of capabilities whereby the first category refers to operational activities of the firm, the second and third resemble that of dynamic capabilities and the fourth category is referred to by him as higher-order capabilities or meta-capabilities, "the capability to develop the capability… ad infinitum" (Collis, 1994, p.148). However, these extant works have not discussed in detail these higher order or meta-capabilities (Ambrosini et al., 2009).

Meta-routines in this context are not routines for changing routines as proposed by Adler et al. (1999) nor do they resemble the capability to change capability perspective but they are theoretical and express the purpose of the lower level practised routines. However, it is not evident whether these meta-routines change and, if so, what leads to these changes.

Internal AC meta-routines consist of routines for facilitating variation within organisations, routines for selection of ideas generated externally and internally, routines for replication/retention/updating and routines for sharing knowledge within the organisation. External meta-routines refers to identifying and accessing externally-generated knowledge.

The framework also discusses two additional routines that exist at the interface of internal and external routines—routines for managing adaptive tension and routines for transferring knowledge back to the organisation. Routines for managing adaptive tension can be compared to the activation trigger discussed in the model by Zahra and George (2002) which compares the organisation's current performance with aspirations and thus provides the necessary feedback loop that may result in resource reconfiguration by the organisation. Furthermore, organisations are only able to benefit from the external knowledge if there are routines to transfer this knowledge internally and integrate with the existing internal knowledge, and this purpose is achieved by routines for transferring knowledge back to the organisation.

Lewin et al. (2011) argued that the difference in these AC routines is translated into firms' performance that in turn depends on the complementarities that exist among the routines and is also moderated by formal organisational structures, past experiences, presence of key people, incentives and reward structure and the institutional structure in which the firm resides.

2.7 Summary

Breakthrough technologies are instrumental for the growth and welfare of nations. However, they face considerable challenges from established technologies and existing technological trajectories and are therefore nurtured and shielded in niches before they emerge and transform into industries. Articulation of shared vision and convergence of expectations, formation of networks and learning are the processes that tend to be important for development of niches and finally transitions. While there is a lot of work on understanding the dynamics and challenges related to the breakthrough technologies in general, early stages related to the emergence of industry are underresearched.

Emergence of industries based on breakthrough technologies is complex and distributed and requires interaction and coordination between a wide variety of heterogeneous actors and stakeholders such as producers, users and institutions. Furthermore, it is largely accepted that due to opportunities arising from emerging technologies both de novo firms as well as incumbents participate in the early stages of emergence. Schumpeter's (1934) works associate invention and emergence with creative destruction of large firms and success of entrepreneurial ventures. However in his later work (1943) creative accumulation is a dominating theme whereby large firms are value-creating actors in innovation processes.

Small entrepreneurial firms, as the literature suggests, face considerable challenges in order to create value and are more prone to failure compared to large incumbents due to the liability of smallness and the liability of newness (Maine and Garnsey, 2006; Demirkan et al., 2013). In this regard, networks and other forms of organising such as ecosystems are considered crucial for the commercialisation of these nascent technologies (Lubik and Garnsey, 2014). However, ecosystem creation and orchestration normally consider entrepreneurial firms as peripheral actors rather than key hub firms. Thus it raises the question of whether an entrepreneurial firm can be a market shaper and orchestrator of an ecosystem rather than a mere follower. Furthermore the mechanisms and processes adopted by these firms to develop capabilities in the emergent space are treated as black box.

The literature suggests that developing breakthrough technology necessitates thinking out of the box and therefore incumbents and large organisations, due to their path dependency and stability, suffer from inertia and are locked out (Schilling, 2002). However, there are outliers and incumbents can be a major source of innovation (Methe et al., 1996; Lechevalier et al., 2014). Retrospective analysis suggests different mechanisms that enable incumbents to survive the gale of creative destruction such as ambidexterity, complementary assets, CEO cognition and corporate venturing. However, what happens during transition and before the emergence of dominant design? Do incumbents invest in inventing or adopt a wait and see attitude? Little is known of the mechanisms adopted during the emerging phase that may prove crucial in explanation for later stages of the life cycle (Jiang et al., 2010).

Contestation and negotiation surround the early phases of emerging industries (Kaplan and Tripsas, 2008). In this context, construction and evolution of markets necessitates hybrid forums that enable sharing of alternate views and convergence by bringing diverse actors together. Emergence of industries is thus coordinated by a range of intermediaries (actors, institutions and instruments) that facilitate networks and shape the technology trajectories undertaken (Kearnes, 2013; Meyer and Kearnes, 2013). These intermediaries do not act as passive match makers or translators but their role is performative and this characterisation underpins understanding the practices and roles they play in emerging industries.

The prominence of organisational routines in understanding organisational capabilities has resulted in recent advancements in analytical perspectives and empirical research to understand the performance implications of routines (Becker et al., 2005). Recent studies have pointed to the importance of routines in creative environments and their association with innovation (Ohly et al., 2006). However, the studies are still few and focused on established industries and stable environment rather than in emerging and uncertain domains. These shortcomings are highlighted by Winter (2013, p.134):

> How does coordination emerge out of chaos via organizational learning? … Studies in the field settings take a large chunk of established organizational performance as given and then discuss how the chunk undergoes incremental change in response to various stimuli.

According to Sele and Grand (2015), describing routines as repetitive, collective and interdependent actions augments their role in everyday activities, however their role in innovation is still less clear and unspecified.

The ambiguity in the definition and complexity associated with operationalisation of routines has resulted in slow progress (Becker et al., 2005; Becker and Zirpoli, 2008; Schulz, 2008). Winter comments that "routines literature is surprisingly weak when it comes to actual operationalization of this important construct" (Foss et al., 2012, p.183). The literature on organisational routines is developing, however there is still scant attention paid to inter-organisational dimensions (exceptions being Zollo et al. (2002) and Doz (1996)) that become important considerations as the knowledge becomes more distributed and require different organisational forms than the traditional hierarchical designs. This raises questions as to what types of routines facilitate coordination outside organisational boundaries.

Emergence and development of new routines is another area that has received scant attention (Cacciatori, 2012). Nelson and Winter's (1982, p.97) discussion on routines is "distinctively" related to organisations that are large and complex and this has raised questions regarding routines development and microfoundations in entrepreneurial new ventures and the role of individuals, interactions, processes and artefacts (Felin et al., 2012).

Moreover, the focus on higher levels such as capabilities, strategic management and ambidexterity has treated these constructs as black box and left many questions unanswered. Recent conceptual and empirical work on microfoundations and on higher order capabilities such as that on absorptive capacity (Lewin et al., 2011), capabilities (Gavetti, 2005) and dynamic capabilities (Teece, 2007; Argote and Ren, 2012; Helfat and Peteraf, 2015), strategic management (Molina-Azorín, 2014) and acquisition integration (Heimeriks et al., 2012) have only scratched the surface (Foss et al., 2012).

Chapter 3: Research Design

3.1 Introduction

The objective of this chapter is to elaborate on the methodological approach adopted during the course of this study. The research context of emerging industry based on breakthrough technologies demands exploration and the research objective to investigate the notion of "routines" necessitates the use of a qualitative approach. Routines and capabilities are thorny concepts, containing tacit as well as problem-solving elements, and are difficult to observe. Therefore, exploring the complexities associated with the construct requires close observations at different levels (Salvato and Rerup, 2011). Qualitative research is considered more appropriate for research aimed at unfolding processes that are complex and require exploration and in-depth understanding. "Qualitative research often advances the field by providing unique, memorable, socially important and theoretically meaningful contributions to scholarly discourse and organizational life" (Gephart 2004, p.461). According to Morgan and Smircich (1980, p.491)), "qualitative research is an approach rather than a particular set of techniques and its appropriateness derives from the nature of the social phenomenon to be explored". Research design in the qualitative tradition, according to Maxwell (2005), is a flexible, ongoing, interactive and reflexive process and therefore does not fit the traditional, prescriptive and linear mode of carrying out the research design.

> The activities of collecting and analyzing data, developing and modifying theory, elaborating and refocusing on the research questions and identifying and addressing validity threats are usually all going on more or less simultaneously, each influencing all of the others. (Maxwell 2005, p.2)

A key factor differentiating qualitative from quantitative research is that the former works with a few cases and a large number of variables while the latter relies on a large number of cases focusing on a few variables (Creswell, 1998).

The chapter will articulate the research objectives and present the conceptual framework and research questions. Section 3.4 discusses the philosophical assumptions and their impact on the design of the study. This is followed by a discussion on the use of case study as a research strategy and a section elaborating on the challenges encountered for data collection in the context of emerging technology and breakthrough industry. Section 3.7 addresses the iterative processes for selection of empirical cases while section 3.8 elaborates on multiple data collection methods, such as the use of secondary data to identify the dynamics in the context of emerging technology, semi-structured interviews and company documentation. Section 3.9 will present the process of data analysis and is followed by a section on research validity.

3.2 Research Objectives and Conceptual Framework

Based on extensive literature review and identified gaps, the study probes the domain of uncertainty and the space of emerging industry, which is still underresearched and developing. The study discusses the emerging industry and related dynamics at three levels – macro, meso and micro – and proposes a conceptual framework (Figure 3.1).

The conceptual framework as elaborated by Miles and Huberman (1994, p.18):

> …explains either graphically, or in narrative form, the main things to be studied – the key factors, concepts or variables – and the presumed relationship among them.

Radical and breakthrough technologies are associated with uncertainty, risk, high expectations, lofty promises and hype. They face challenges not only from existing dominant technologies but also from the new developing options. The transition of breakthrough technologies from niches to commercialisation and finally emergence necessitates careful experimentation, shielding and nurturing from mainstream markets, expectation building, and learning that tends to be iterative and interactive, thus requiring a broad and heterogeneous set of actors (Caniels and Romijan, 2008).

Breakthrough technology, in the context of this study is Organic and Printed Electronics (OPE), and is discussed in Chapter 4 and Chapter 5. OPE being in the early ferment stage, represents a considerable challenge in exploring the innovation management strategies adopted by organisations. This dynamic forms the first research objective of the thesis.

Research Objective 1: How does potentially disruptive and breakthrough technology evolves to become an emerging industry?

The distributed nature of knowledge and the increased emphasis on external sources of knowledge require developing novel inter-organisational and intra-organisational routines at the level of firms, both large incumbent and small entrepreneurial. However, the literature on capabilities does not elaborate on the processes and routines, but uses proxy measures and treats them as black box. A recent notable contribution in discussing microfoundations of capabilities and adopting the routine-based model is that by Lewin et al. (2011) that informs the routine-based firm level analysis.

Routines align interests, provide coordination and cooperation and serve as governance mechanisms in the inter-organisational context, as discussed by Zollo et al. (2002) in their study of alliances. However, there are very few studies that discuss inter-organisational learning, as most of the work is concentrated in theory development or at organisational level (Mante and Sydow, 2007). These findings are also shared by Parmigiani and Howard-Grenville (2011, p.423). Moreover, what types of routines are mobilised by actors in an emerging and dynamic context is still an area to be explored. The identified gap forms the second research objective for the thesis.

Research Objective 2: To understand the microfoundation of organisational capabilities and thereby investigate the dynamics of inter-organisational and intra-organisational routines for breakthrough technologies in emerging industries.

The study extends the discussion of the routine-based view of capability development in the context of breakthrough technology and emerging industries, focusing not only on incumbent organisations where it is argued that established routines increase inertia and decrease flexibility that may result in being locked out, but also investigating how technological ventures orchestrate the development of capabilities, which have not been the source of empirical enquiry in the scholarly literature (Aldrich and Yang, 2014). Bessant et al. (2005, p.1368) further elaborated that the real challenge is not technological change, as that can be competence enhancing, but is in:

> …building the capability within the firm so that it is prepared for, able to pick up on and proactively deal with innovation opportunities and threats created by emerging discontinuous conditions. In other words to develop alternative routines for discontinuous innovation (do different routines) which can sit alongside those for steady state.

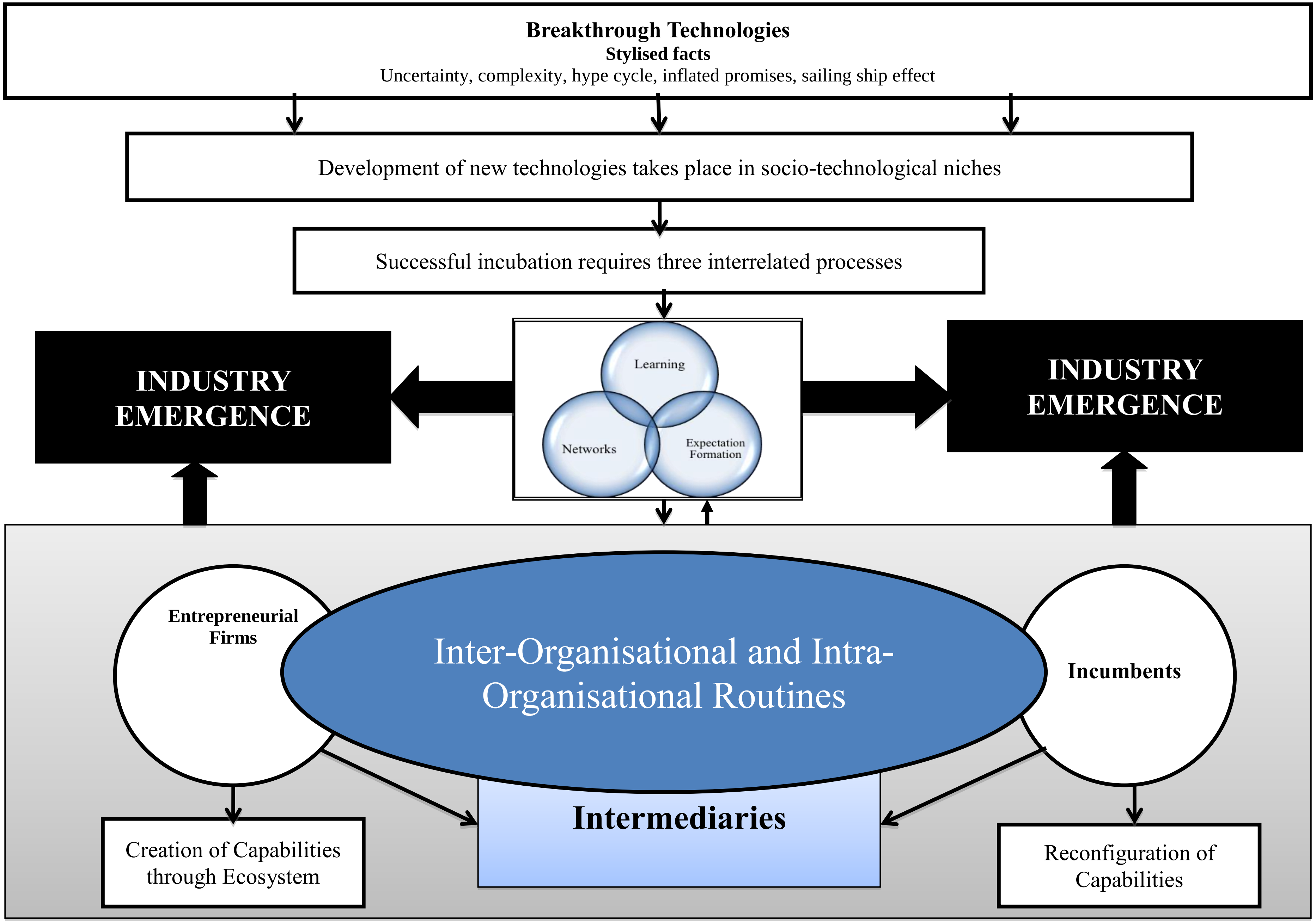
Entrepreneurial ventures are considered as a source of opportunity creation and discovery. The literature, while acknowledging the importance of processes in value creation, has not discussed in detail or provided a “compelling explanation” for the ability of some young firms as well as a few established companies to “continuously create, define, discover and exploit entrepreneurial opportunities" (Zahra et al. 2006, p.917). According to Winter (2013, p.134), "mostly, studies in field settings take a large chunk of established organizational performance as given". Exploring the routines in new high technology ventures and in an emerging context will provide understanding of the underresearched theme of the emergence of capabilities (Zahra et al., 2006). "A thorough understanding of how routines emerge is necessary to derive the performance benefits they yield for organizations" (Bapuji et al., 2012, p.1).

Organisations within a new population, that is of emerging industry, lack cognitive legitimacy; "much of the knowledge of a new industry is implicit, held by the founders and their employees in uncodified form" (Aldrich, 1999, p.235). The role played by intermediaries within the ecosystem of breakthrough technologies and emerging industries is increasingly important. They provide the relevant space for contestation and negotiation in the context of breakthrough technologies. However, most of the work in the context of innovation intermediaries is in the agriculture and health sectors.

The study's focus is not only on the macro perspectives but also looks at the role of new technology-based firms, incumbents or large organisations, intermediaries and associations. "Wicked environments" and technological change contribute to dysfunctionality of existing routines and also hinder developing new ones (Pentland and Hærem, 2015). It can be argued that exploring the diversity of roles and actor groups (material providers, integrators and intermediaries) within the developing and evolving value chain provides a more dynamic orientation as compared to a static structural approach (Markard and Truffer, 2008).

The study discusses the ongoing developments of the breakthrough technology. The temporal aspect adds richness to the study and addresses the retrospective bias prevalent in the study of emerging industries.

Figure 3-1 Conceptual Framework



3.3 Research Questions

The overall objective of the study are to understand how a potentially disruptive and breakthrough technology evolves to become an emerging industry and further investigate the dynamics of inter-organisational and intra-organisational routines in the context of breakthrough technologies and emerging industries. These themes are studies in the context of a specific breakthrough technology-Organic and Printed Electronics. In order to achieve these objectives three specific research questions are articulated, each including more specific sub-questions. In addition, a fourth question is also raised to provide background for the study and the main research questions.

1. How does an entrepreneurial firm create new markets for a new breakthrough technology?
    a. How does an entrepreneurial firm orchestrate the development of an ecosystem?
    b. What are the organisational routines that an entrepreneurial firm needs to create and orchestrate new markets?
    c. How do these routines emerge in an entrepreneurial firm?

2. How does a large incumbent firm respond to the challenge of creative destruction?
    a. What routines are developed by incumbent organization for capability reconfiguration during the emergence phase of a breakthrough technology?

3. What is the role of intermediaries (RTOs and Industry Association) in helping the development of a breakthrough technology in the early stages of an industry emergence?

4. What are the characteristics, challenges and dynamics OPE as a breakthrough technology?
    a. What facilitated the development of ecosystem within two main hubs—UK and Germany?

3.4 Philosophical Assumptions—Critical Realism

Philosophical assumptions relate to the issues of ontology, epistemology, axiology and methodology. Guba and Lincoln (1994, p.105) argued that:

> [The] questions of method are secondary to questions of paradigm, which we define as the basic belief system or worldview that guides the investigator, not only in choices of method but in ontologically and epistemologically fundamental ways.

The researcher's philosophical positions have important implications for research methods employed, analysis and interpretation, and evaluation criteria (Johnson et al., 2006; Guba and Lincoln, 1994; Saunders et al., 2009).

The philosophical position adopted by the researcher in this study, following Easton (2010, p.119), is that of "realism" or post positivism as described by Guba and Lincoln (1994). The ontological assumption in realism is the existence of the world independent of man. There are different types of realism: scientific; naïve; direct; and critical; however, in the context of this study "**critical realism**" associated with Roy Bhaskar (1978) has been followed.

Critical realism gives an account of the philosophy of science, a meta-theory, with an emphasis on ontology rather than on epistemology. It talks about transitive and intransitive objects, the existence of reality independent of our knowledge of it, stratification and differentiation of reality, the existence of mechanisms and structures as opposed to atomistic events, and analysis of causality in terms of interactions and tendencies (Burnett, 2007). Critical realists consider reality as stratified and consisting of the domains of real, actual and empirical (Outhwaite, 1987; Sayer, 1992; Collier, 1994; Bhaskar, 1998; Mingers, 2004). The domain of the real consists of mechanisms, structures, power, tendencies, events and experiences. "They may be said to be real, though it is rarely that they are actually manifest and rarer still they are empirically identified by men" (Bhaskar, 1998, p.34). The domain of the actual consists of events that are generated by the interaction of the mechanisms and are independent of experiences and perception. Finally, the domain of the empirical consists of events that are experienced or observed. According to critical realist philosophy the fundamental goal of theory as it is widely accepted is not to predict but to provide understanding of the processes (Manicas, 2006). Causality, as argued by realists, cannot be explained as statistical generalisation of successive discrete events but in tendencies and transfactuality. This reflects a retroductive research methodology as opposed to deductive, inductive or abductive approaches whose purpose is to explain rather than predict, correlate, redescribe or recontextualise.

> Retroduction is a mode of inference that aims at discovering the underlying structures or mechanisms that produce tendencies or regularities under certain conditions through a process of model building, testing and evaluation in which complex and time-consuming procedures are required to unearth them. (Reed, 2005, p.1631)
>
> It consists in the movement (on the basis of analogy and metaphor amongst other things) from a conception of some phenomenon of interest to a conception of some totally different type of thing, mechanism, structure or condition that is responsible for the given phenomenon. (Lawson, 1994, p.264)

Retroduction is a movement from surface phenomenon to identification of deeper underlying mechanisms (Lawson, 1994). It, therefore, aims to infer beyond empirical regularities and seeks explanation for the transfactual conditions (Danermark et al., 2002). It aims at "discovery" as opposed to deduction and induction that tend to be more concerned with "justification" (Frauley and Pearce, 2007, p.19).

A critical realist view that the knowledge is fallible has an implication for research design as it makes it an "ongoing and iterative process" (Ackroyd, 2004). The world is open, complex and changing and therefore there will be identification of new mechanisms or better explanations for the existing ones that provide new insight. Critical realism thus plays an evaluative and emancipatory role in understanding social phenomena (Jashapara, 2007).

The realist argues against the reduction of structure and agency and focuses on dynamism that results from complex interaction, power relations and socio-historical context. This has an impact on explanation of social change and conceptualisation of emergent organisational phenomena, forms and practices (Reed, 2005). Organisations in this context can be regarded as structures that are transformed and reproduced by the activity of agents and they both have their distinct power and mechanisms that are irreducible.

Therefore in the context of this research where the routines (intra-organisational and inter-organisational) are not deterministic but have the tendency to act in a specific way and in the specific context of emerging industries, the adoption of a critical realist philosophy provides a logical philosophical stance as it allows the researcher to see that reality is stratified and composed of domains of the real, the empirical and the actual and thus adoption of a qualitative approach for identifying the generative mechanisms is justified.

The realist rejects a cookbook prescription of method... this implies “that the particular choices should depend on the nature of object of study and what one wants to learn about it” thus advocating practical advocacy (Sayer, 2000, p.19). In contrast to positivism and interpretivism, critical realism advocates use of intensive research designs. Intensive research focuses on substantial relations, generative mechanisms and causal explanations and, due to this complexity, focuses on a limited number of cases while extensive research focuses on discovering regularities, patterns in a large population, formal relations and taxonomic groups (Sayer, 1992; Danermark et al., 2002). The study uses case study as a research strategy in line with its appropriability to critical realism as argued by Easton (2010).

3.5 Research Strategies

Case study has been suggested as a useful strategy in exploratory, descriptive and explanatory studies and provides answers to ‘why, how as well as what’ questions (Yin, 2009). It is defined as:

> …an in depth exploration from multiple perspectives of the complexity and uniqueness of a particular project, policy, institution, programme or system in a real life context... The primary objective is to generate an in depth understanding of a specific topic... (Simons, 2009, p.21)

Easton (2010), as mentioned earlier, identifies case study as an intensive research strategy and the best companion to the critical realist approach. Case studies tend to be dynamic compared to surveys that are more static where the associations between selected variables limit the researcher from digging into deeper realities. It allows flexibility and iterative process research thus moving between different and unexplored stages of research and can be defined as a “research method that involves investigating one or a small number of social entities or situations about which data are collected using multiple sources of data and developing a holistic description through an iterative research process” (Easton, 2010). According to Hartley (2004, p.323) “the case study is particularly suited to research questions which require detailed understanding of social or organizational processes because of the rich data collected in context.”

All the above discussed attributes and the research objective of deeper understanding of the underresearched phenomenon guided the choice of case study as a research method. Yin (2009) has identified four different designs for case study: “single case (holistic) design, single case (embedded) design, multiple-case (holistic) designs and multiple-case (embedded) designs" while Stake (1995) categorised the case study as either intrinsic, instrumental or collective. According to Thomas (2011, p.91) the "choice about purpose, approach and process interact variously to produce an array of permutations and ultimately each unique study." The study has employed a single qualitative case study (embedded design) of Organic and Printed Electronics (OPE). The main reason that supports the selection of the single case is its uniqueness and intrinsic nature as it provides the rare opportunity to explore the ongoing real-time dynamics of a breakthrough technology and emerging industry rather than exploring it retrospectively. In a critical realist tradition, case study does not provide generalisation and therefore there are no ideal numbers of cases or representative sample size. According to Easton (2010, p.119), "[a] single case study must be able to stand on its own. The key opportunity it has to offer is to understand a phenomenon in depth and comprehensively". These views are also elaborated by Pratt (2009): "there is no "magic number" of interviews or observations that should be conducted in a qualitative research project. What is "enough" depends on what question a researcher seeks to answer".

Within the single embedded case, multiple levels such as macro, meso and micro and different units of analysis were selected. At the macro or more global level, the emergence of the OPE industry is discussed within Europe in two prominent hubs – the UK and Germany; at the meso or collective level, the role of two types of intermediaries – the research and technology organisation (RTO) and the industry association – form part of the discussion. At the micro level, two firm level subcases were selected and are discussed thoroughly. The two selected cases were revelatory and included (1) a case based on a small entrepreneurial firm and its creation of routines while (2) the other case discusses the role of incumbents and investigates the dynamics of reconfiguration routines. The final selection of the levels and cases was an iterative process and was continuously refined as the research progressed with the data collection and analysis.

The chosen case study strategy employed a number of data collection techniques in line with the realist philosophy that served the purpose of triangulation and provided detailed and rich insights. However, before moving further, the next section will discuss the challenges encountered in the data collection for the study of breakthrough technologies in emerging industries.

3.6 Challenges of Data Collection for Breakthrough Technologies in Emerging Industries

Forbes and Kirsch (2011) identified various challenges associated with the study of emerging industries, thus contributing to the understudied phenomenon. These challenges relate to the ephemeral nature of data associated with industry in general and in particular with organisations, owing to the high disbanding rates that makes it difficult to identify critical events associated with industry infrastructure. Organisational level challenges for data collection are related to getting access to both de novo and de alio firms, and to restricted insights, owing to the threat associated with information spillovers in this pre-commercialisation phase.

Understanding the dynamics prevalent in the emerging industry and gaining the trust of participants within the industry thus necessitated using a variety of qualitative approaches for data collection and included: secondary data and archives; participation in field-configuring events; and engaging with heterogeneous actors not limited to producer firms but with practitioners such as consultants (technological and market), institutional entrepreneurs, government officials and other non-profit actors such as trade associations and standard setting bodies.

3.7 Iterative Process of Case Selection

The research process that spans the time from 2011 to 2013[2] as shown in Figure 3.2 has been iterative and designed in phases. The challenges associated with this study were manifold and included understanding of the terminologies related to the technology and what constitutes its boundaries, identification of relevant players and gaining their trust owing to the pre-commercialisation nature of the field. In order to understand the language of actors and dynamics of the technology, participation in the networks emerging around the technology was ensured. The researcher initially looked at the various secondary reports and identified main industry events and main actors. According to Garud (2008), **conference** serves as an avenue for a variety of activities such as identification of actors, their networks and the discourses around future visions of the technology.

[2] Exception being Solvay where few follow-up interviews were conducted for further clarification in 2015 after doing analysis and writing of the case

> People attending conferences typically adopt roles that facilitate informal interviews: they come expecting to be approached by strangers, are predisposed to respond politely, and offer a business card listing their name, job title, employing organization, and contact information. (Lampel and Meyer, 2008, p.1031)

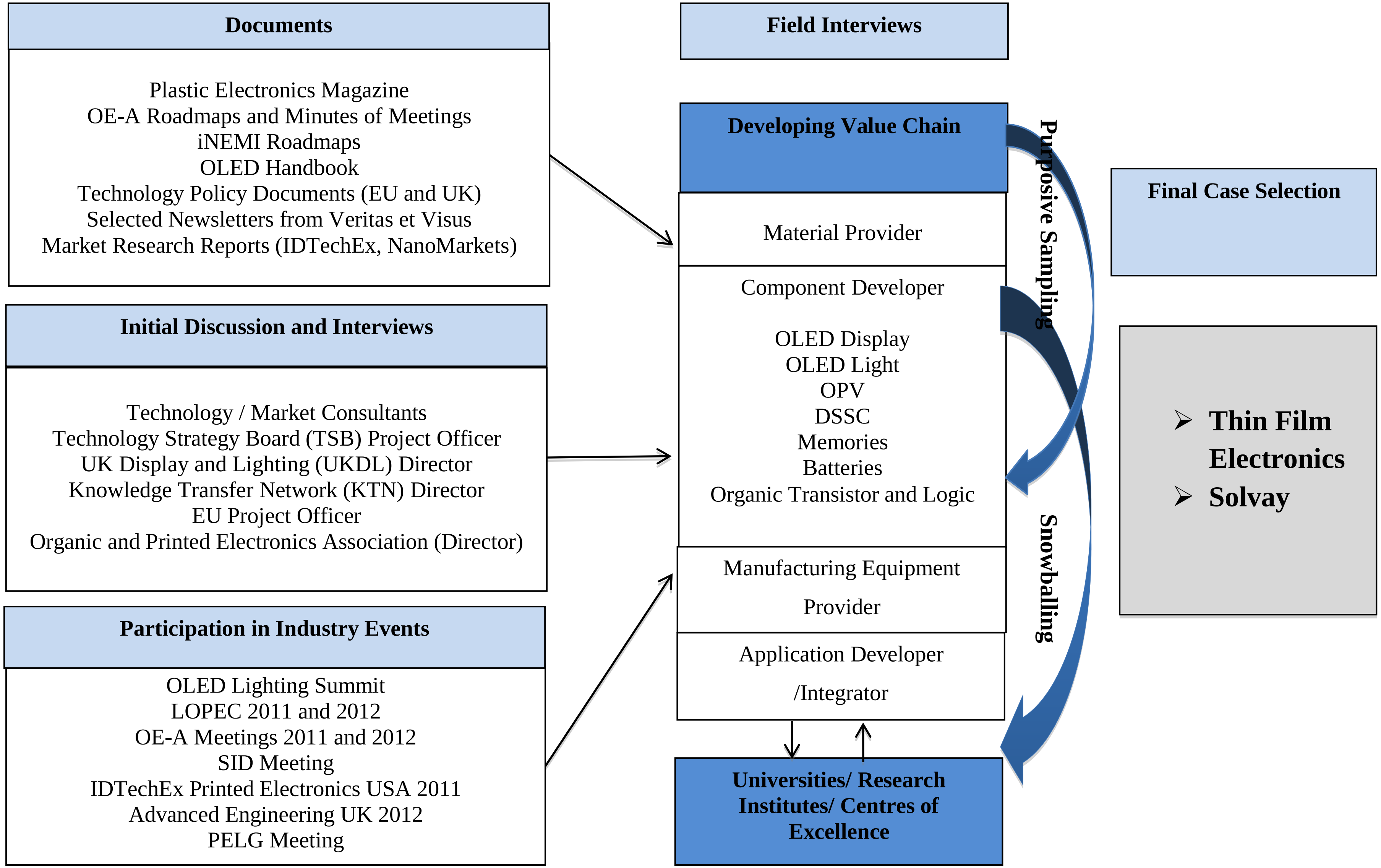
The first event that the researcher participated in was that organised by an OLED insider in the UK, OLED Lighting Design Summit, in June 2011. The initial event contributed to the learning regarding challenges associated with the emerging technology, the importance of a collaborative approach for the industry development and the presence of heterogenous players such as designers, material providers, technology developers, government officials and users. It soon became evident that the dynamics of this emerging industry cannot be fully comprehended by merely looking at one possible application domain, that is of OLED lighting, as the field is still looking for the winning application. Meanwhile, during the search process, the researcher identified the Organic Electronics Association (OE-A) as the industry association and participated in its yearly “Large-Area, Organic and Printed Electronics Convention”, LOPEC 2011, held in Frankfurt, Germany. Conference participation resulted in developing a personal relationship with OE-A, getting the support of their board members, gaining access to their exclusive members-only website and identifying the relevant players, and paved the way for further participation and presentation of research in their working group meetings held at Lohr am Main (Germany) in 2011 and Cambridge (UK) in 2012. Presence at OE-A related events established the credibility of the researcher, clarified the position of players within the developing value chain and ensured access to the key decision makers and informants in the application domains.

Other events where the researcher participated were those organised by the Society for Information Display (SID) at Imperial College, London that proved to be important for getting access to networks around science and academics. Participation at Printed Electronics USA 2011 organised by leading industry consultant IDTechEx at Santa Clara proved useful in introducing the researcher to the proliferation of terms being used within this domain (such as Organic, Printed, Plastic, Flexible) and broadened the research horizon to “Printed Electronics” instead of being limited to “Organic Electronics” only. These events illustrated the ferment stage of the technology, provided a rich real time experience of unfolding of events as the industry progressed and also helped in identification of the main players and in recruiting more participants.

The OPE industry is characterised by complexity and the presence of a large number of actors. To facilitate understanding of the field, expert interviews were also conducted initially with technological consultant Dr Bev Brown as well as with market consultants and with Raghu Das of IDTechEx, to get a broad overview of the industry.

The overall understanding of the field dynamics evolved and improved throughout the fieldwork. The researcher soon became aware of the presence of clusters within Europe and focused on getting deeper insights at hub level within the specific context of the UK and Germany. The factors that guided the selection of the clusters or hubs were the level of activity, funding, presence of leading start-ups, and a thriving academic community.

Figure 3-2 Iterative Process of Case Selection



In this regard face-to-face meetings and informal discussion were arranged with Electronics, Sensors and Photonics Knowledge Transfer Network (ESPKTN) Director Ric Allot and with a Technology Strategy Board (TSB) officer. In addition, unstructured interviews with individuals that played an important role such as Chris Williams (former Director of UK Display and Lighting) within the UK landscape paved the way for understanding the policy dimensions, identifying the increasingly important role of Centres of Excellence and establishing connections with players within the UK. Participation was ensured at the Plastic Electronics Leadership Group (PELG)[3] meeting held in November 2012 that resulted in gaining support from the UK network.

Email exchanges with Professor Karl Leo (leading institutional entrepreneur for Dresden, Germany, discussed in greater depth in Chapter 5) resulted in active involvement with Organic Electronics Saxony in Dresden, Germany and interviews with leading players such as Fraunhofer IPMS, a research and technology institute.

In addition to the primary data collection method, secondary data and updated market information complemented the understanding of the industry and provided a global overview. The sources of secondary data include +Plastic Electronics Magazine[4], Frost and Sullivan reports, the IDTechEx report on “Printed, Organic & Flexible Electronics Forecasts, Players & Opportunities 2011-2021,” the International Electronics Manufacturing Initiative’s (iNEMI) 2011 Roadmap for Large Area Flexible Electronics, and the OE-A Roadmaps (2011, 2013, 2015). In addition, policy documents at European level as well as for the UK were reviewed.

The formal and informal discussions, secondary data and participation in events helped in identifying and getting access to meso level actors, that is research and technology institutes and industry associations.

The second phase was selecting organisations and exemplary cases for in-depth study of the routine dynamics. This required broadening the search to other countries in Europe, notably Belgium, Sweden and Finland, rather than limiting it to Germany and the UK alone. Selection was based on two dimensions: (1) firms that were transversal along the developing value chain such as material suppliers and equipment providers; and (2) firms active within

[3] PELG is the volunteer group representing the UK OPE community and is discussed in Chapter 5
[4] +Plastic Electronics magazine is a bimonthly publication providing news and in-depth analysis on the organic, printed and plastic electronics industry. The author subscribed the magazine from 2011-2015

five application domains of Organic Printed Electronics that include Flexible Displays, OLED Lighting, Third Generation Photovoltaic, Electronics and Components, and Integrated Smart System (discussed in detail in Chapter 4). The non-probability "purposive sampling" was mainly employed to ensure that "units are deliberatively selected to reflect particular features" such as "relevance and diversity" (Ritchie et al., 2003, p.78). The selected organisations included both start-ups and incumbents. On a few occasions, snowballing was also used. Snowballing is a technique whereby the respondents are selected based on the recommendation of existing respondents. According to Yin (2009), snowballing is acceptable as the selection of additional respondents is purposeful rather than based on convenience.

From these field interviews, the researcher gained an insight of the importance of the transversal role of material providers that were mostly large incumbent organisations and the critical and missing role of integrators within OPE. It was found that there was a large number of component providers but very few integrators and, for the industry to succeed, the latter tend to be instrumental. Thus "firm level" cases that were particularly enlightening and information-rich and that allowed diversity and data access were selected. Two cases discussed within this study include:

- Norwegian entrepreneurial organisation Thin Film Electronics, with core competency in memory (Electronics and Components). The firm adopted product orientation and an ecosystem approach for the creation of routines.
- An incumbent material supplier, Solvay, that adopted a reconfiguration model to build competency in Organic and Printed Electronics.

The above-mentioned cases provided interesting dynamics, opportunity for in-depth exploration, and variation owing to their size (small entrepreneurial firm and large incumbent organisation), background IP and position within the developing value chain (integrator and upstream material).

3.8 Approaches for Data Collection

Research within emerging industries requires collecting records or data at various levels such as: 1) producer firms; 2) universities and research institutes; and 3) government agencies and associations (Hellman, 2007). There are numerous techniques that are more suitable to study producer organisations. Some adopt a natural science model commonly referred to as quantitative research, associated with objectivity, rigour, reliability, validity and systematic procedures, while others advocate and emphasise understanding meanings and intersubjectivity to study complexity in organisations (Daft, 1983). It could be argued that the dichotomisation between using quantitative and qualitative techniques is overemphasised (Morgan and Smircich, 1980) and that research should be considered as an art.

> As a craft, research is interesting, exciting and satisfying. The challenge for researchers is to go beyond sheer techniques, whether quantitative or qualitative and to interject the craft attitude into the research process. (Daft, 1983, p.540)

According to Ritchie and Lewis (2007), approaches for data collection can be divided into two categories – those developed to study a phenomenon in natural settings, referred to as naturally occurring data and including techniques such as observation, documentary analysis, discourse analysis and conversation analysis, and those referred to as generated data that give insights into people's perspectives and include such techniques as biographical methods, individual interviews, paired interviews and focus groups. The data collection approach that has been employed to answer the research questions at the micro or firm level is composed of semi-structured interviews and analysis of documents such as press releases, annual reports, specialised and generalised industry media reports and news. The decision to adopt a particular method depends on both our epistemological assumptions as well as technical justification, and these two aspects are distinct. The philosophical justification for selecting these particular methods is based on the adoption of the realist position that knowledge consists of both transitive and intransitive dimensions. As Sayer (1992, p.16) argued, "Knowledge as a product, a resource, a skill, in all its various forms, is 'both the ever-present condition and continually reproduced outcome of human agency'. Science is not a thing but a social activity".

However, to understand the general dynamics prevalent within the emerging industry and investigate the role of intermediaries especially RTOs and industry association, the initial stage was more exploratory whereby non-obtrusive measures such as observation techniques were employed while participating in field-configuring events (FCE). The later stage involved interviewing of the key personnel such as board members of OE-A and higher level managers or director of prominent RTOs to understand in depth the dynamics related to the industry such as its emergence, evolution and challenges.

3.8.1 Field-Configuring Events and Observation Techniques

According to Kellehear (see Lee 2000, p.1) "We ask people about themselves, and they tell us… the assumption is that important "truths" about people are gained through talk…" However, asking does not always result in obtaining the complete understanding of the case, as Hodder (2000, p.705) commented: "what people say is different from what people do". Furthermore, the presence of the interviewer may also affect participant responses and result in "interviewer bias". In order to overcome this weakness of the single data collection method it is complemented by other methods in accordance with the philosophical assumptions.

According to Pratt (2009), the researcher needs to be clear about his or her position and participation in the field. Gold (1958) suggested a range for the researcher-subject relationship that may vary from complete participation to the other extreme where the researcher is only an observer. To answer the research questions, data can also be gathered by other non-reactive and unobtrusive ways – a term coined by Webb et al. (1966) (see Lee, 2000). Unobtrusive measures include data sources such as traces, non-participant observation and documentary evidences. Proponents of unobtrusive methods assume "noise is rare" and data that might seem trivial can prove important and can be a source of fresh, creative insight and perspectives for the researcher. This is in line with what Gouldner referred to as "methodological romanticism" (see Lee, 2000) and is also relevant to the critical realist perspective. Critical realism aims to find generative mechanisms that produce events in open systems and, as organisations are complex, open systems, so there are many mechanisms operative at the same time that tend to impact the events or phenomena. 'Non-participants', covert observation results in uncovering aspects and realities not known to the researcher in advance and they can also act in a supplemental role to validate the responses in the interviews (Robson, 2002). However, there are problems of interpretation and rigour associated with unobtrusive measures.

In this study, unstructured, informal observations through participating within field-configuring events were used in the initial exploratory stage of the study. These were mainly aimed at gathering insights into the prevalent dynamics within the field. For instance, participation in roadmapping activities that took place in working group meetings helped in understanding of the entire process. According to Lampel and Meyer (2008, p.1030), "field-configuring events present unique methodological opportunities to social scientists… they facilitate the study of emergence, transformation, and other dynamic processes that are difficult to capture with conventional methodologies”

3.8.2 Interview Design

Qualitative interviews as opposed to quantitative interviews do not see the respondent as a subject but as an active participant (King, 2004). Qualitative interviews tend to be more flexible as compared to quantitative, that is, based on a fixed set of questions to maximise reliability and validity. According to Kvale and Brinkmann (2009, p.2) “an interview is literally an *inter view*, an interchange of views between two persons conversing about a theme of mutual interest”. The qualitative interview varies in structure from highly structured to totally unstructured and also offers flexibility in terms of focus ranging from broad to narrowly focused themes (King, 2004a). The purpose of using qualitative interview as opposed to structured interviews is to understand the emic perspective of the respondent. Kvale (1996) describes interview as a craft: “it does not follow content and context free rules of method, but rests on the judgement of a qualified researcher” (Kvale, 1996, p.105).

Following a realist epistemological position, the semi-structured interview process has been adopted at the firm level as it allows the provision of selecting a research theme and imparting structure, and at the same time it offers flexibility to probe participants to get an in-depth understanding of their perspectives and build on responses. It provides an additional advantage of serendipity – leading into new areas that had not been previously included in the interview guide but may prove useful to understand the research topic. The interview guide (presented in the Appendix 1) was prepared at the onset for firm level with the main objective of investigating the intra-organisational and inter-organisational routines. Operationalisation of the research questions into interview questions.

To operationalise the research questions into interview questions, the routine-based conceptual model of Lewin et al. (2011) was used. They proposed the taxonomy of absorptive capacity based on four internal and two external meta-routines. Internal meta-routines comprised of routines for facilitating variation, selection, sharing knowledge within organisation and for reflecting and updating of selected routines. External meta-routines mainly aim at accessing and acquiring external knowledge. These meta-routines are expressed through observable practiced routines and were illustrated through variety of examples based on extensive empirical literature review. For deeper insights into the inter-organisational dimension, the interviewees were probed about collaborative practices in specific collaboration projects that existed in the public domain and were identified by the researcher based on secondary search.

Furthermore, as the study also involved interviewing organizations at meso level such as industry association and research and technology organisations, the design of the interviews needed modification as here the main focus was on understanding the roles of these intermediaries in the context of emerging industries and routine-based model comprising of internal and external dimensions was not of much relevance. Here, unstructured interview approach was adopted. Appendix 2 presents summary of the main broad themes of the unstructured interviews related to industry association and research and technology organisation.

Similarly, at the more global level, interviews were in-depth and unstructured as they required broad and sometimes retrospective understanding of the processes and events. Different techniques such as face-to-face interviewing, telephone interviewing, and electronic interviewing can be employed for semi-structured interviews. Telephone interviews offer advantages associated with "access, speed and lower cost" (Saunders et al., 2009, p.349) however, as compared to face-to-face interviews, they do not provide the opportunity to witness non-verbal cues of the participants and are not effective in establishing rapport and trust with participants (Robson, 2002). Electronic interviews refers to the interviews that are synchronous as well as asynchronous (Morgan and Symon, 2004; Saunders et al., 2009). They prove to be useful to get access to busy managers especially in multinational organisational settings. Due to sophisticated technological development this mode of interviewing can be considered as continually evolving and this may tend to overcome spatial and contextual disadvantages associated with this technique.

More than 100 interviews were conducted during the course of the field work research, each ranging from 45 minutes to 3 hours. In total 133 interviews were conducted, however, 60 interviews inform analysis and writing up of this study The details of the interviews (date, organisation name[5], number of interviews and follow-ups in particular organisation, mode of interviews and place of interview) are presented in Appendix 3. All the interviews were

[5] Pseudonyms are used for confidentiality purposes

recorded and then transcribed by a professional transcriber. For ethical considerations, participation information sheet (attached as Appendix 4) was also provided to the respondents to explain clearly the objectives of the study, aspects related to use of information and confidentiality. The respondents are therefore not identified in the thesis and the codes (comprising their name and organisation name) have been used instead. These measures were taken to secure respondents' anonymity and confidentiality. Prior to the recording of the interviews, informed consent was also sought from the participants. The majority of these interviews were conducted face to face at the participant's location, however, in a few instances, follow-up interviews were also required, whereby telephonic and electronic (Skype) interviews were conducted. Face-to-face interviews proved instrumental to gain trust of the participants and provided opportunity for in-depth probing and finally recruiting more participants within the organisation. The brief summary of the interviews that have been part of the analysis for this study are shown in Table 3.1.

Table 3-1 Number of Interviews

Interviews	Number of Interviews	Duration
Thin Film Electronics case	10	13 hours 26 minutes
Solvay case	16	20 hours 33 minutes
Industry and Intermediaries	34	55 hours 48 minutes

3.8.3 Company Documentation and Other Secondary Data

Organisational documentation consists of written and non-written materials. Written materials comprise company annual reports, press releases, policy directives, organisational websites, and organisational communications such as emails, letters or memos. Non-written materials include television programmes, DVDs and CDs as well as organisational databases (Saunders et al., 2009). These documents can be an important source of information for the qualitative researcher in order to gain a better perspective at various levels and learn about historical as well as contemporary issues; they provide guidelines and insight in areas that require exploration, and may also result in altering of interview guidelines. Prior (2004) emphasised three features of documentation analysis for the social researcher: document as product, that is, how they are produced; document in action, which implies how they are used; third, as text and identity – how documents translate into identity. However, there are many critical arguments about the rigour associated with these documents as they tend to be subjective, sometimes politically motivated and contextual (Forster, 1994). The purpose of using them is not from a constructive perspective to analyse the language and associated text, but rather to get a complete picture of the emerging industry at various levels.

Table 3.2 summarises the data collection sources employed in the study.

Table 3-2 Sources of Data

Level	Primary	Secondary
Industry Level	Unstructured Interviews Informal Observations at Field-Configuring Events	• Industry Association Minutes of Meeting • Roadmaps (iNEMI and OE-A) • Other OE-A Confidential Presentation Available to its Members Only • IDTechEx, Frost and Sullivan Reports • Weekly Newsletter from IDTechEx, Printed Electronics World and OSA • Policy Documents for EU and UK • National Science Foundation Reports on Flexible Electronics • Plastic Electronics Magazine and Exclusive Content • OPE Journal • UKDL Newsletter • Current and Historical Issue (2006-2015) of "Flexible Substrate" from Veritas et Visus
Intermediaries ➢ Research and Technology Institutes ➢ Industry Association	Unstructured Interviews Informal Observations at the Association Level	• Websites • Presentations • Press Releases • News Articles (General and Industry Specialised)

Firm Level ➢ Thin Film Electronics (TFE) and its Ecosystem Partners ➢ Solvay and COPE	Interviews	• Company Website • Presentations • Annual Reports • Press Releases • News Articles (General and Industry Specialised) • Book (Solvay) • Social Media such as Twitter and LinkedIn for TFE

3.9 Data Analysis

One of the difficulties in qualitative research is the accumulation of large amounts of data (Bryman, 2009). There are various approaches that can be employed for qualitative analysis such as content analysis, grounded theory, discourse analysis and template analysis. The approach in line with our epistemological position and selected methods is that of template analysis as it allows development of a codebook based on interpretation of emerging themes in addition to the a priori themes from the literature by the researcher. This method can be contrasted with content analysis that is based on objectively finding out the categories, and with grounded theory which is based on open coding and where the researcher does not begin with a preconceived theory in mind. The template analysis offers more flexibility and structure (King, 2004b).

Three activities are associated with data analysis as identified by Miles and Huberman (1994): data reduction, data display and conclusion drawing and verification. However, the interpretation of data from a template requires a careful balance of identifying and selecting the relevant and emergent themes which is sometimes very difficult for the novice researcher (King, 2004b).

Data analysis was carried out in three rounds and aimed at retroduction. The initial round was comprised of reading transcripts, assigning a priori themes informed by the Lewin et al. (2011) routine-based model of absorptive capacity. The first stage was thus based on descriptive themes. At this stage the coding software NVivo was used for a few interviews with the aim of the initial organising of large amounts of textual data, development of structure and identification of categories. At this point a few emergent themes were identified from the data such as the importance of ecosystem for Thin Film Electronics, and universities for Solvay. The emergent themes also sometimes required further probing and thus follow-up interviews were conducted. Thus the analysis and data collection was an iterative process. The second stage comprised writing the descriptive cases (firm level, industry level) based on secondary data as well as identified categories. The final round of analysis aimed at moving away from the flat description generated at stage two to more in-depth interpretation of the findings. This required moving back and forth between raw data and theoretical explanations.

3.10 Research Validity

Though the consensus exists that qualitative research needs to demonstrate the credibility of the findings, writing about research validity in a qualitative context is challenging, as noted by Creswell and Miller (2000). Validity is defined as "how accurately the account represents participants' realities of the social phenomena and is credible to them" (*ibid.*, pp.124-125). Yin (2009) identified construct validity, internal validity and external validity to ensure quality of the empirical research and case study in particular. Construct validity is aimed at identifying correct operational measures, internal validity is used for explanatory and causal analysis to seek generative explanations, while external validity is more concerned with generalisability .

In this study validation was achieved by deploying various measures and lenses such as that of the research participants, the researcher and that of the external reviewer. The drafts of the descriptive cases that were developed during the second stage of data analysis were sent to the research participants via email. The research participants were asked if the presented data reflected the accurate state of affairs. Triangulation and use of multiple sources of data was another validity instrument that used a researcher's lens. It was dominant in this research design. Providing thick description of the data is another possible way to ensure validity as it enables the reader to understand the context fully. Peer reviewing as defined by Creswell and Miller (2000, p.129) "is the review of the data and research process by someone who is familiar with the research or the phenomenon being explored". For this study the debriefing was mainly done by the supervisors and an external reviewer. They continuously challenged assumptions, asked hard questions, and discussed the findings and their applicability.

3.11 Conclusions

The chapter discussed the research methodology for this study. It gave a detailed account of the philosophical assumptions that have guided the design of the study. The research design adopted for this study is that of a single embedded multilevel case design, driven by both exploratory and explanatory objectives. The context of emerging industry and the analysis of the organisational routines, however, imposed challenges for the study that required careful consideration for each stage of the design, that is, sampling, selection and recruitment of participants, and handling, analysis and interpretation of large amounts of primary and secondary data.

Chapter 4: The Context: Organic and Printed Electronics

4.1 Introduction

This chapter sets the empirical context of the thesis by defining and describing characteristics of Organic and Printed Electronics (OPE) technology. It gives the global perspective, highlights the importance of the technology and its main applications and identifies the main actors, both incumbent as well as new ventures. The chapter gives an indication of the level of funding for this technology across the world thus indicating its importance. In the last section, the discussion is about setting of standards, covering efforts at both public and private standard development organisations (SDO).

4.2 Definition of Organic and Printed Electronics

Organic and Printed Electronics refers to "electronics based on semiconducting organic (carbon based material), [...] that makes it possible to produce flexible, bendable or stretchable electronic products" (King, 2009). Organic and Printed Electronics is a branch of electronics dealing with conductive polymers, plastics, or small molecules. It is called 'organic' electronics because the polymers and small molecules are carbon based. This contrasts with traditional electronics (or metal electronics), which relies on inorganic semiconductors such as silicon or gallium arsenide. OPE enables the use of new organic and inorganic materials with additive manufacturing techniques that can be printed on a range of substrates.

OPE as a field of scientific research has received considerable attention over the past decade. According to Kelley et al. (2004) broad search terms including memories, organic thin film transistors (OTFT), organic light emitting diodes (OLED) and photovoltaics resulted in around 40,000 publications for the period 1998-2003. "More researchers continue to join the field, with few dropping out each year, even though, as a community, we still await the key applications that may drive organic electronics toward mature industrial persistence." (Kelley et al., 2004 p.4413). According to the report prepared by the World Technology Evaluation Center and commissioned by the National Science Foundation (NSF) and the Office of Naval

Research (ONR):

> Continued advances in electronics, photonics, and magnetic systems are critically important in sustaining the nation’s economic growth, particularly in the areas of telecommunications, information technology, wearable microprocessors, organic memories, efficient solid-state lighting, alternate power generation sources, and healthcare engineering (such as the use of conductive polymers as artificial muscles and in nerve-tissue replacement). (Dodabalapur, 2010)

Though the OPE space has witnessed tremendous progress in material development, device design and deposition processes that has resulted in increased interest among actors, practitioners and investors, it still awaits a winning application that could bring desired revolution and disruption.

4.3 Organic and Printed Electronics: from Silicon to Carbon

Organic materials were initially considered as insulators. The first organic semiconductor was reported in 1950. However, the discovery of highly conductive polymers is credited to Alan J. Heeger, Alan G. MacDiarmid and Hideki Shirakawa who were awarded a Nobel Prize in Chemistry in 2000. Pioneering efforts can be attributed to work done by Ching Tang and Steven Van Slyke at Eastman Kodak (small molecules) and Jeremy Burroughes at Cambridge University (solution processed polymers). Tang developed the first organic solar cell and organic light emitting diode, with papers published in *Applied Physical Letters* in 1986 and 1987 respectively (Forrest, 2012).

Organic and Printed Electronics, also referred to by partially overlapping terms as plastic, flexible, organic, polymer or organic large area electronics (OLAE), once considered science fiction and the domain of pure academic research, has now found uses in commercial applications such as in OLED displays. Stephen Forrest, a distinguished scholar in the field, commented on its progress in an article published in *Nature*, 2004:

> Organic electronics are beginning to make significant inroads into the commercial world, and if the field continues to progress at its current, rapid pace, electronics based on organic thin-film materials will soon become a mainstay of our technological existence. Already products based on active thin-film organic devices are in the market place, most notably the displays of several mobile electronic appliances. Yet the future holds even greater promise for this technology, with an entirely new generation of ultralow-cost, lightweight and even flexible electronic devices in the offing, which will perform

> functions traditionally accomplished using much more expensive components based on conventional semiconductor materials such as silicon. (Forrest 2004, p.911)

OPE can be referred to generally as “electronics beyond the classical approach” (OE-A, 2011). It can also be defined as “printing of circuits on media such as paper and textiles but also on a large number of potential media” (Kantola et al., 2009, p.66). According to Ross Bringans at PARC, “Flexible electronics refers to both products and manufacturing techniques.” The discourse on the definition of printed, organic flexible electronics and its boundaries can be summed up based on comments by Michael Andrews of L-3 Communications:

> The first point to clarify was the definition of flexible electronics. This was a point often left unanswered… because it means different things in terms of substrates and technological application. But at the end of the day…, it gets down to where it fits into some desire for products that are lighter weight, more rugged, and more capable, both for the commercial world and for providing security for the nation. (Shivakumar, 2013)

OPE, as shown in Table 4.1, is considered to be a paradigm shift from the conventional silicon-based manufacturing that tends to require expensive vacuum-based equipment and is produced in batches as opposed to printed electronics that has the provision to be printed continuously at ambient temperatures, using fewer and simpler processing steps. OPE is envisioned to be a winning platform which would not be replacing the multibillion-dollar silicon industry; rather, its role would be complementary, providing opportunities for design flexibility, products and emerging applications not possible with silicon (Bock et al., 2003; Li et al., 2011).

The advantages offered by Printed Electronics as compared to traditional silicon-based electronics are: low cost, for example costs for setting up manufacturing for silicon chips are approximately $2 billion compared with printing chips that may cost up to $10 million (Frost and Sullivan, 2013); a variety of additive manufacturing techniques such as screen printing, gravure, inkjet, flexography and others; use of functional inks (organic and inorganic); and flexible, low-cost substrates such as glass, metal and polymers.

Table 4-1 Comparison of Conventional and Printed Electronics Manufacturing Techniques

Conventional Processing	PE Processing
Subtractive batch processes (sheet deposition with photolithographic + etching layer definitions)	Additive continuous processes (printing material only in the required areas)
Controlled (e.g. vacuum) environment	Ambient (temperature and pressure) conditions
Fixed, long production runs of "same product"	Flexible, short production runs – "flexible" product functionality
High equipment, materials and infrastructure costs	Lower equipment, materials and infrastructure costs

Source: King , 2009[6]

Organic and Printed Electronics as a scientific and multidisciplinary field, or "cluster of technologies" (Dosi, 1984), requires developing and combining competencies across physics, chemistry, and engineering. It has the potential to provide synergies and requires the expertise of different industries (chemical, mechanical, printing, electrical, packaging and consumer electronics) that are learning to collaborate and talk to each other. It is also considered as the third revolutionary wave for printing (whereby the first wave started in Gutenberg in 1440) and promises to enable the production of low-cost, high-volume electronic devices.

4.4 Market Potential and Applications for OPE

According to Dr Bringans of PARC, "although flexible electronics will lead to a variety of

[6] Mapping Technological Competence in Plastic Electronics in the UK Supporting Documentation

new technologies—and give rise to interesting business opportunities—in the end, “applications will drive the technology.” […] Consumers are less interested in technology for technology’s sake; people want technology to solve their problems.”[7]

The global market for Organic and Printed Electronics is forecasted to rise from $29.80 billion in 2015 to $73.69 billion by 2020 according to the leading consultant IDTechEx (2015). IDTechEx have been active in the field of organic, printed and flexible electronics since 1999 and in addition to market reports also organise two well attended yearly conferences in Germany and the USA dedicated to OPE. Other estimates of market potential for OPE such as those provided by Frost and Sullivan (2014) and Smithers Pira (2013)[8], illustrated in Figure 4.1, suggest more optimistic growth such as $190 billion by the year 2025. However, the majority of the figures reflect the recent progress in OLED (organic light emitting diode) displays and conductive inks. Organic and Printed Electronics Association (OE-A) members predict an increase of 20% in sales volume in 2015.

A large number of potential applications and markets are envisioned for OPE owing to its flexibility, unique form factor, low-temperature processing and energy efficiency. The major applications as shown in Figure 4.2 include organic light emitting diodes for display, lighting and signage, batteries, sensors, memory and organic photovoltaics. These applications have the potential to transform our lives by targeting numerous industries such as automotive, packaging, logistics, building, energy, medical and pharmaceuticals to name a few. Figure 4.3 shows some examples of products that have already made their way into the markets, such as OPV-powered bags and mobile chargers, OLED for architectural lighting, printed memories for brand protection and NFC-enabled tags for consumer applications.

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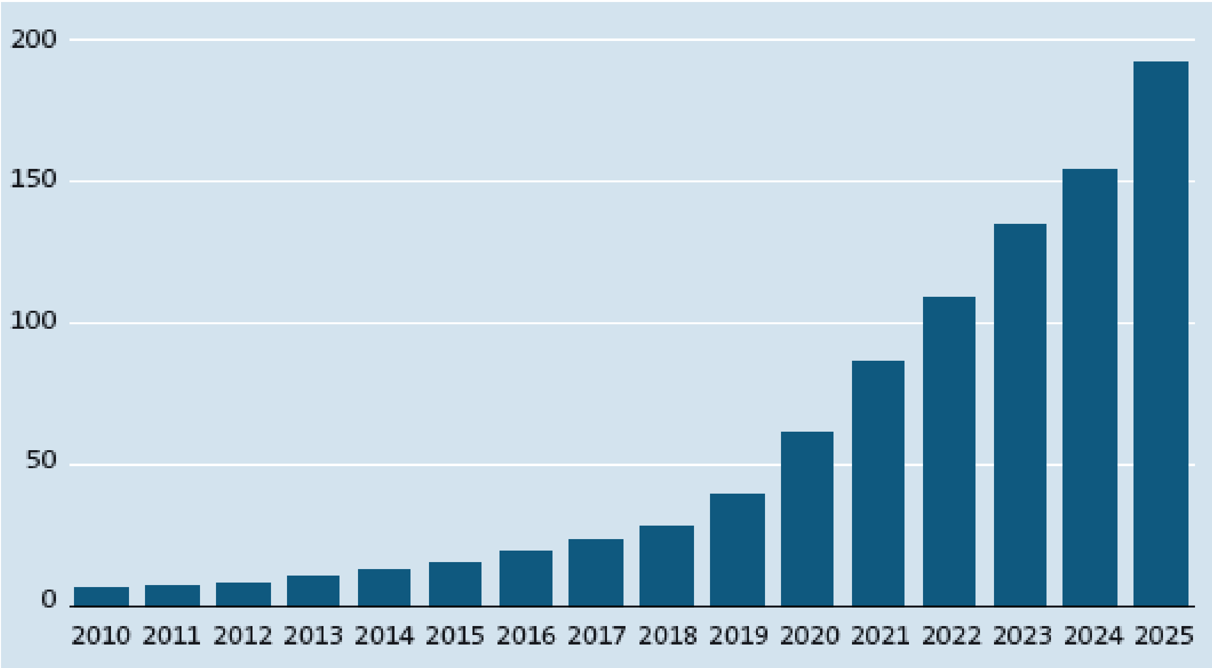
[7] Introduction, *Flexible Electronics for Security, Manufacturing, and Growth in the United States: Summary of a Symposium.* Washington, DC: The National Academies Press, 2013

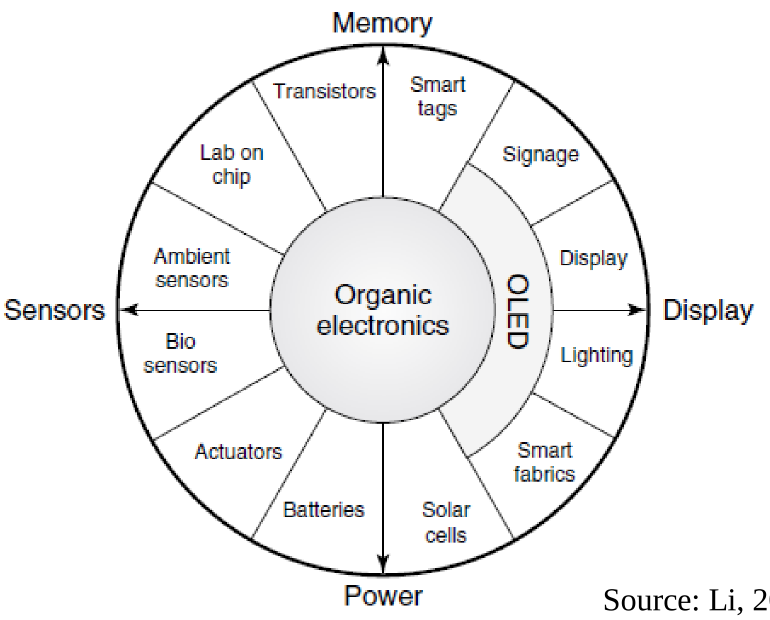
[8] OE-A. (2013). *White Paper: OE-A Roadmap for Organic and Printed Electronics*. 5th edition. [Online]. Available at: http://www.oe-a.org/group/roadmap_2_1374595343714/home/-/groupview/21547?gid=21547 (Accessed: 15 December 2015).

Figure 4-1 Market Potential of Organic and Printed Electronics (US$ billion) (2010-2025)



Source: Smithers Pira, 2013 [9]

Figure 4-2 Applications of Organic and Printed Electronics



Source: Li, 2011

[9] OE-A, Organic and Printed Electronics Applications, Technologies and Suppliers, 5th Edition

Figure 4-3 How OPE will transform the way we live today

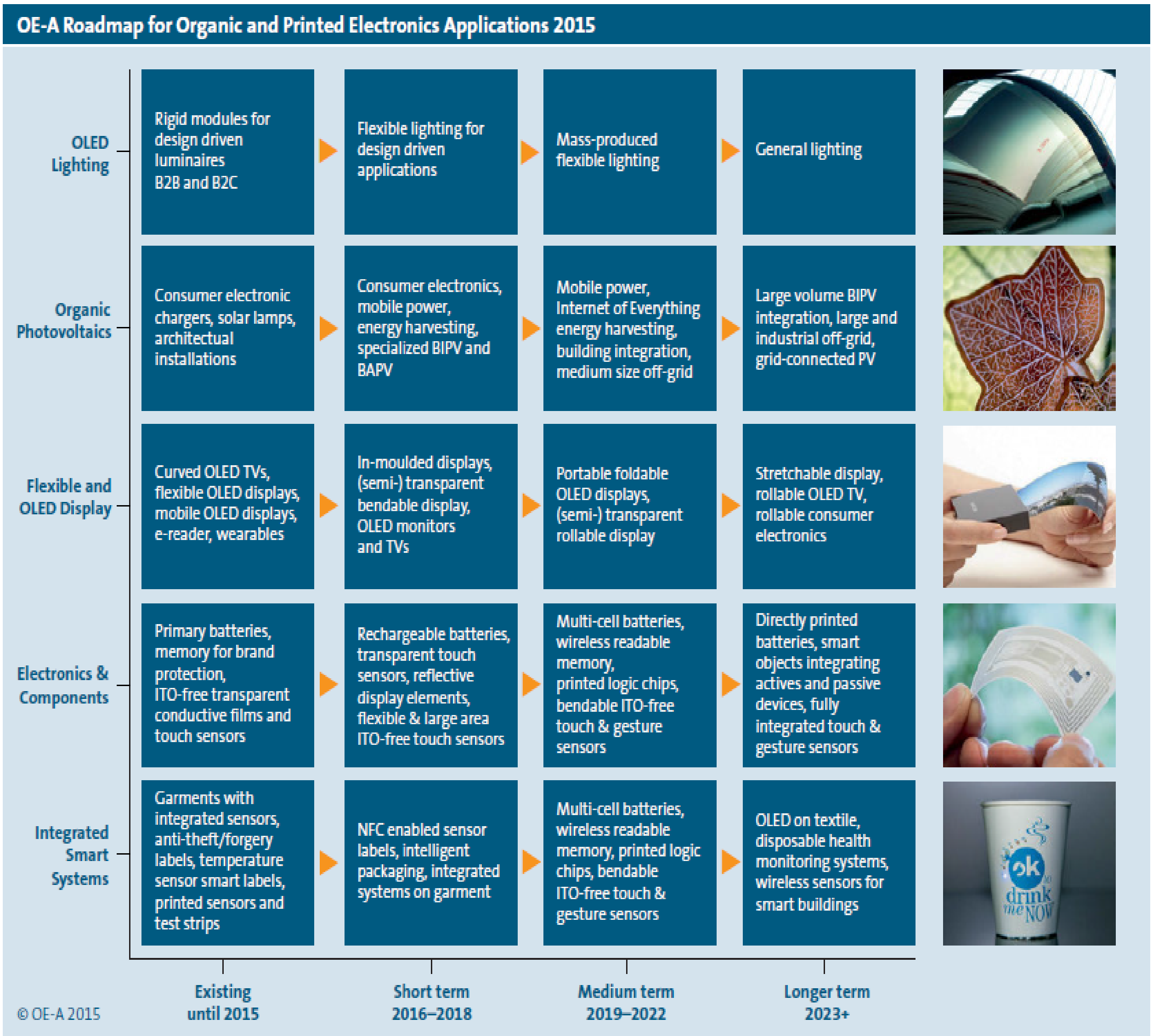
4.5 Roadmap for Organic and Printed Electronics

The Organic and Printed Electronics Association (OE-A), an international trade association representing the industry, has published the sixth edition of its roadmap of OPE in 2015 that is an update of the previous version published in 2013. The roadmap (Figure 4.4) shows the evolution of the technology and its application in various fields and indicates key trends in the five prominent clusters or applications for OPE:

- Organic LED (OLED) Lighting
- Printable, Organic Photovoltaics (OPV)
- Flexible Displays
- Electronics and Components (printed memory and batteries, active components and passive components)
- Integrated Smart Systems (ISS, including smart objects (also RFID), sensors and smart textiles)

Within each cluster shown in Figure 4.4, current technology status as of 2015, short- and medium-term market introductions and future long-term possibilities are identified. According to OE-A (2015), "Past experience of new technology shows us that we are most likely to be surprised by unexpected applications, and this will almost certainly happen in the exciting but still young organic electronics industry as well. Therefore the technology and the market in this field will continuously be watched and the roadmap will be updated on a regular basis". The following sections will discuss these clusters in detail.

Figure 4-4 Roadmap for Organic and Printed Electronics



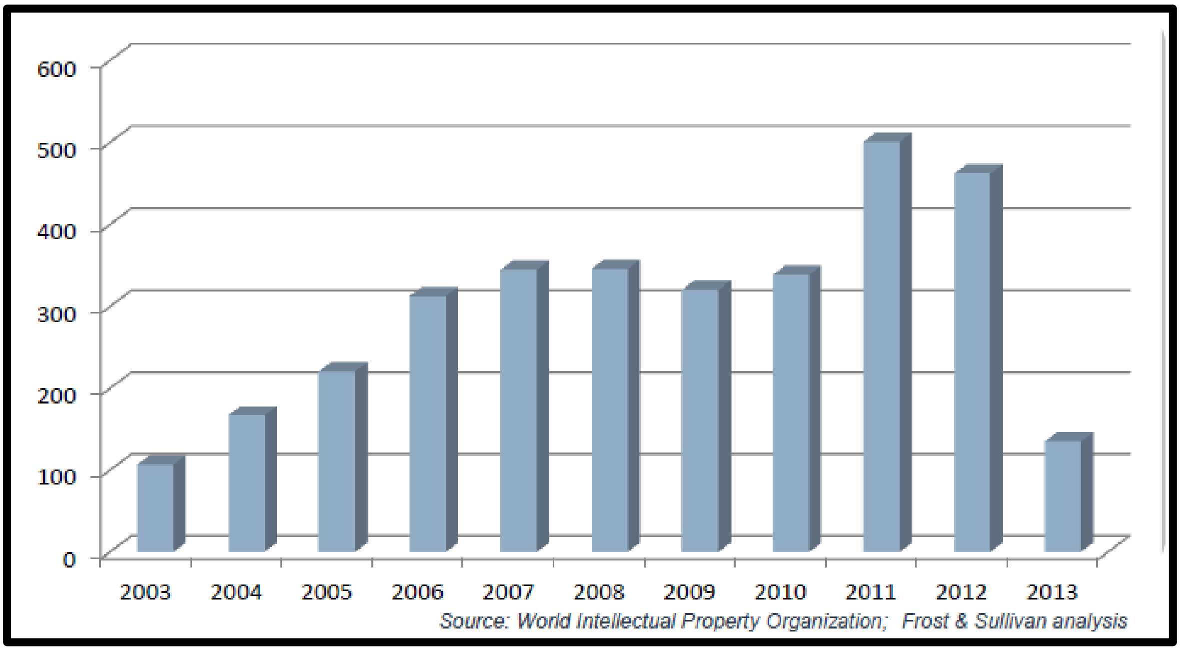
4.5.1 Flexible Displays

OLED display is considered to be a growing sector for OPE technology as is evident from the rising number of OLED patents shown in Figure 4.5. Other areas with growth potential include lighting photovoltaic panels, the use of printed sensors for healthcare and printed memories within the toy and game industry.

The display industry at present is dominated by liquid crystal display (LCD) and has a potential market greater than $100 billion/year (IDTechEx, 2013). Printed displays are further classified as emissive (OLED) or reflective (electrophoretic). OLED displays offer performance advantages such as thinner form factor, flexibility and higher contrast when compared with LCD and plasma, but still face technical and commercial challenges such as limited lifetime, difficulties in scaling up the manufacturing processes, lower yields and higher prices that have impacted their wider adoption. Following huge investments by Samsung, Sony and LG, OLEDs are being widely used in applications such as mobile phones (representing 88% revenue; see Figure 4.7) using vapour deposition methods, however, they are still not being printed nor have achieved the flexibility target considered as the unique selling proposition for printed electronics. The application of OLED in larger displays such as television, considered to be the second largest opportunity for OEMs, has not materialised fully yet and faces delays despite announcements and demonstrations by Samsung, LG, AUO and collaborative arrangements between Sony and Panasonic. In 2007, Sony was the first to demonstrate its 11-inch OLED TV XEL-1 priced at €1770. “Sony’s product gave an indication of how far OLED production still needed to go in order to compete with LCDs” (Rogers, 2011). Recently LG Electronics launched a 55-inch television priced three times higher at $10,000 compared to an LCD TV of the same size.

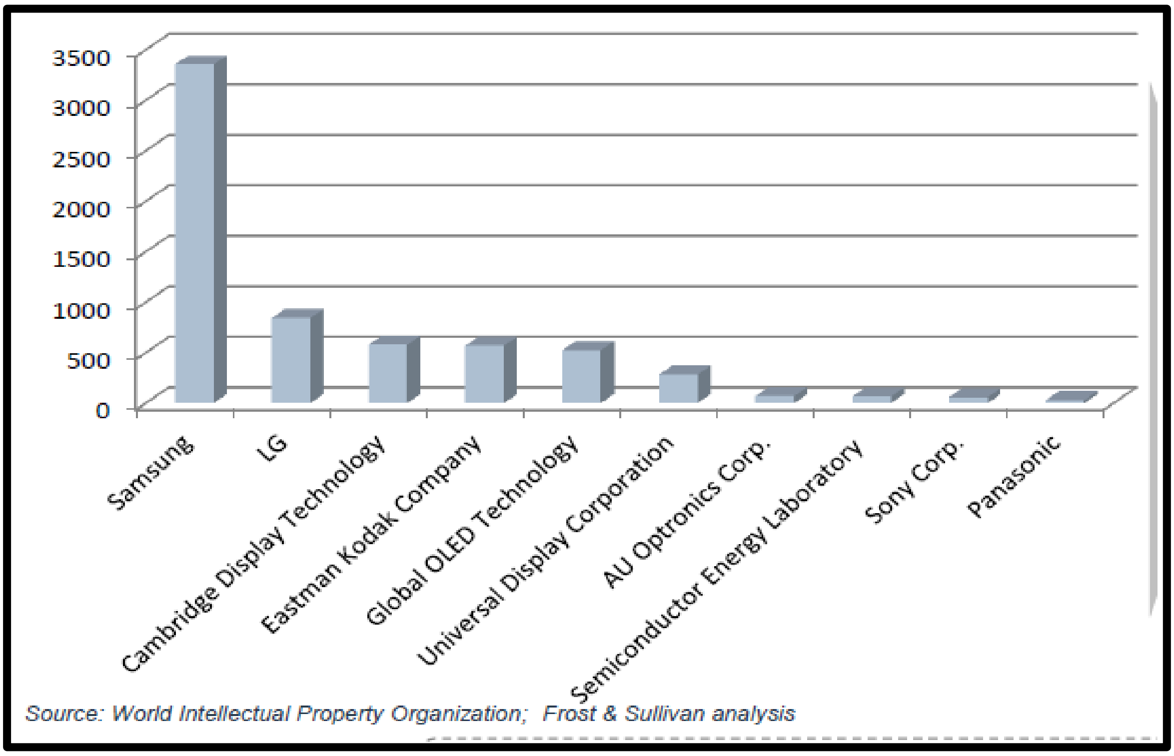
Most of the OLED display production is concentrated in Asia (see Figure 4.7) while the US and Europe, despite their technological developments, key patents portfolio and strong research base, still face the challenges related to “things invented here but manufactured elsewhere.” Key players (see the top patent assignees in Figure 4.6) within this space include Samsung, LG, Universal Display Corporation, Cambridge Display Technology, and Global OLED Technology. According to an estimate by Frost and Sullivan (2013), markets for OLED will “grow from $4.7 billion in 2012 to $26 billion in 2018.”

Figure 4-5 OLED Patents for Display Applications



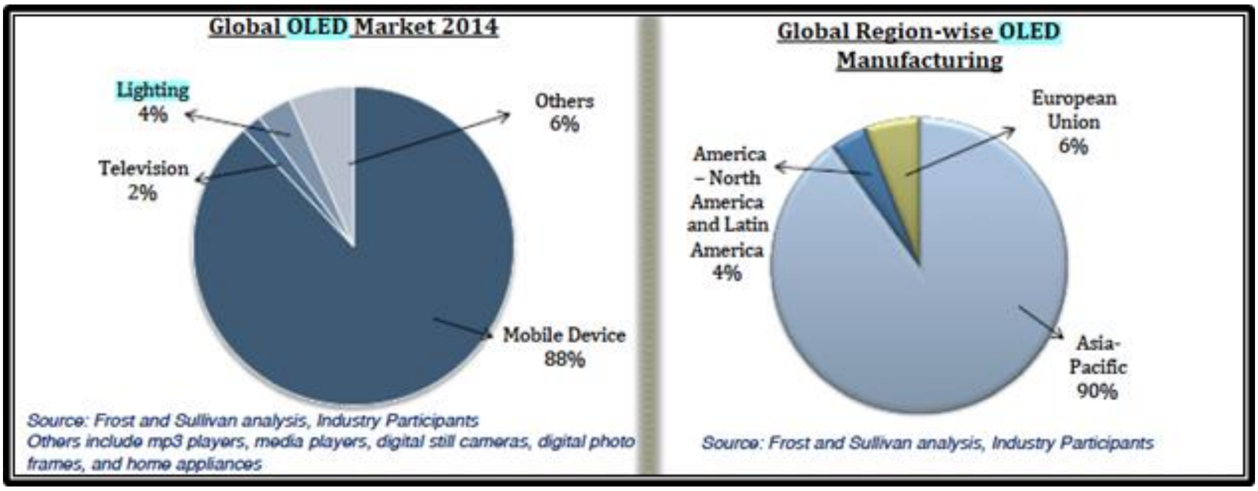
Source: Frost and Sullivan, 2013

Figure 4-6 Top Assignees for OLED Patents



Source: Frost and Sullivan, 2013

Figure 4-7 OLED Penetration



Source: Frost and Sullivan, 2014

Electrophoretic display was also considered to have commercialisation potential for e-readers and digital signage and had active players, notably E Ink (USA), Plastic Logic (UK) and Polymer Vision (Netherlands). However, there have been certain setbacks and shakeouts within the industry such as the divestment of Polymer Vision by Wistron. Polymer Vision (PV) was formed in 2004 by Philips and spun out from Philips in 2007 after receiving investment of around €21 million by Luxembourg Technology Capital Group. In 2009 PV was faced with financial challenges for the further development of the technology and went into receivership and was bought by Wistron for €13 million. PV can be classified as a visionary company that presented the idea of rollable display long before the proliferation of smart phones, Kindles and tablets on the market (see Figure 4.8).

Figure 4-8 Rollable Display Readius by Polymer Vision

Source: Polymer Vision Website

Plastic Logic, a spinout from Cambridge University, announced its flexible e-reader in 2010. However, the product was not released and later, in 2013, Plastic Logic announced a strategic change in business, and transformed itself in 2015 to target wearable electronics and the Internet of Things.

4.5.2 OLED Lighting

Lighting consumes one fifth (19%) of the total electricity generated globally. Commercial sectors comprising offices, warehouses and educational buildings are the largest users of electric lighting, consuming 43% of the total.[10] Lighting is also one of the largest contributors to greenhouse gases, therefore use of energy efficient lighting has a significant reduction on energy consumption**.** Solid State Lighting (SSL) (organic LED and inorganic LED) constitutes a more viable and efficient technology compared to traditional sources such as incandescent, fluorescent and HID (high energy density). **OLED lighting** (see Figure 4.9) offers advantages as a flexible and diffused light source as compared to LED, which is a point source.

[10]http://lightinglab.fi/IEAAnnex45/guidebook/guidebook_summary_report.pdf

Figure 4-9 OLED lighting

Source: OE-A, 2015

However, the products and prototypes available at present are not able to compete with traditional lighting sources, such as fluorescent, on cost and also face competition from their counterpart LED on lifetime and efficiency. Lux Research predicts that prices for OLED will drop from “$18 per lumen to $0.71/ lumen on glass and $0.18/lumen on flexible substrates by 2020 and will be able to command market share of $58 million in total market of $75 billion” (Ver-Bruggen, 2011, p.48).

An article in *Japan Times* covering the Lighting Japan 2014 event suggested that the Japanese OLED lighting market will be worth around ¥100 billion by 2020. Some of the experts are of the view that OLED and LED technologies are complementary while others believe that LED will be the dominant technology of the future.

> One challenge that could remain for OLEDs in the long-term is that consumers have progressed far down the path of widescale LED adoption by the time OLEDs are mature enough – in terms of cost and performance– to take their expected market share. As a result the move to solid-state lighting may in fact hinder the progress of OLEDs. (Rogers, 2011, p.38)

> OLED lighting is so different in form factor, however, it makes it more difficult for the technology to fit so neatly into conventional lighting infrastructure…. OLED lighting has

> the full luminaire challenge also to contend with. (Ver-Bruggen, 2011, p.51)

At present OLED lighting is used for niche applications such as decorative, architectural and designer lighting, and within automotive. According to Barry Young, director of the OLED Association:

> OLEDs needed to find ‘sweet spots’ for the technology, rather than trying to immediately replace incandescent bulbs or fluorescent tubes. (*Plastic Electronics Magazine*, 2011)

Due to their potentially high socio-economic impact, OLEDs have been able to attract the attention of government, academia and industry alike. In addition to the presence of incumbent traditional lighting companies such as Osram, Philips, GE and Panasonic there are many new entrants that include panel manufacturers such as Ledon (now Tridonic), Konica Minolta, Lumiotec, Blackbody, PolyPhotonix and technology developers such as Cambridge Display Technology, Novaled and Universal Display Corporation.

Table 4.2 provides an account of the level of pilot product investments and some important projects such as OLLA and OLED100 that have contributed to the developments within OLED lighting.

Table 4-2 OLED Lighting Progress

Year	Projects and Milestones
2004	OLLA-Organic LED for lighting application project was sponsored under EC 6th Framework Programme. The project cost was €12.0 million.
2007-2010	UK Government granted funding for the development of OLED lighting. TOPLESS project received £3.3 million and included Thorn Lighting, Cambridge Display Technology and University of Durham.
2008	OLED 100.eu project was sponsored under EC 7th Framework Programme. The project cost was €12.5 million.
2008	Lumiotec, a Japanese joint venture, was formed by Mitsubishi Heavy Industries, ROHM, Toppan Printing and Mitsui for €43 million. Currently it has a production capacity of 60,000 panels per year.
2009	Philips introduced their Lumiblade Panel.
2009	Osram introduced their Orbeos and AER Panels.
2010	Lumiotec started shipping their OLED lighting kit.
2010	Blackbody (subsidiary of Astron Fiamm) invested €30 million in the production facilities at Toulon, France to make OLED panels.
2010-2013	Thin Organic Prototypes, Design, Research, Applications with End user Recognition (TOPDRAWER) project followed TOPLESS project and received investment of £4.3 million. This project was led by Thorn Lighting and involved Durham University, Pilkington, Conductive Inkjet Technologies, Tridonic, and Cambridge Display Technology to demonstrate the ability to manufacture a printed lighting panel usable in aesthetic designs.
2011	Philips invested €40 million in their production plant at Aachen to support OLED lighting.
2011	Osram invested €20 million in new pilot production line at Regensburg.
2012-2015	Flex-o-Fab project for roll-to-roll processing of OLED lighting received an investment of €7.1 million under the EU 7th Framework Programme.
2013	Astron Fiamm, that supplies decorative OLED lighting under the brand “Blackbody”, opened the first OLED lighting showroom in New York’s Soho district.
2014	Konica Minolta invested €70 million to mass produce flexible OLED lighting panels.
2014	Taiwan under the leadership of ITRI (Industrial Technological Research Institute) established OLCA (Organic Light Emitting Diode Lighting Commercialization Alliance) to bring all the supply chain partners together and make Taiwan a leading OLED lighting player. Its members include Merck, RiT Display, WiseChip, Corning, Tongtai Machine & Tool and the TLFEA (Taiwan Lighting Fixture Export Association).
2014	German Federal Ministry of Education and Research BMBF initiated €5.9 million, two-year project named R2D2 that included Fraunhofer Institute of Organic Electronics FEP, Novaled, Von Ardenne, Osram and end users such as Audi (automotive), Hella Hueck and Diehl Stiftung (aerospace).

Source: Author

4.5.3 Third Generation Photovoltaics

Thin Film Photovoltaics using non-silicon materials is considered to be the next potential market for printed electronics after OLED displays, according to IDTechEx (2011), because of the strong social and political emphasis on sustainable energy sources (see forecasts Figure 4.11). The number of available competing technologies and materials other than crystalline silicon (also referred to as generation 1) that currently dominate the market include Copper Indium Gallium Selenide (CIGS), Cadmium Telluride (CdTe), amorphous silicon (a-Si) (generation 2), dye sensitised solar cell (DSSC), and organic photovoltaic (OPV) (generation 3). Each of these technologies has varying challenges and strengths (shown in Figure 4.10).

First generation solar cells provide the highest efficiency but at higher cost compared to second generation that have lower efficiency at reduced cost. Third generation photovoltaic aims to achieve increased efficiencies over those offered by first or second generation technologies, eventually decreasing the present cost level of $1/watt to $0.20/watt (Conibeer, 2007).

Figure 4-10 Efficiency and Cost Projections for I, II and III Generation

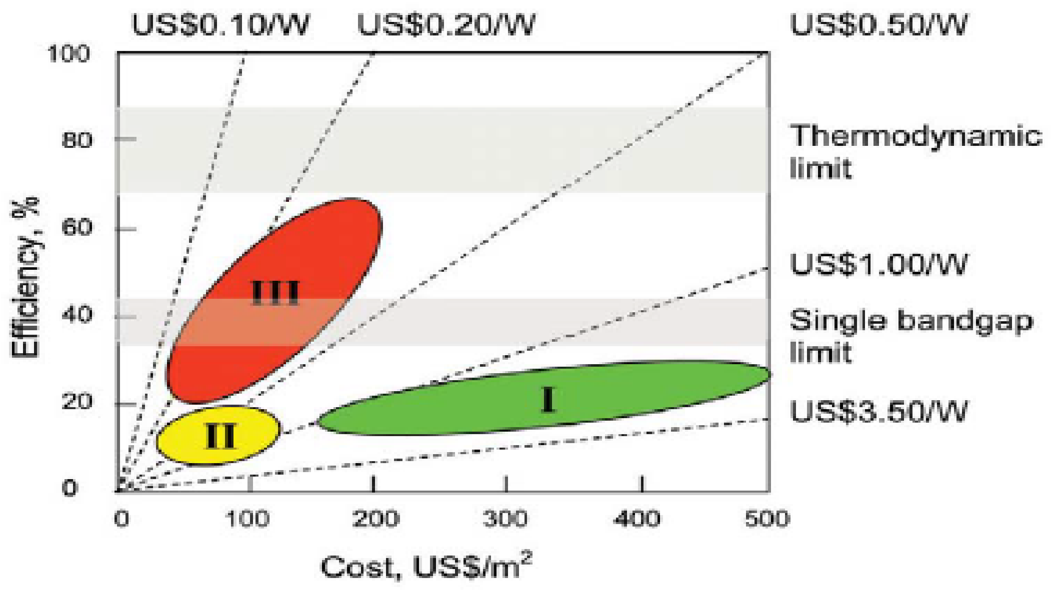


Fig. 1 Efficiency and cost projections for first- (I), second- (II), and third-generation (III) PV technologies (wafer-based, thin films, and advanced thin films, respectively).

Source: Conibeer, 2007

Among the third generation technologies, Organic Photovoltaic (**OPV)** is still in its research phase and faces challenges due to higher module efficiencies (>15%) and lifetime (>30 years) of the existing silicon technologies, but offers advantages such as its light weight, flexibility and lower production costs. According to Nanomarkets report, Materials, Applications and Opportunities in Organic Photovoltaics (2011), OPV will find applications in niche markets and faces challenges from incumbent technologies and also from dye sensitised solar cell (DSSC). These views are also shared by analyst firm Lux Research who predicts the market growth to be $159 million by 2020 whereby $64 million would be used for defence-related applications. "Commercial deployments of organic photovoltaic (OPV) modules will fail to live up to their hype, and remain a niche technology until 2020 at the earliest."[11] The recent shakeout within OPV such as the case of Konarka, considered to be an iconic firm in the sector, has raised further doubts in the minds of investors about the future of the technology and has impacted the leadership position of the US. Konarka was founded by Nobel Laureate Alan G. Heeger and spun out in 2001 from University of Massachusetts, Lowell. It held most of the IP for OPV and around $200 million (€159 million) was invested in the company. Other strategic investments within OPV include those made by Heliatek GmbH (founded in 2006 by the Technical University of Dresden and the University of Ulm), who have spent $19 million (€14 million) in their production facilities at Dresden.

OPV offers unique selling propositions such as transparency, flexibility and conformability and is suited for applications such as: (1) Transport: automotive (2) BIPV: glass/metal facades (3) Fast deployable apps: light structures as shelters, sun shades, greenhouses.

The **dye sensitised solar cell (DSSC)** was invented by Professor Graetzel in 1991 at École Polytechnique Fédérale de Lausanne (EPFL) in Switzerland. DSSC offers improved performance under low light conditions and thus is most suited for indoor, energy-harvesting applications. Building-integrated photovoltaic (BIPV) is another potential area where DSSC can offer advantages such as diverse colours, shape and transparency. Nanomarkets (2014)[12] expects that by 2019, BIPV will account for 67% of revenues. Most of the firms involved in DSSC, like OPV, are small firms; the prominent players include G24i (UK), Oxford Photovoltaics and Dyesol (Australia).

[11] http://optics.org/news/2/4/24
[12] http://www.prweb.com/releases/2014/02/prweb11598846.htm

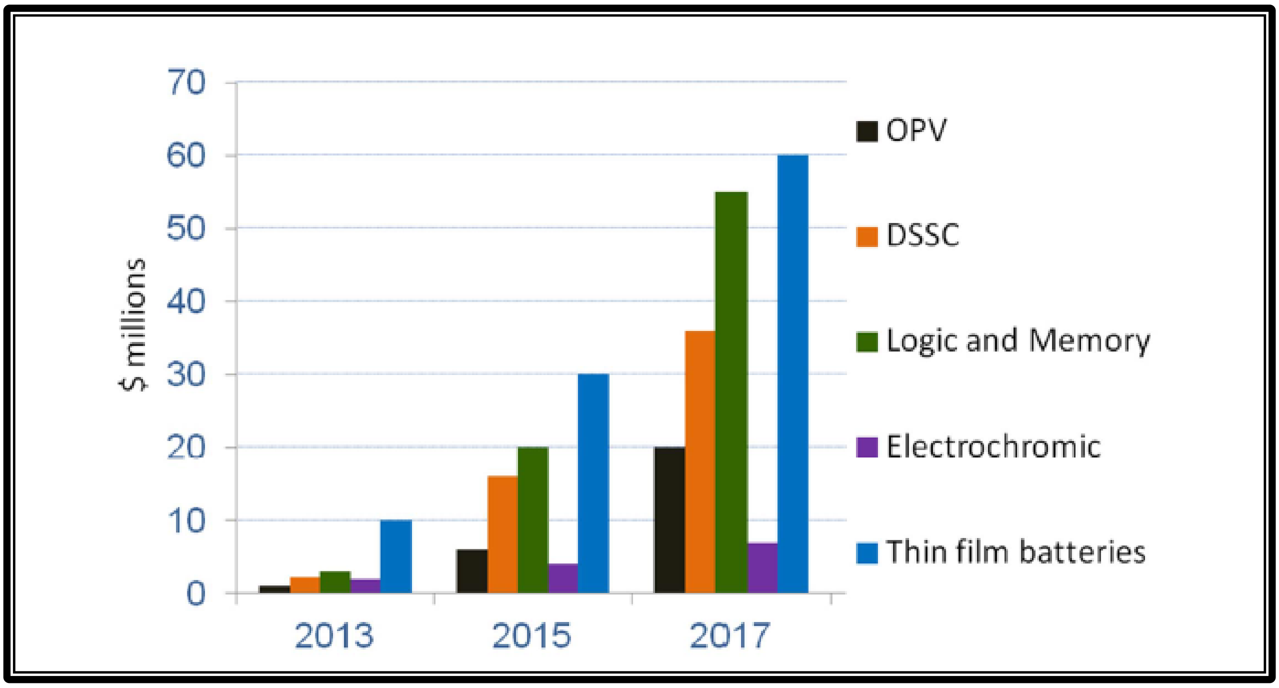
Regardless of the dynamics witnessed within the PV industry (e.g. subsidy-supported production in China that resulted in oversupply of PV modules and pricing pressures for US and European manufacturers), there has been a recent surge in investments and interest in third generation photovoltaic especially in DSSC (for overview see Table 4.3). According to the report by National Science Foundation, “The price of a silicon panel fell from $3.40 per watt in 2008 to $1.28 per watt by the end of 2011, and as of mid-2013 it was reportedly heading toward 50 cents” (Siegel and Shivakumar, 2014, p.83).

Table 4-3 OPV and DSSC Progress

Year	Projects and Milestones
2006-2007	Dyesol and Corus (bought by Tata Steel Europe in 2009) initiated a feasibility study that resulted in a joint collaboration and opening of a PV accelerator facility in Shotton, Wales in 2008. The aim of the project was to develop, manufacture and market a metal roof with dye sensitised cell functionality. The £11 million project received a grant of £5 million from the Welsh government.
2010	Konica Minolta and Konarka signed a comprehensive R&D agreement and strategic investment agreement whereby Konica Minolta invested $20 million.
2010	Cambridge start-up Eight19 received $7.4 million investment from Carbon Trust and French company Rhodia.
2010	EPSRC (Engineering and Physical Science Research Council) awarded £9.5 million to an academic and industrial consortium led by Swansea University named SPECIFIC. In addition to Swansea it includes Imperial College, and Bangor, Cardiff, Glyndwr, Bath and Sheffield universities. Tata Steel, BASF and NSG Pilkington are among the industrial partners. It is aimed at developing functional coated steel and glass products to be used in existing and new buildings.
2010-2013	HIFLEX project received €3.7 million investment under the EU 7^{th} Framework Programme and was aimed at development of an indium-free OPV module for R2R processing.
2011-2016	SUNFLOWER (Sustainable Novel Flexible Organic Watts Efficiently Reliable) project received €10.1 million funding under the European 7^{th} Framework Programme.
2011-2014	X-10D project aimed to increase the power conversion efficiency to achieve at least 12% on cell level, 1cm², and 9% on module level, 100 cm². The project was led by IMEC and received €8.6 million under the EU 7^{th} Framework Programme.
2011	The Dutch province of Noord-Brabant contributed €38 million to create a new shared laboratory in Eindhoven with state-of-the-art equipment for Solliance, an OPV shared research programme. Solliance is an initiative of IMEC, ECN, Holst Centre and Eindhoven University of Technology (Eindhoven-Leuven-Aachen triangle). Its three main themes are thin film Si, copper indium gallium selenide (CIGS) and organic PV (OPV).
2012	Heliatek initiated a €14 million roll-to-roll OPV production plant.

Source: Author

Figure 4-11 OPV and DSSC Forecasts[13]



Source: IDTechEx, 2013

4.5.4 Electronics and Components

Electronics and Components are the toolkit or building block for future printed electronics products and include printed memory, batteries, active devices such as transistors and passive components such as antennae and resistors. According to the IDTechEx report "Printed, Organic & Flexible Electronics Forecasts, Players & Opportunities 2011-2021", the market for thin film logic in 2011 was only $2 million that mainly consisted of prototypes and demonstration samples. Many players (around 500) were involved in developing memory and logic but there were no commercial successes. Printed memories combined with logic circuits is another growth area for OPE as has been evident with the first commercial orders secured by Thin Film Electronics (a manufacturer of printed non-volatile rewritable memory, NVRAM) for luxury goods anti-counterfeiting. Printed memories are used for applications that require storing of information. Printed polymer memories coupled with printed sensors, batteries, display and printed transistors to drive the logic are finding application in smart

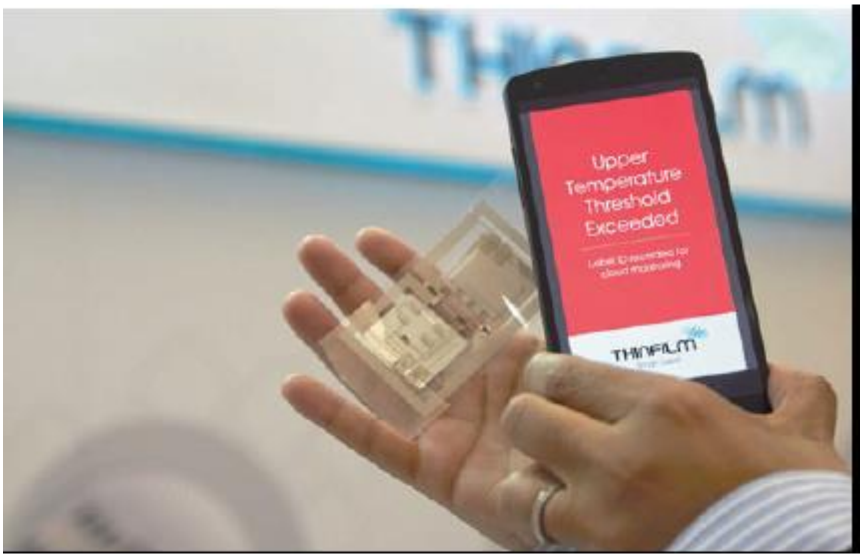
[13] Presentation given by Raghu Das of IDTechEx on January 22, 2013 at the Organic Electronics Material Event organised by Materials Chemistry Group SCI at Brunel University, UK. Author participated in the conference.

integrated circuits enabling diffusion in horizontal markets such as packaging, logistics and security applications.

4.5.5 Integrated Smart Systems (ISS)

ISS bring together core functionalities such as input devices (sensors), power (batteries) and output devices (display) along with memory and logic to form integrated printed electronics circuits for a variety of applications such as smart packaging, temperature sensing for medicines, wearables, automotive and healthcare and perishable products. An example of integrated system product was recently demonstrated by Thin Film Electronics (see Figure 4.12). The product enables temperature-sensing combining printed electronics technology and NFC[14] functionality.

Figure 4-12 Printed Temperature Label



Source: OE-A, 2015

[14] Near field Communication

4.6 Funding, Government Initiatives and Support

Breakthrough technologies offer new opportunities and are a source of economic growth. The benefits offered by OPE have been the driver of increased financial support from government, venture capital, consortia and other organisations like National Science Foundation, Department of Energy, Defense Advanced Research Projects Agency (DARPA), and New Energy and Industrial Technology Development Organization (NEDO) in Japan, for the development of this emerging technology that faces a long gestation period and heightened competition from existing technologies. The regional and national support takes various forms, such as grants for collaborative research and development programmes, technical support via fostering clusters and pilot production centres or knowledge transfer initiatives to enhance university-industry participation. An accurate compilation of allocated funds around the world is very difficult to obtain; however, using a variety of secondary data it is possible to build an estimation of the amount invested in the technology by various stakeholders.

According to the Lux Research report "Printing for Profits: Investments and Opportunities in Printed, Flexible, and Organic Electronics" around €5.6 billion was invested by venture capitalists into flexible, printed organic electronics during the period 2006-2012.[15] Display and smart packaging received the largest share of the funding, accounting for 37% and 23% respectively. The venture-based model is not entirely suited to OPE, due to the longer time that has been required for commercialising the technology. Large chemical companies recognising the opportunity have developed corporate venture capital (CVC) arms to monitor the progress within the field. Dow Chemicals, Intel and Samsung are among the corporate venture capital trendsetters for this technology. In addition, BASF and Solvay have also developed CVC initiatives. BASF has invested in Heliatek and, formerly, Polyera while Solvay initially invested in Plextronics and Polyera.

A large number of R&D projects amounting to more than €100 million have been financed under the EU 6th Framework Programme (FP6, 2002-2006) and 51 projects amounting to more than €220 million have been funded under the 7th (research) Framework Programme (FP7, 2007-2013) with the aim of building European leadership in the industry and preventing the drain of resources towards Asia. Additionally, many national governments

[15] Printed Electronics Magazine 5(5), 2013.

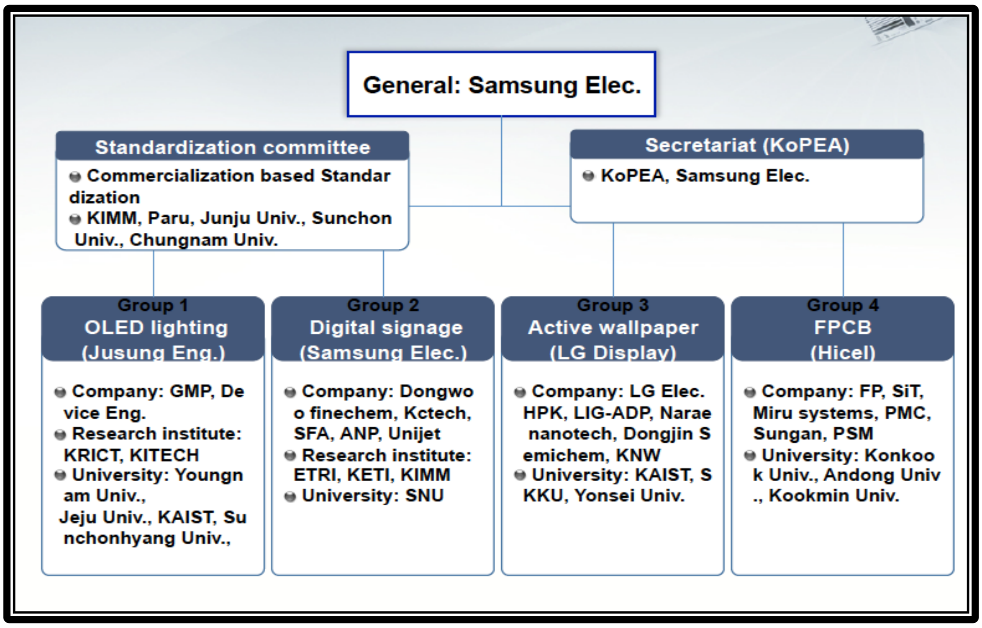
provide financial support for collaborative research and development through the provision of grants, often in a competitive process. The Canadian Government announced the funding of around $40 million for development of Organic and Printed Electronics in 2013[16]. Table 4.4 indicates that the US Army has been investing within the field since 1990. $100 million was invested for Display Technology Centre at Arizona State University. Around $56 million was invested by the State of Ohio under its own programme named NorTech.

In South East Asia, however, investments started later but more aggressively. Flexible electronics became the main focus in Taiwan in 2006 and during the five-year period from 2006-2011 around $200 million was invested by the government as reported by the National Academy of Science's 2013 study. South Korea is at the forefront in the field of OPE as has been witnessed over the years by the success of Samsung and LG. In 2012, the Ministry of Trade, Industry and Energy (MOTIE) announced a six-year (2012-2018) flagship project named Printed Electronics Total Solution Development Project. The multiparty project was led by Samsung (see details in Figure 4.13) and included 47 other organisations (universities, research institutes and companies). A total of US$50 million was allocated to the project aimed at achieving commercialisation for printed electronics. These schemes can be ideal for progressing the development of a system in which several companies provide technology elements. The project is expected to bring €52 billion in sales, €17 billion of investment in equipment and would generate 64,000 new jobs by 2025.[17]

[16] http://www.plusplasticelectronics.com/retailpackaging/canadian-government-announces-new-printed-electronics-program-91193.aspx

[17] http://www.rvo.nl/sites/default/files/Zuid-Korea%20-%20Printed%20electronics.pdf

Figure 4-13 Printed Electronics Total Development Solution Consortium



Source: Innovate UK, 2012[18]

Frequent events and conferences are organised at national and international level by consultants like IDTechEx, IntertechPira and Plastic Electronics Foundation, with the aim of bringing the players onto a common platform and promoting collaboration, building the supply chain, creating awareness and generating required pull. Roadmapping and standard development initiatives are pursued by associations, prominent ones being the Organic Electronics Association (OE-A), Photonics 21, IPC's Printed Electronics Management Council Steering Committee, Printed Electronics Arena (PEA), FlexTech Alliance, Korean Printed Electronics Association (KoPEA), Japan Advanced Printed Electronics Technology Research Association (JAPERA), and International Electronics Manufacturing Initiative (iNEMI) (Frost and Sullivan, 2011).

Table 4.4 indicates the level of funding within the area of OPE. However, the figures below are not the true picture of the investments that have gone into this area. One of the reasons highlighted in the 2014 reports on "Flexible Electronics Opportunity" by National Science Foundation, is that "funding data for flexible electronics is commonly not segregated and is widely dispersed under headings such as "nanotechnology," "new materials," "high technology equipment," and "green energy." " Another reason is the partial availability of data, for example in the case of Korea.

[18] https://connect.innovateuk.org/

Table 4-4 Funding Around the World

Government Initiatives	Period	Funding (US $) Million
United States		
Army Partners with Arizona State University	2004-2014	100
Ohio NorTech	2003-2010	56
NSF-BioFlex	2012	20
Europe		
EU 6th Framework Programme	2002-2006	Approx. 113.6
EU 7th Framework Programme	2007-2013	250
UK EPSRC (Engineering and Physical Research Council)	2009	105
UK Technology Strategy Board	2005-2010	122.51
UK Technology Strategy Board (Manufacturing Electronics Systems of the Future)	2014	7.31 (£4.75 million)
Germany (BMBF)	Through 2011	264.00
Holst Centre Netherlands[19]	2013-2016	81.43
Asia		
Taiwan	2006-2011	200
Japan (NEDO) New Energy and Industrial Technology Development Organization	2008-2012	274
Korea Printed Electronics Total Solution Development Project	2012	50

Source: National Academies Press (2014), The Flexible Electronics Opportunity, Author's Interviews, Innovate UK Website

[19] http://www.holstcentre.com/en/NewsPress/NewsList/Funding2013.aspx

4.7 Standards

As the field of OPE is gaining momentum with increasing trends towards product development and scaling up of manufacturing, the stakeholders have stressed the importance of developing standards. Both public and private standard developing organisations are actively engaged in this process as shown in Figure 4.14 and Table 4.5. These include International Electrotechnical Commission (IEC), International Microelectronics and Packaging Society (IMAPS), Specialty Graphic Imaging Association (SGIA), Printing Industries of America (PIA), The Association for Suppliers of Printing, Publishing and Converting Technologies (NPES), and Institute of Electrical and Electronics Engineers (IEEE).

Initial activity towards defining common standards started in 2004 and was established within the Institute of Electrical and Electronics Engineering (IEEE), which resulted in the development of IEEE 1620™ and IEEE 1620.1™ standards. The main participants were Motorola, Kodak, University of Michigan and Plastic Logic. IPC (Association Connecting Electronics Industries) realised the OPE opportunity in 2008 and in 2010 an exploratory working group was formed to facilitate the growth of the OPE industry and become the "repository for Printed Electronics Intellectual Assets: roadmaps, standards, guidelines, and best-practices" (Gamota, 2013).

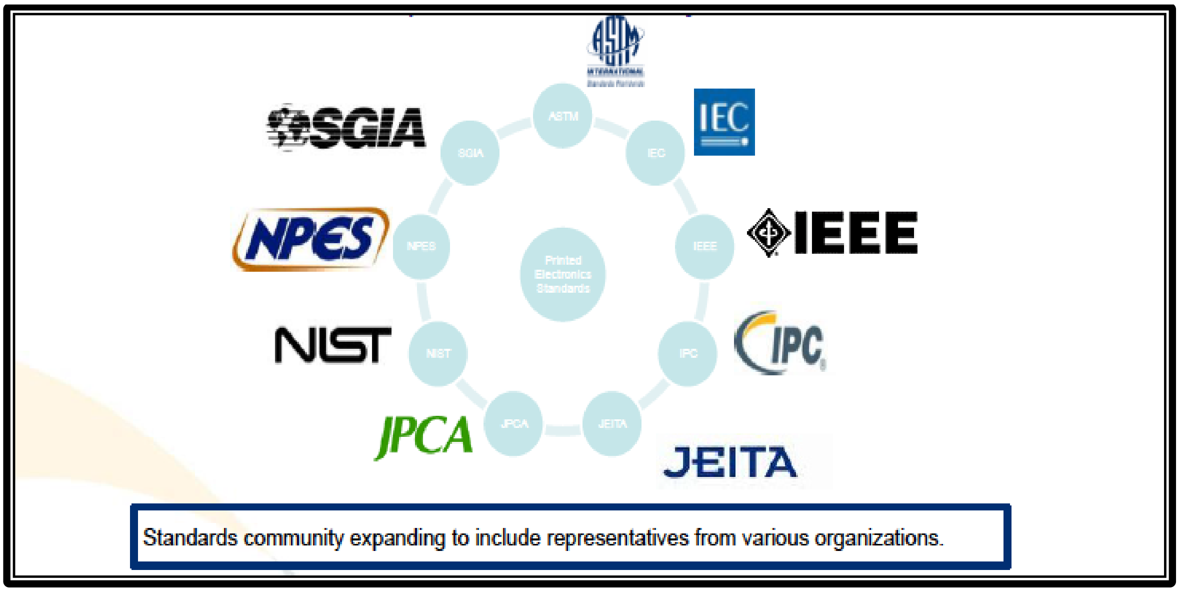
> Historically, the adoption of standards has shown that it facilitates the growth of an emerging field and reduces the burden placed on individual companies to invest significant resources in the development of company specific compliance documentation. (Gamota, 2013)[20]

In 2011 IEC (International Electrotechnical Commission) launched the technical committee TC119 initiative to address standardisation within the space of printed electronics. South Korea was the original promoter of this initiative. IEC TC 119 now has 70 participants from 13 participating countries and 8 observer countries. It also collaborates with other standard setting committees such as IPC and IEEE. The scope of this activity is to standardise terminology, materials, processes, equipment, printed products, and quality assurance which are related to the printing technology for manufacturing electronic and electrical devices. The

[20] http://www.magazines007.com/pdf/PCB-Aug2013.pdf

activities as shown in Figure 4.15 are divided into five working groups that include Terminology, Materials, Equipment, Printability and Quality assessment. In addition to that there are two ad hoc groups Printed Products and Roadmapping. As evident from Figure 4.15, working of IEC TC 119 is strongly dominated by Asian countries. The technical committee TC 119 is presently working on 10 standardised projects out of which Asian experts proposed 8. The first standards from this committee are projected to be published by the end of 2016.

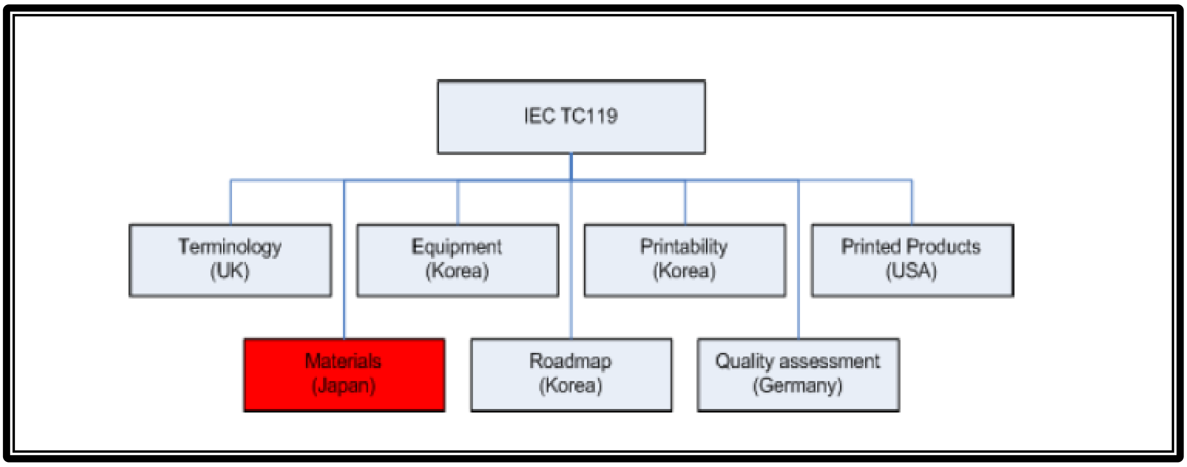
Figure 4-14 Printed Electronics Standard Development Community[21]



Source: IPC, 2014

[21]http://www.gaa.org/sites/default/files/PDF/proceedingsCS/PrintedElec/2014/PESymp2014Proceedings_Carter.pdf

Figure 4-15 Proposed IEC TC 119 Work Packages



Source: IPC, 2014

Table 4-5 Standardisation Efforts

Standards Development Organization	Effort Description and Update
ASTM International	Portfolio of standards for printed membrane switches published: materials, design, processing, and performance. (Standards groups continue to identify topics.)
International Electrotechnical Commission (IEC)	New Technical Committee for Printed Electronics established: IEC TC 119 (New Projects for standards development are being identified and ad-hoc working groups are being established and populated.)
IEEE	IEEE 1620-2008[5] *Standard for Test Methods for the Characterization of Organic Transistors and Materials* (Published in 2004; modified in 2008)
	IEEE 1620.1-2006[6] *Standard for Test Methods for the Characterization of Organic Transistor-Based Ring Oscillators* (Published in 2006, the IEEE mandated five-year review was completed in 2011.)
IPC	D-60 IPC Printed Electronics Standards Committee
	Subcommittee D-61 IPC/JPCA-2291[7] *Design Guidelines for Printed Electronics* (Approved by ballot on May 16 2013. To be published in July 2013.)
	Subcommittee D-62 IPC/JPCA-4921[8] *Requirements for Printed Electronics Based Materials* (Published in July 2012; updates for inclusion in Revision A are being captured.)
	Subcommittee D-63 IPC/JPCA-4591[9] *Requirements for Printed Electronics Functional Materials* (Published in December 2012; updates for inclusion in Revision A are being captured.)
	D-64 Subcommittee IPC/JPCA-6901[10] *Performance Requirements for Printed Electronics Assemblies* (In Draft.)
	D-65 Subcommittee *Test Method Development and Validation* (In formation.)
	D-66 Process Subcommittee (New)
JPCA[11]	Strategic alliance with IPC established to co-develop portfolio of printed electronics standards.

Source: Gamota, 2013

4.8 Conclusions

This chapter presented the background for selecting this breakthrough technology. Organic and Printed Electronics is considered to be a paradigm shift from conventional silicon-based products. It offers various operational and manufacturing advantages such as low cost, flexibility and additive manufacturing techniques. Owing to the advantages offered the technology has the potential to be disruptive but the development and progress have been slower than was expected. A lot of hype was created around this new technology, resulting in elevated expectations and number of entrants in the field. A considerable amount of public money has been invested on the basis of these expectations and the potential of OPE to address sustainability challenges; this has resulted in some progress, but the killer application is still unidentified. There have been attempts to build product ecosystems by start-up and spin-off companies like Plastic Logic (UK) for their e-reader, Konarka (USA) for solar panels and Polymer Vision (Netherlands) for flexible displays, alongside corporate giants like Samsung and LG for OLED displays and Philips and Osram for OLED lighting. From the account of the characteristics of OPE provided in the present chapter it is clear that there have been more shakeouts than successes and penetration is limited to selected domains. OPE is on the monitoring radar of a large number of upstream material companies that are investing money in this domain. Furthermore, the printing technologies proposition is not limited to competing with silicon technologies, but also aims to find complementarities and functionalities not possible with silicon.

Further details of the dynamics of this technology will be provided in the more analytical Chapter 5, whilst in-depth cases of companies playing a central role in the development of OPE will be presented and discussed in Chapters 6 and 7. The role of intermediaries such as research institutes and industry associations (e.g. OE-A) will be elaborated in Chapter 8.

Chapter 5: Dynamics and Emergence of Organic and Printed Electronics

5.1 Introduction

Chapter 4 introduced the context of Organic and Printed Electronics (OPE) and elaborated on the envisioned application domains such as OLED lighting, flexible displays, third generation photovoltaic, components and integrated smart systems for this pervasive technology. OPE is considered to be one of the key enabling technologies with a high economic potential and broader societal implications. These visions have been shaping political intervention, coordinated actions and emergence of hybrid forums and techno-economic networks. At present there are approximately 3000 organisations active in the field within three competing regions (USA, Europe, Asia); this includes universities, research institutes, and large organisations as well as start-ups (IDTechEx, 2011; Frost and Sullivan, 2010). According to the leading market experts IDTechEx (2011), "in all areas it is the electronics and chemical plastics industries that are doing most of the development, with strong support from the printing industry." The chapter will discuss the progressive emergence of the ecosystem in the two most active countries within the European region—UK and Germany. In the UK, competencies required for development of the embryonic value chain are spread across the entire region with a strong ecosystem in Cambridge. Within Germany there are two main clusters of OPE: Innovation Lab in in the Rhine-Neckar metropolitan region and Organic Electronics Saxony in Dresden. Furthermore, the chapter will briefly highlight the challenges faced at the current ferment phase and the discourses that proliferate the space of OPE.

5.2 Stylised Facts

The progress and development within Organic and Printed Electronics can be compared to the other "science-based businesses" such as biotechnology and nanotechnology, which are characterised by a long period of risky investments, uncertainty, and where entrepreneurial ventures and start-ups are involved in scientific discoveries owing to higher technical challenges. Pisano (2010, p.471) defined science-based businesses as "entities that both participate in the creation and advancement of science and attempt to capture financial returns from this participation. They are not simply "users" of science, but contributors to it as well." Breakthrough technologies require an integration and recombination of existing and new technologies that is more complex and challenging compared to the modularity often found in the context of more mature industries.

"Science-based businesses emerge at the intersection of multiple bodies of science", are confronted with challenges about risk, integration and learning, and their anatomy differs from other high tech sectors like software and semiconductors (Pisano, 2006, 2010). Typical of the early stage of emerging technologies and also relevant in the context of printed electronics, is the initial hype, large shakeouts, and SMEs and start-ups facing difficulties when it comes to securing seed capital due to the high uncertainties associated with commercial applications.

> While investors tend to agree with OLAE developers and entrepreneurs upon the long term market potential and the relative advantage of OLAE with respect to silicon based industries, the long and capital intensive development cycles and lack of market readiness make investors restrained. If a venture capital company is planning to exit an investment within 5-7 years, then at least in most cases they will expect the application market to be already there at the time of investment. (Kettunen et al., 2011, p.34)

"The combination of lack of articulated demand (with end users, but also with business customers) and lack of articulated directions for product development creates a situation where actors are reluctant to invest" (Parandian et al., 2012, p.573) and results in waiting games.

The advancement of material and other related technologies indicates a greater technology push than market pull (King, 2009; Kettunen et al., 2011). The uncertainty is not only around technology developments but also around its usefulness, the killer application and complementary inventions:

> New technologies are unrealized potentials—building blocks whose eventual impact will depend on what is designed and constructed with them. The shape they ultimately take will be determined by our ability to visualize how they might be applied in new contexts… Often, however, there is no way of knowing which new discoveries may turn out be relevant or to what realm of human activity they may eventually apply. (Rosenberg, 1995, pp.181-184)

In this era of ferment and uncertainty, competition exists not only between incumbents and new technology regimes for a particular application (e.g., OLED versus LCD in the TV market, and OLED versus fluorescent and LED in lighting), but also within new and emerging regimes such as for OLED where competition exists between small molecules and solution processable technologies. This early technology development phase is marked by umbrella promises (Parandian et al., 2012), hype cycles, shakeouts, uncertainty regarding the dominant design and critical performance characteristics (Anderson and Tushman, 1990; Tushman and Rosenkopf, 1992).

> Some questions remain open… We have not yet been able to define Moore's law for organic electronics or identify a "killer application" for the long term. Organic Electronics is still a very young field and there are still many different parameters that are important for further success of organic electronics; it is not clear which of these might have the most important role or how they will scale. (OE-A, 2011, p.23)

> Except for the areas of OLED display, there also are not yet enough products that can meet this demand and that can be commercialised in the foreseeable future. Products in the other areas of application are, according to expert statements, still in the demonstration stage and not yet mature for serial production. Companies rightly fear that market introduction performed too early would lead to warranty claims and disappointment among the users. (Acatech, 2011, p.48)

The dynamics within OPE technology can neither be explained using sequence of events nor are a result of blind variation or exogenous shocks but appear to be chaotic, with interest initially sparked as a result of scientific discoveries resulting from research within world class universities such as the Cavendish Lab (Cambridge, UK). The scientific advances, and the establishment of a number of new technology-based firms and spin-offs, have created a momentum around technological opportunities resulting in hype cycles and attracting investments from public and private sources. However, moving from research to market for the initially low performing technology like OPE may take decades, a process also referred to as "Valley of Death" (Raven and Geels, 2010) and which necessitates the creation of protected space for "hopeful monstrosities" (Mokyr, 1990, p.291).

To explore the evolution of printed electronics we have to look at it from a global perspective. "Most of the high technology industries increasingly emerges from a convergence of local and global factors" (Murtha et al., 2001, p.29). It is not limited only to invention in universities and knowledge development and accumulation within companies, nor can its richness be captured fully by looking at formation of hotspots in geographical proximity. It is also about “individuals working together and in solitude to create that knowledge” (Murtha et al., 2001, p.35). Much of the knowledge is tacit and embedded within individuals and their experiences, as they drive OPE. Mobility of individuals facilitates knowledge sharing, exchanges, recombination, codification and formation of networks. Thus “the circulation of knowledge equates with the circulation of researchers or engineers themselves” (Bozeman et al. 2007, p.808).

> As in Winesburg, Ohio, in the flat panel display industry almost everyone knows everyone else. There’s quite a bit of talk, but a lot of information travels from person to person despite remaining unspoken. Secrets have a way of getting out… There are heroes, saints, and rebels but also jealousies, victims and disappointments.” (Murtha et al., 2001, p.44)

Owing to the interactive nature of technology development, the emergence of the OPE ecosystem is shaped by a range of new “hybrid forums” and institutional arrangements as will be elaborated in the context of the UK (Callon et al., 2002). Hybrid forums are “a type of quasi-public spaces—spaces defined by a contingent and fluctuating membership but also spaces with a regulated structure and rules that condition the relations between actors” (Kearnes, 2013, p.459).

Competition within a knowledge-based industry is about accumulation of knowledge, learning and speed. The analysis of developments and unfolding of events within this emerging field resonates with that of Murtha et al. (2001, p.31) within the flat panel display industry that “new high-technology industries often bubble under the surface for many years in several countries before they suddenly achieve critical mass and commercialize at global scale in one or more of them.”

The following sections will outline the discourses and challenges that proliferate in the space of Organic and Printed Electronics.

5.3 Is Printed or Organic Electronics Disruptive?

The producers of OPE mostly associate the low performance of OPE to its disruption potential; but according to Sheats (2004) OPE does not pass the litmus test of disruption of low initial performance and a low-cost proposition for early envisioned application of RFID (radio frequency identification tag) and display backplanes. Furthermore, he asserted, “The alleged failings of silicon are to a large extent simply not real: it is neither high cost, nor incompatible with large areas or temperature-sensitive materials" (Sheats, 2004, p.1985). These discourses have been identified during the interviews as well and are presented below. It is evident from these excerpts that as the space evolves, these debates are still active and provide evidence of the socio-cognitive shaping of the technology. The debate around what players think is disruption is articulated in defining what are the possibilities for working with printed electronics, who will be the ultimate winners and what would be the position of the firms in the developing supply chain. According to Hilgartner and Lewenstein (2004) the notion of emerging technologies "conveys an unmistakable connotations of revolutionary potential."

> So, actually printed emissive display really has no USP compared to embedded technology so everyone said that Printed Electronics was disruptive. Actually, it wasn't disruptive! It was just a me too technology […] Look at displays 14-15 years on, it is all LCD with a quality, vibrancy, high definition, 500 Hz refresh rate, so its 3D, ultra-thin film, it is doing all the things that you thought only OLED could do, you can do with TFTs now. […] The only thing printed electronics is disruptive on, is if you can make it flexible. If you are printing it on just glass with rigid form factor totally, not disruptive in my view. (Respondent SYO)

> I tend to regard a disruptive technology as something that would come up that had never been thought of before and completely transforms the situation and creates new incumbents and new industrial players. I think ultimately printed electronics will offer a vast amount of new capability […] But ultimately the people who will be providing those will be the same people who are currently providing. The chemical companies providing organics won't suddenly stride the globe as a colossus of the industry. It will still be Samsung, Philips, etc.

> It's just the next generation, to me […] perhaps partly because some of the ideas within it have already been so discounted. And at the end of the day we talk about […] the sort of electronic paper or map you can buy maybe and crumple it up, carry it around in your shirt pocket and read the Internet. I think that will come. But I don't think the man in the street will find it all that surprising, because in a way they already have been prepared to expect that. (Respondent EES)

5.4 Lofty Expectations and Initial Hype

The earlier theme prevalent in academic papers and among industry participants is the low-cost promise of OPE compared to silicon and its earlier vision that everything can be printed using manufacturing methods such as inkjet printing (Sheats, 2004). This vision resulted in elevating false expectations for the emerging technology. In reality, the fabrication methods and tools that worked well in the laboratory environment faced tremendous challenges and became expensive when moved to mass scale production.

According to Fortun (2001, p.146), “Just as there can be no truth without fiction, just as every operation of language is essentially promissory and thus ‘unfounded’ in the classical sense, there can be no science without speculation, there can be no economy without hype, there can be no ‘now’ without a contingent, promised, spectral and speculated future.”

At that time the discussion was around the limitations of silicon and how new technology such as plastics would be complementary to the existing technology. These trends were a matter of discussion in both specialised and generalised media.

> Existing silicon-based technology likely will reach the limits of our ability to build smaller and faster chips in 10 to 20 years, warn scientists and industry analysts. Potential limitations of silicon chips include heat dissipation, power consumption and signal noise from current bleeding through the ultrathin insulation layers of transistors. (Lawton, 2002)

The big names like Lucent and IBM were talking about the disruptive potential of this new technology. According to John Rogers, director of nanotechnology research at Lucent Technologies Inc.'s Bell Labs:

> Plastic circuits could revolutionize big segments of consumer devices. It's conceivable that we could see bumper stickers that change messages or cereal boxes that connect to the Internet and provide personalized content based on the breakfast-eater's preference. (Lawton, 2002)

“Between 2002 and 2006 it began to gain interest because very large companies were working on it. We had people like HP, Canon, Epson, Dai Nippon Printing, Xerox and many others involved. So this is not a frivolous sector any more,” commented Raghu Das of IDTechEx in an interview with the author.

The initial focus was on RFID and OLED displays. Past success of LCD technology was the driver for the involvement of large chemical companies like Merck, DuPont, Bayer, Dow Chemicals and Sumitomo. The expectation was that OLED displays would be the next wave after LCD. In addition to the chemical companies other prominent players within the field were Philips, Siemens, Xerox, Motorola and GE. A large number of start-ups also emerged to pursue new opportunities offered by OPE, notably Plastic Logic, which spun out of Cavendish in 2000 and opted for an e-reader application. PolyIC is another interesting start-up that was formed in 2003 in Nuremberg, Germany as a result of a joint venture between Siemens (electronics) and Kurz (printing company). They initially pursued the approach of item level RFID tagging for logistics control and the ultimate aim was to dispense with the need for check-out people in a supermarket. The shopping basket would be fitted with an RFID reader, the cost would be provided once groceries were put in the basket, and the shopper would be charged with some sort of smart card technology.

> From the all-over market I can state that there was a big hype phase for RFID where big projects were there to say RFID will be… whatever business. And, of course, Siemens thought… and there were even projects and units to say, "Ah, OK, we have a standard RFID business and the future RFID business will be then from PolyIC." That was their interest, their main interest. (Respondent WMP)

RFID has not been a success story due to technical difficulties. Philips initially pursued the application but based on its experience with silicon RFID soon realised that the ORFID (organic RFID) would not be able to compete on cost with its silicon counterpart. Siemens soon lost interest in PolyIC and now it is 100% owned by Leonhard Kurz Stiftung & Co. KG. One of the technology consultants interviewed, while discussing RFID's initial hype, commented on PolyIC technology:

> PolyIC have done a good job developing a roll-to-roll technology. They also have roll-to-roll analysis of RFID tags they are making. They have got very nice printing approach. They have automated testing. They have done a good job developing the methodology. Unfortunately the price point of the tags makes it non-competitive […]
>
> In most of these emerging technologies there are many early loss leaders and companies, who unfortunately don't make any money on it. (Respondent BB)

The roll-to-roll production and the use of standard printing equipment for organic electronics is another vision propagated by the players that has contributed to much of the hype and expectations regarding low production cost, high throughput, use of exciting technologies and therefore rapid progress along the learning curve. It was estimated that a printed electronics (PE) plant would cost $30 million as compared to the $3 billion cost for a silicon fab[22]. The elevated vision gathered more momentum when companies like Motorola demonstrated that

[22] Y. Neuvo, S. Ylonen (Eds.); Bit Bang – Rays to the Future; Helsinki University Print (2009)

they were able to produce 50 kilometres of circuitry using conventional printing techniques (Chalamala and Temple, 2005).

> A second problem is the seductive vision of "printed electronics." One actually finds marketing communications seriously asserting the expectation that organic RFID tags, for example, will be printed in the same process, at the same time, as the printing of visual labels on packaging. No one familiar with both the science of organic electronic processes and materials and the graphic arts printing environment would put such a vision forward, yet just this idea is probably responsible for driving a significant portion of the R&D investment in the field. And if so many people are saying it, who wants to be left out? (Sheats, 2004, 1986)

> At Motorola Inc., in Schaumburg, Ill., senior manager Daniel Gamota and his colleagues are taking printed electronics one step further […] Gamota and his team rent time on such printers from graphics arts companies and replace the standard printing inks with an assortment of electrically functional inks, which could be conducting, semiconducting, or insulating and organic or inorganic. So far they have produced more than 50 kilometers of circuitry, mostly timing and control circuits that switch at tens of hertz. These still-experimental circuits are too slow, even for displays. But they are fast enough to make electronically active labels for consumer packaging. So, for example, a timing circuit could switch on an indicator when a product reaches its expiration date. Or a sensor could detect when a package of food has spoiled. (Chalamala and Temple, 2005, p.54)

5.5 Actors' Heterogeneity

The ecosystem of OPE is still evolving and is comprised of heterogeneous actors as shown in Figure 5.1. Apart from the traditional and upstream players like the chemical industry and substrate providers, others players are from industries as diverse as mechanical engineering, printing, packaging and consumer goods, reflecting the distributed nature of knowledge. A wide range of competencies need to be developed and integrated, such as in material development, device design and manufacturing processes, to enable functionality of the product. Some of the players are dedicated to OPE technology development while others are attracted due to the huge potential of this emerging technology in their markets.

Materials play a key role in the progress of OPE and include a variety of electrically active materials such as conductors, semiconductors, dielectrics, encapsulating, luminescent, electrochromic or electrophoretic materials. According to Marks (2010), "Materials are truly "the stuff that dreams are made of"; for hybrid flexible electronics, the accessibility, tunability, and durability of materials constrain what can be invented, fabricated, and ultimately, manufactured". The key players, in addition to the large number of established chemical companies such as BASF, Merck, Sumitomo, Solvay and Heraeus, also include other small innovative players such as CDT, Universal Display Corporation, Novaled, Plextronics, SmartKem and Polyera with a large intellectual portfolio targeting a diverse range of applications.

The use of a wide variety of surfaces or substrates is a differentiating factor for plastic electronics. The substrate can be glass, metal, paper, textiles or polyester films. The most commonly used substrates presently are glass, where there are big players such as Dow Corning, or polyester films where DuPont Teijin dominates the market.

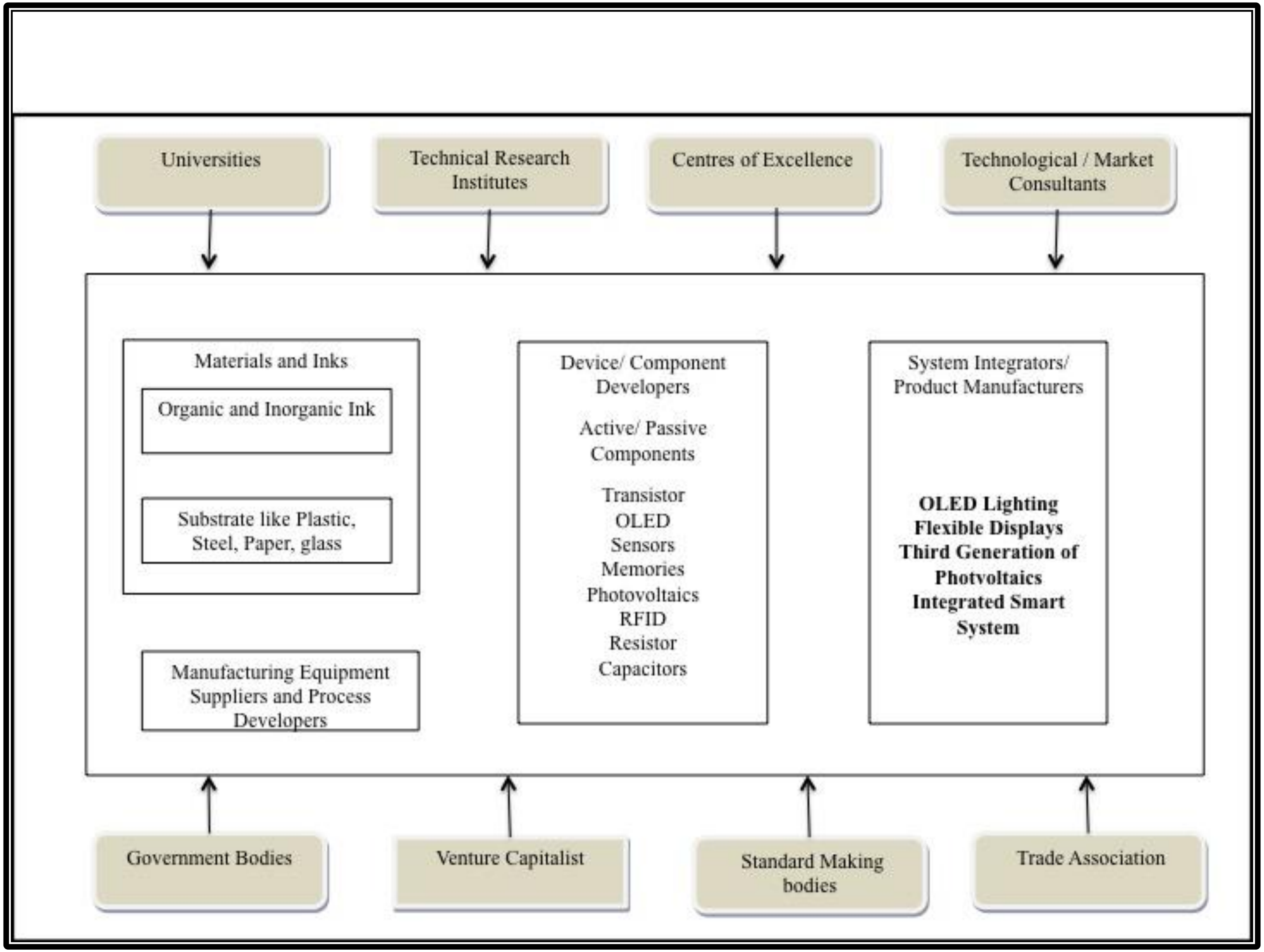
A diverse number of deposition and printing techniques can be used for processing of functional materials and manufacturing components. These include inkjet printing, screen, gravure, coating, as well vacuum deposition and lithography equipment. Experimentation, demonstration and prototyping serve as mechanisms for learning for the emerging technologies and this has also been the case with OPE. Equipment providers initially focused on providing an R&D-based tool for universities or new technology-based firms; however, with the maturation of the technology and the move from demonstration to prototypes and finally to production, there is a requirement for close coordination and iterative processes between materials suppliers, device developers and equipment providers.

According to a recent IDTechEx Webinar, Equipment for Printed, Flexible and Organic Electronics Trends, Markets, Money (2015), the value chain for printing is fragmented and there are more than 100 companies involved. The heterogeneity is not only limited to the methods employed but also extends to business models. Screen printing is commonly used while "inkjet printing for commercial electronics is still very limited – most is at R&D and prototyping level, as it provides a convenient way to make a few devices using small quantities of material" (Das, 2015).

Materials and processes are combined to produce various active and passive components and devices such as diodes, transistors, memories, and sensors. There is a large number of small companies who are producing individual components such as Enfucell, Blue Spark (providers of paper battery), Kovio (transistors) to name a few. However, to envision the disruptive potential associated with OPE, these individual components need to be integrated to address applications such as smart packaging and brand protection where ubiquity achieved with OPE opens new market applications. There are very few players who are acting as integrators and offering complete systems to the brand owners. Recently there has been progress in this direction with the strategic move of the small players, notably Thin Film Electronics and PragmatIC Printing, from product orientation to system orientation.

The network around OPE can be defined as a techno-economic network as increasingly the author witnessed a “coordinated set of heterogeneous actors—public laboratories, centres for technical research, companies, financial organisations, users and the government—who participate collectively in the conception, development, production and distribution of goods. (Callon, 1992, p.73)

Figure 5-1 Actors' Heterogeneity in Organic and Printed Electronics



Source: Author

5.6 European Landscape

Europe has very strong R&D with a large number of established academic institutions, small and established players within the OPE value chain, from materials to components, devices, equipment manufacturers and system integrators. Being a hub for prominent chemical companies like Merck, Cambridge Display Technology, Novaled, BASF and Solvay, Europe potentially benefits from the critical mass of technical competency needed to be a global leader and capture the opportunity offered by the disruptive potential of OPE, according to the Strategic Research Agenda (EC, 2009).[23] It tends to possess a strong advantage when it comes to organic materials and device design. In addition to that, the existing competencies in printing further strengthen Europe's position. However, there are application challenges, with few committed big players to create the necessary pull. Moreover, most of the manufacturing is concentrated in Asia, especially in the case of displays where backplane technology is controlled by the LCD industry (Kettunen et al., 2011).

The space for OPE within Europe is mainly driven by a large number of SMEs and start-ups alongside large firms, similar to that for biotechnology (Lemarie et al., 2000), consistent with the Schumpeter Mark I patterns of creative destruction, wherein smaller entrepreneurial firms play a dominant and defining role. However, the dominance of larger or smaller firms is technology specific and varies according to the stage of industry life cycle (Malerba and Orsenigo, 1996) and it is not unlikely that larger firms will play a stronger role at a later stage of the industry life cycle, consistent with Schumpeter Mark II activities, which are controlled by larger firms.

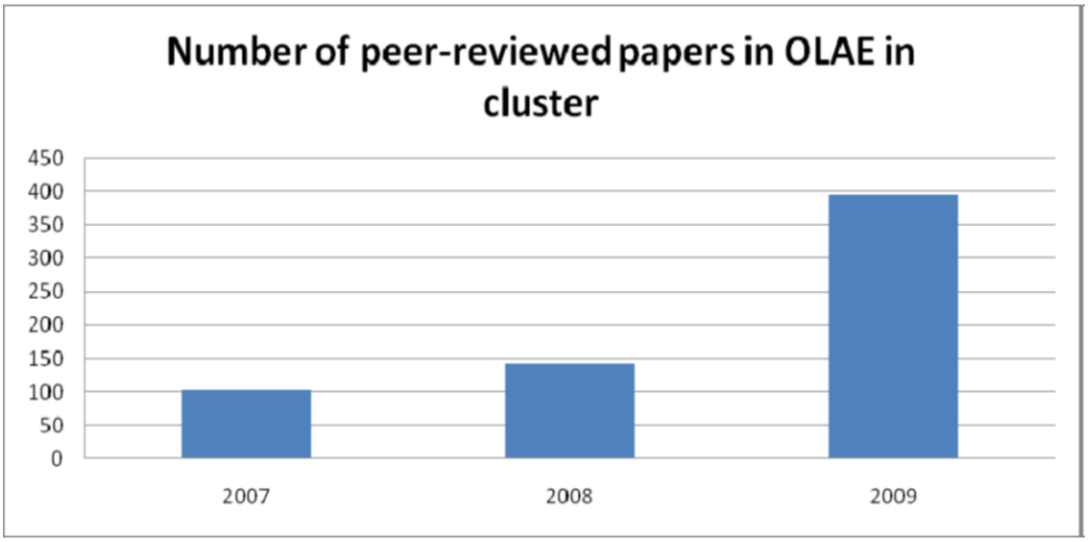
There are currently 400 organisations (SMEs, research institutes, universities) active within 17 clusters in 13 countries in Europe (Austria, Germany, France, Greece, Finland, Italy, Switzerland, Sweden, Portugal, Belgium, Netherlands, Spain, UK), with notable clusters like Organic Electronics Saxony (OES) in Dresden and

[23] The Strategic Research Agenda "Towards the Green Electronics in Europe" is the outcome of the FP7 OPERA (Organic/ Plastic Electronics Research Alliance) project and the coordinated effort of the stakeholders. Around 70 companies and research institutes from 15 European countries contributed with the basic aim to create the synergies and complementarities within the emerging European cluster, to develop a future vision and devise the strategy for successful exploitation of Organic and Printed Electronics.

Innovation Lab in Germany, Cambridge in the UK and Holst Centre in Eindhoven. Figure 5.2 provides evidence of the increased employment opportunities offered by the growing OPE industry owing to the activities within Europe. In addition to that Figure 5.3 demonstrates the rise in the number of publications and peer- reviewed papers.

Figure 5-2 Growth of Employment in OPE

Figure 5-3 Increased Publication



Source: EC, 2011

Owing to the increased opportunities offered by OPE and Europe's strong position, two stakeholder meetings were held in Brussels on 30th May 2007 and 1st October 2007 to identify specific needs of the European Community, establish priorities and improve coordination among the organic OPE hubs. This resulted in the "Quadriga Initiative" and funding of four coordinating projects—PolyNet, PolyMap, PRODI and OPERA within the 7th Framework Programme.

PolyNet is a Network of Excellence for the exploitation of organic and large area electronics and aimed at providing research cooperation. PRODI aimed at integrating European printing, coating and advanced manufacturing equipment providers with the goal of identifying the future equipment and processes requirements that would enable the vision of roll-to-roll (R2R) printing. PolyMap's objective was mapping of national and regional funding and setting up of an ERA-Net to establish transnational cooperation in OPE. It also aimed at developing roadmaps to complement the roadmapping activities of the Organic and Printed Electronics Association (OE-A). OPERA (Organic/Plastic Electronics Research Alliance) proposed to establish cooperation between academics and industry.

In 2011 COLAE (Commercialisation of Organic and Large Area Electronics) was established under FP7 based on results of the OPERA project, with the aim of accelerating the commercialisation and exploitation of organic and large area electronics, by coordinating resources among 18 research and development centres in Europe. It also established a virtual foundry for start-ups and entrepreneurs active in the field of large area electronics. While these clusters differ in their competencies and structure, they provide coordination and collaboration between academia, research institutes, companies and national and regional public authorities, and act as catalysts in the development and improvement of the technology readiness level (TRL) of organic electronics from technology demonstrators to pilot and pre-production level (EC, 2011).

The next section will discuss the emergence of OPE in the two most vibrant clusters of Europe – UK and Germany.

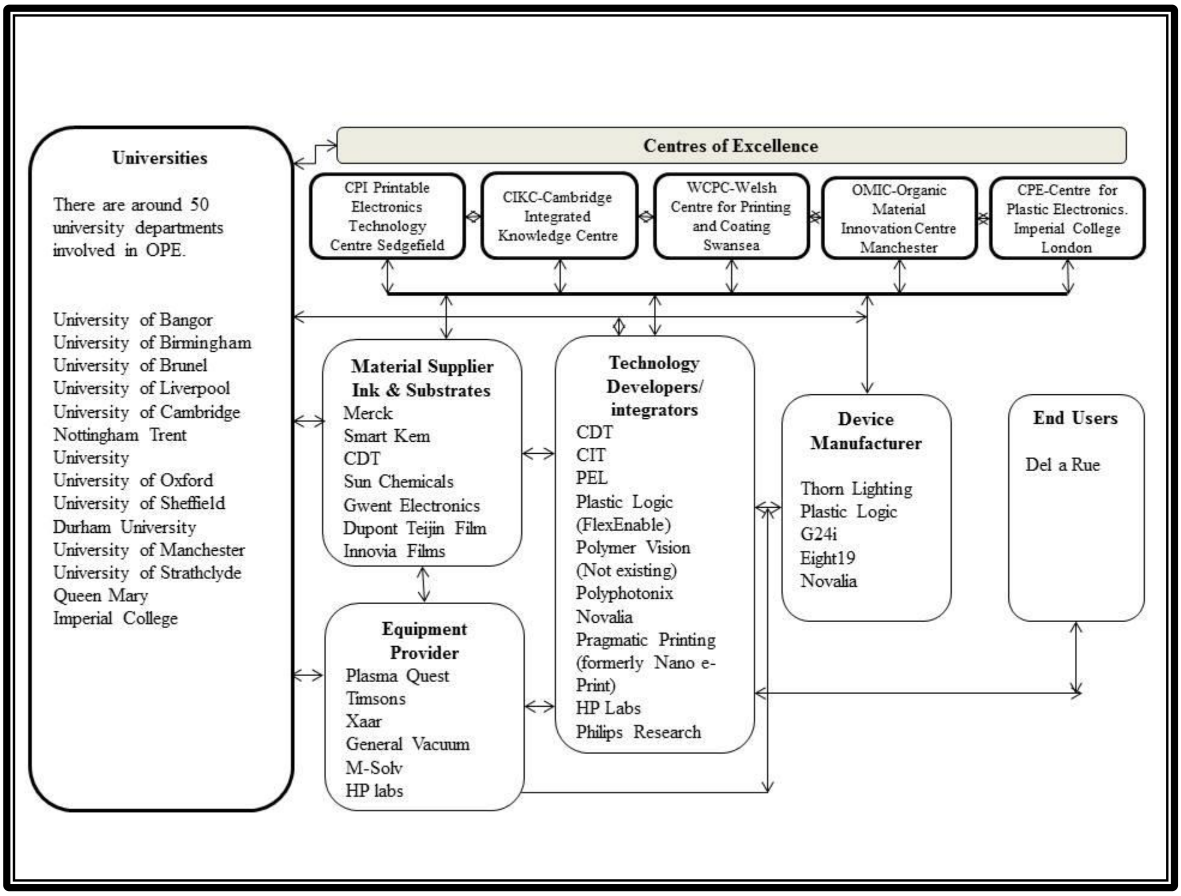
5.6.1 Emergence of Ecosystem in the UK

New industries do not emerge out of a vacuum. According to Boschma et al. (2013), capabilities at the regional level rather than structure at the national level contribute more to the emergence of new industries. According to Caliskan and Callon (2009, p.371), market construction "involves institutional arrangements and material assemblages without which nothing economic could exist or be sustained." Technological progress is the main driver that contributes to emergence (Krafft et al., 2014), as has been the case with OPE. The discovery of highly conductive polymers is credited to Alan J. Heeger, Alan G. MacDiarmid and Hideki Shirakawa who were awarded a Nobel Prize in Chemistry in 2000 for their revolutionary discovery in 1977 that plastics can be made conductive. However, it was the experiment conducted at Cambridge's Cavendish Lab in 1989 by Jeremy Burroughes, who was working for his PhD in the research group of Richard Friend that generated substantial research as well as commercial interest in the possible disruptive potential of light emitting polymers within the UK.

The UK ecosystem, shown in Figure 5.4, comprises around 33 universities involved in OPE. At present there are around 134 companies involved in OPE, 97 of them SMEs, with competencies in substrate and material development, equipment manufacture, device designs, prototype design and finally manufacturing, providing employment to over 2,500 individuals and generating revenue of £234 million (Plastic Electronics Leadership Group Sector Study, 2014). These include start-ups such as Cambridge Display Technology (P-OLED [24] technology), Plastic Logic (device design), PragmatIC Printing (logic) and G24i (DSSC), as well as R&D departments in large firms, notably DuPont Teijin (substrate provider), Merck (chemical company) and equipment providers like Xaar. In addition, there are five Centres of Excellence that provide coordination between research in university and the demands of industry. However, the main weakness of the UK is the absence of end users and lack of integrators that could bring together individual components developed by SME.

[24] P-OLED-polymer or solution-based organic light emitting diodes

Figure 5-4 UK Ecosystem



Source: Author

The next section will discuss the role of Friend's Group and spinouts from University of Cambridge such as Cambridge Display Technology and Plastic Logic, also the formation of other institutional structures and hybrid groups, and other events that unfolded over the period of time and shaped the ecosystem around OPE.

5.6.1.1 Cambridge Display Technology

The inventors Richard Friend, Jeremy Burroughes and Donal Bradley, realising the importance of the discovery of semiconducting polymers, decided to file for the patent application in 1990 before the results were published in Nature. However, since at that time universities didn't have any mechanisms to fund patent filing, the inventors decided to protect the invention by filing the patent application themselves and in

1992 formed the company CDT—Cambridge Display Technology (Kenward, 1999; Minshall et al., 2007). The historical background and context for CDT's establishment in 1992 can be described as a nascent market not only surrounded by ambiguity and unclear product definition (Santos and Eisenhardt, 2009) but also facing dominant incumbent technology and a non-existent supply chain. CDT's solution processable technology (P-OLED) faced competition not only from established incumbent LCD technology but also from small molecules, another alternative to OLED, that was at least 10 years ahead and was led by companies like Samsung, Kodak and Universal Display Corporation.

> Our unique selling point was solution processing. […] To make value out of that unique selling point "Wow, look what we got!" and then nobody's going to develop it, because everybody's on evaporated. So to leverage our USP we had to invest hundreds of millions of dollars to make it come true. (Respondent JVC)

CDT soon recognised the uncertainties associated with the new technology and adopted a role of "Technology Evangelist", developing partnerships and collaborations directed towards building of the ecosystem. Some of the notable strategic partnerships were with established companies like Philips, DuPont, Osram and Seiko Epson.

> What that means is it's a show-me story. So you have to show me. So you have to first make things, displays, demos…. the concept is we had to print things, we had to show everybody that this technology was interesting—until the companies start to see themselves, "Hey, you know, it might be worthwhile to have a programme internally to look at this technology." (Respondent JVC)

Once the initial interest in the potential of P-OLED (Polymer OLED) was developed, the management further decided to invest in device fabrication and develop IP from a process development point of view. Thus, their Godmanchester 14" manufacturing facility with a project budget of $25 million was opened in 2002. These activities were mainly aimed at developing the supply chain for the fledgling, emerging industry and to demonstrate its viability.

> We thought developing materials in isolation, testing them in simple test cells wouldn't tell us enough about what are the requirements for manufacturing and that's certainly been the case, that materials that seem to have passed lots of tests along their route have then had to be pushed back a bit and remodified for the manufacturing-like processes. (Respondent JBC)

In 2004 CDT became the first spinout from Cambridge to have its shares floated on NASDAQ (Minshall et al., 2007). These developments provided the impetus for the establishment of the so-called “Plastic Electronics Industry” in the UK.

5.6.1.2 Plastic Logic

The story of Plastic Logic traces back to the work carried out on organic semiconductors by Sir Richard Friend in the Cavendish Laboratory during the mid-1980s. Friend’s group, with Henning Sirringhaus, Hitachi Professor at the University of Cambridge, made the first plastic transistors in 1988, which were a mere “scientific curiosity at that time” as they suffered from low mobilities. Plastic transistors at the time did not attract much attention within the broad industrial and scientific community due to the rapid advances of the incumbent silicon technology. However, with the improvement in mobilities and deposition technology the new field aroused the needed interest among industrial groups and started to attract investments. Sirringhaus, along with his PhD student Takeo Kawase, was able to print a few transistors that worked very well and created a lot of interest regarding possibilities for the technology. National Geographic UK aired a documentary in August 2002, “Fantastic Plastics: a Future Near You”, that highlighted Plastic Logic’s technology.

Other players involved in the technology, as reported by Financial Times in November 2000, include “Lucent Technologies, IBM, DuPont and Xerox of the US, Mitsubishi and Hitachi of Japan, Philips of the Netherlands and Hoechst of Germany.”

Since its formation in 2000 Plastic Logic has been able to gain the confidence of investors and has received more than $200 million in funding that includes investors such as Oak Investment Partners, Tudor Investments, BASF Venture Capital, Intel Capital, Dow Chemical, Bank of America, Morningside, Siemens Venture Capital and PolyTechnos Venture Partners. In 2008, it opened its fabrication plant in Dresden for producing e-readers.

5.6.1.3 Herman Hauser and Amadeus Capital Venture

An interesting link within the UK story is the role played by technology entrepreneur and co-founder of UK’s first Venture Capital Funds’, Amadeus Capital Partners—

Herman Hauser, who also invested in CDT. He was a proponent of the plastic electronics industry in the UK and raised £1.75 million as seed funding for Plastic Logic to commercialise its technology. He was among the few who truly believed in the potential for plastic electronics and e-readers, the first application targeted for Plastic Logic's backplane technology, and shared the vision that it would soon revolutionise the printing and publishing industry.

> "I remember visiting Richard and his group in the Cavendish," says Hauser. "They only had a few transistors working at this time [1998] and when they stopped working they prodded them with toothpicks!" Luckily, Hauser, with his background in physics and interest in electronics, instantly recognised that Friend, Sirringhaus and their colleagues had made a very fundamental breakthrough. (2009)[25]

> And I think Hermann was very important in two senses. He was decisive. He could bring Amadeus with him […] And the other thing that was enormously important about Hermann is his ability to attract other investors in, that were bigger than him. (Respondent SVP)

Hauser proposed a 10-year plan and the launch of a £100 million programme to the UK government to capitalise on the rising opportunity in plastic electronics. He advised the setting up of a centre that could coordinate activities. (Marsh, 2009)

> "In due course, plastic chips could turn into an industry as large as the silicon-based semiconductor industry," Mr. Hauser said. "Britain has pretty much given up on [developing products for] the silicon industry but we've got a great chance to do well in this new sector." (Marsh, 2009)

5.6.1.4 The Role of the Knowledge Transfer Network (KTN)

The initial success of CDT and Plastic Logic created expectations within the UK that it may be able to gain a leadership position due to the existing capabilities in the form of a strong academic base in material research, devices, equipment manufacture and the printing industry.

> So you had these start-up companies with some very clever ideas that were eager to try and exploit them, but they were operating in isolation. (Respondent CW)

[25] http://www.cam.ac.uk/research/news/plastic-logic-from-innovation-to-impact

The then Department of Trade and Industry (DTI) (now BIS—Business, Innovation and Skills) realised the potential of emerging activities within OPE and in January 2004 funded, under the LINK ISD programme, the formation of FLEXYNET – a networking group for players within plastic electronics. The need to form a formal network was agreed by the academic and business community themselves who met for the first time in what has become a closed annual workshop.

> The networks, the Flexynet networks that were being created at the time and sponsored by the government, for the first time in a long while in the UK, allowed academia to start to interface with… better with industry. And we started to understand this complex area. (Respondent TTP)

FLEXYNET later (April 2005) evolved into the UK Display Network and then became the UK Display and Lighting (UKDL) KTN in April 2006. In 2009 the UKDL KTN merged with Photonics KTN and became the Photonics and Plastic Electronics KTN, which then merged with Sensors KTN to form ESPKTN (Electronics, Sensors and Photonics Knowledge Transfer Network). ESPKTN at that time had 1000 members, of which 600-700 were active in PE. Collaboration and cooperation among varied partners was the thrust of activities that were conducted under the umbrella of the Knowledge Transfer Network. The KTN also worked closely with UK Trade and Investment (UKTI) to organise trade missions (inward and outward) thereby increasing opportunities for collaboration with international players.

The activities and workshop played a pivotal role in building of the early ecosystem and bringing together both traditional large and emerging players. Furthermore, these efforts made OPE the object of policy intervention.

> So we got a whole group of people. We did a lot of head-banging, a lot of shouting and pushing……….trying to persuade people, "Come on, open up, talk. Let... there is no market. You haven't got a product. It doesn't exist. This technology doesn't exist yet. If you don't collaborate with people who may one day be your competitor, there'll never be a market.
>
> And because of that, fairly... almost Communist approach, like there is nothing, therefore all work together... and they actually agreed. They did that. (Respondent CW)
>
> And we saw a tremendous support and collaboration between these companies around the UK, and universities from around the UK, and there was a swapping of information and a discussion of what they thought the needs and the requirements would be, and a sharing of views so that we were able to establish what the states

> of the barriers were in different parts of the technology across the whole supply chain.
>
> So you have this stage where you have the early stage pioneers who've got the great ideas of where they want to go, don't have control of all the processes, and you've got a selection of more traditional companies, traditional suppliers, encouraged to come along and take part in these activities.
>
> When they're face to face in a room, sat next to each other, having a chat, that's when they say, “Hey, we could actually make this work. I think I could modify my equipment to give you what you say you need.
>
> And that's how… so many of these collaborative and commercial relationships being created. (Respondent CW)

The activities and networking events organised by the KTN created a vibrant and close-linked network of companies and academics engaged in OPE across materials, processes, devices and equipment that in turn facilitated the emergence of an ecosystem around OPE in the UK. After the initial convergence of the community, the KTN’s later activities were directed towards exploitation and creating the desired user pull by introducing the potential of OPE to end users such as the automobile industry, healthcare, aerospace, security or FMCG [26] where possible applications could be envisioned.

> What we have been concentrating on in last few months, is trying to connect those technology companies to design community and end users through product designers, artist, architects… so there is a real pull for the technology rather than technology push. (Respondent RA)

5.6.1.5 Policy Level Initiatives

The promises and expectations related to the disruptive potential of the OPE technology have resulted in policy initiatives around the UK and Europe (Parandian et al., 2012). OPE has been identified as one of the six priority areas having the potential to produce returns in five years by the Council for Science and Technology (CST) report in 2007. Professor Sir David King, former government Chief Scientific Adviser, highlighted:

> In Britain we have a world-leading position in a technology that could wipe out silicon chip technology and could convert photovoltaics into easily accessible

[26] FMCG - fast moving consumer good

> materials at a much cheaper price, and I am talking about plastic electronics. (House of Commons, 2009)

In 2008, the Economic and Social Research Council (ESRC) sponsored the project conducted by Dr Zella King of University of Reading. The work resulted in developing "the Competency Matrix" that placed the UK in a dominant position. The Department for Business Enterprise and Regulatory Reform (BERR) in collaboration with UK Trade and Investment (UKTI) also published "Plastic Electronics in the UK – A guide to UK capability" in 2008 that provided evidence of an existing ecosystem. A great deal of interest and enthusiasm was generated through these activities that resulted in the use of plastic electronics as a case study by the House of Commons Innovation, Universities, Science and Skills Committee's review of engineering[27].

The UK Plastic Electronics Strategy was launched December 2009 by Lord Mandelson, Secretary of State for Business, Innovation and Skills, and prepared along with an industry-led strategy group. It identifies the competitive advantage that the UK possesses, key challenges and future initiatives to harness the potential that PE offers and maintain a leadership position within the field. According to Ric Allot (former Director of Plastic Electronics ESPKTN), "Plastic Electronics Strategy has five elements; creating coherent leadership, stimulating application and business opportunities, growing and exploiting the national science and technology resources, building a business based environment and skills and training" (Pitcher, 2011).

5.6.1.5.1 Funding

There have been around 59 collaborative projects supported by various Technology Strategy Board (TSB) and private initiatives. In addition to that there were 8 projects in the Northern Way PE demonstrator programme in 2010. The total funds allocated over the period 2005–2010 for 67 projects amounted to around £79.5 million that included government grants as well as partner contributions (Technology Strategy Board, 2011)[28]. The distribution of projects in terms of competencies and market application is as shown below in Figure 5.5 and Figure 5.6 respectively.

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[27] http://www.publications.parliament.uk/pa/cm200708/cmselect/cmdius/memo/599/ucm1.pdf

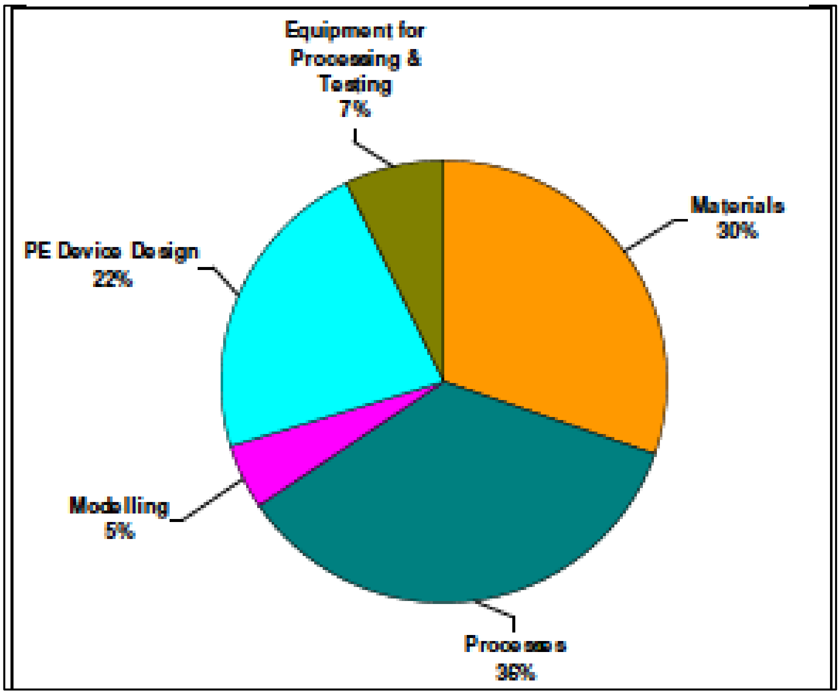
[28] The report was provided to the researcher in an interview

From Figure 5.5 it is evident that most of the projects funded were for developing competencies in materials (30%), process (36%) and device design (22%). In terms of applications, the main application areas were high end consumer application devices like e-reader, OLED TV (16%), communicating objects like greeting cards, smart packaging and devices (31%).

The UK academic community has also been actively involved in the research and development of novel material, device and manufacturing processes. The EPSRC (Engineering and Physical Sciences Research Council) that funds precompetitive research has invested £68.2 million that includes university projects, training of PhD students and collaborative projects with industry. Research excellence and complementarity are not limited to the five centres of excellence, as there are other active clusters such as Bangor, Strathclyde, Hull, Oxford and London to support SMEs and start-ups (House of Commons' Innovation, Universities, Science and Skills Committee, 2008/9).

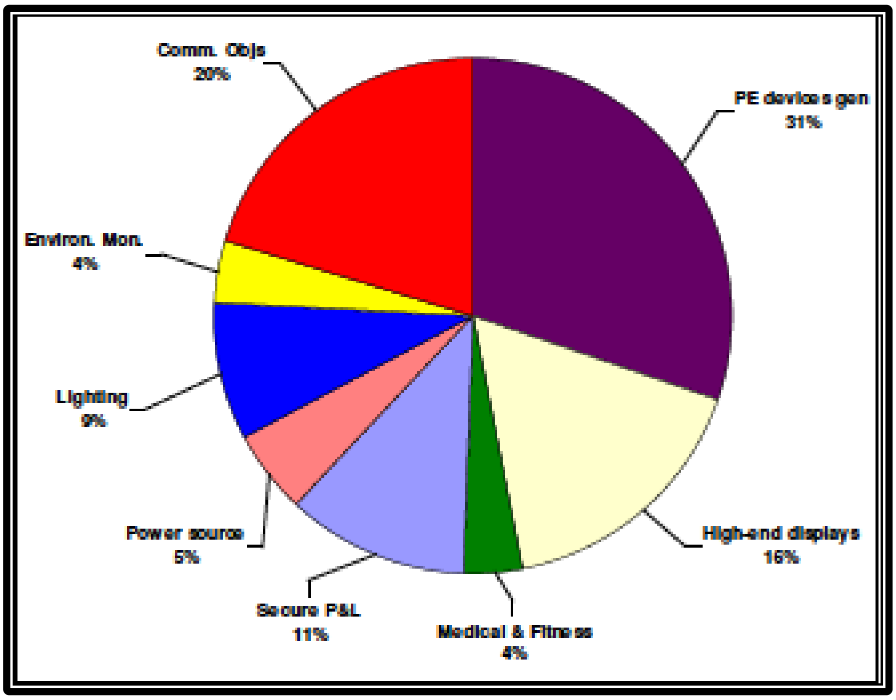
The Department of Business Innovation and Skills (BIS) invested around £20 million in 2009 for setting up a state-of-the-art prototyping and manufacturing capability, PETEC at Sedgefield, now known as the UK National Centre for Printable Electronics.

Figure 5-5 Project Distribution as per Competencies



Source: Technology Strategy Board, 2011

Figure 5-6 Project Distribution in terms of Application



Source: Technology Strategy Board, 2011

5.6.1.5.2 *Printed Electronics Centres of Excellence*

In order to achieve penetration and move the technology from lab to fab, coordination and collaboration among the heterogeneous players are required. In addition to the active role played by Technology Strategy Board and the Knowledge Transfer Network (KTN), coordination is further achieved through Printed Electronics Centres of Excellence (PECoE) **(**shown in Figure 5.7), that accelerate development and provide open access facilities across five independent centres – Cambridge Integrated Knowledge Centre (CIKC) in Cambridge, Printable Electronics Technology Centre (PETEC) (now known as CPI Printable Electronics Centre) in Sedgefield, Welsh Centre for Printing and Coating (WCPC) in Swansea, Organic Materials Innovation Centre (OMIC) in Manchester and Imperial College, London (Centre for Plastic Electronics). The five Centres of Excellence possess complementary skills and a wide range of expertise required for OPE as discussed in the figure. CPI Printable Electronics Centre provides a prototyping facility and its main focus is on commercialisation and scaling up of processes. Welsh Centre for Printing and Coating has world-class expertise in printing and coating processes. Cambridge Integrated Knowledge Centre develops advanced devices, manufacturing processes and also produces demonstrators while Organic Material Innovation Centre expertise is in specialist organic materials. Imperial College’s Centre for Plastic Electronics addresses the design, synthesis and characterisation of organic materials and design and fabrication of devices. It has a wide range of competencies in physics, chemistry, material and chemical engineering.

These initiatives aim to provide the necessary infrastructure to address the future training needs and skill set required for the progress of the industry. Furthermore, in 2013 the EPSRC Centre for Innovative Manufacturing in Large Area Electronics was set up to bring together the expertise of all the academic centres of excellence in collaborative projects.

Organic and Printed Electronics, as discussed earlier, requires multidisciplinary expertise and skills and system thinking in the young workforce and researcher. To cater to the industry demand for young scientists within plastic electronics, the PECDT (Plastic Electronics Centre for Doctoral Training), funded by EPSRC in 2009 (at present training 50 students), is hosted at Imperial College of London. The Centre is a result of collaboration between Imperial College and Queen Mary University of London and works closely with industry in designing of the courses, covering a broad range of disciplines from materials development to system integration.

Figure 5-7 Printed Electronics Centres of Excellence

Printable Electronics Technology Centre (formerly PETEC)

The Printable Electronics Technology Centre (PETEC) located at Sedgefield is a design, development and prototyping facility. It aims at commercialisation of printable electronics products to market quickly by offering facilities and expertise that are rarely available in-house in one firm and absent in case of start-ups.

Welsh Centre for Printing and Coating (WCPC)

The Welsh Centre for Printing and Coating - One of the World's leading centres for research and development of printing and coating processes, specialising in the application of materials by all forms of printing processes. Since 1994 WCPC has continued to develop fundamental understanding and expertise in screen, flexographic, offset gravure, rotogravure, digital and pad printing.

Cambridge Integrated Knowledge Centre (CIKC)

The CIKC was set up in 2007. It brings together the university's research activities in molecular and macromolecular materials and draws on the expertise of the Judge Business School, the Institute for Manufacturing and the Centre for Business Research to create innovative knowledge exchange spanning business research, training and specific exploitation. Their expertise is mainly on devices and processes.

Organic Material Innovation Centre (OMIC)

The Organic Materials Innovation Centre is a University Innovation Centre for the specialty organic materials and polymer industries. The Centre was established in 2004 with support from the UK Government. OMIC provides expertise in the development of new conducting, semi-conducting and dielectric materials and their formulation for controlled deposition – printing onto a wide range of substrates.

Imperial College Centre for Plastic Electronics

The Centre for Plastic Electronics brings together the departments of Physics, Chemistry and Materials to address the design, synthesis and characterisation of PE materials, the design and fabrication of a wide variety of PE devices (including organic/inorganic hybrids) and the modelling of both.

The Centre interacts strongly with industry and is closely integrated with the Imperial Doctoral Training Centre in Plastic Electronics, within which it seeks to train the PE technology leaders of the future.

Source: Adapted from Printable Electronics Technology Centre, The Welsh Centre for Printing and Coating (WCPC), The Cambridge Integrated Knowledge Centre (CIKC), The Organic Materials Innovation Centre (OMIC) and Imperial College Doctoral Training Centre Websites

5.6.1.5.3 Plastic Electronics Leadership Group (PELG)

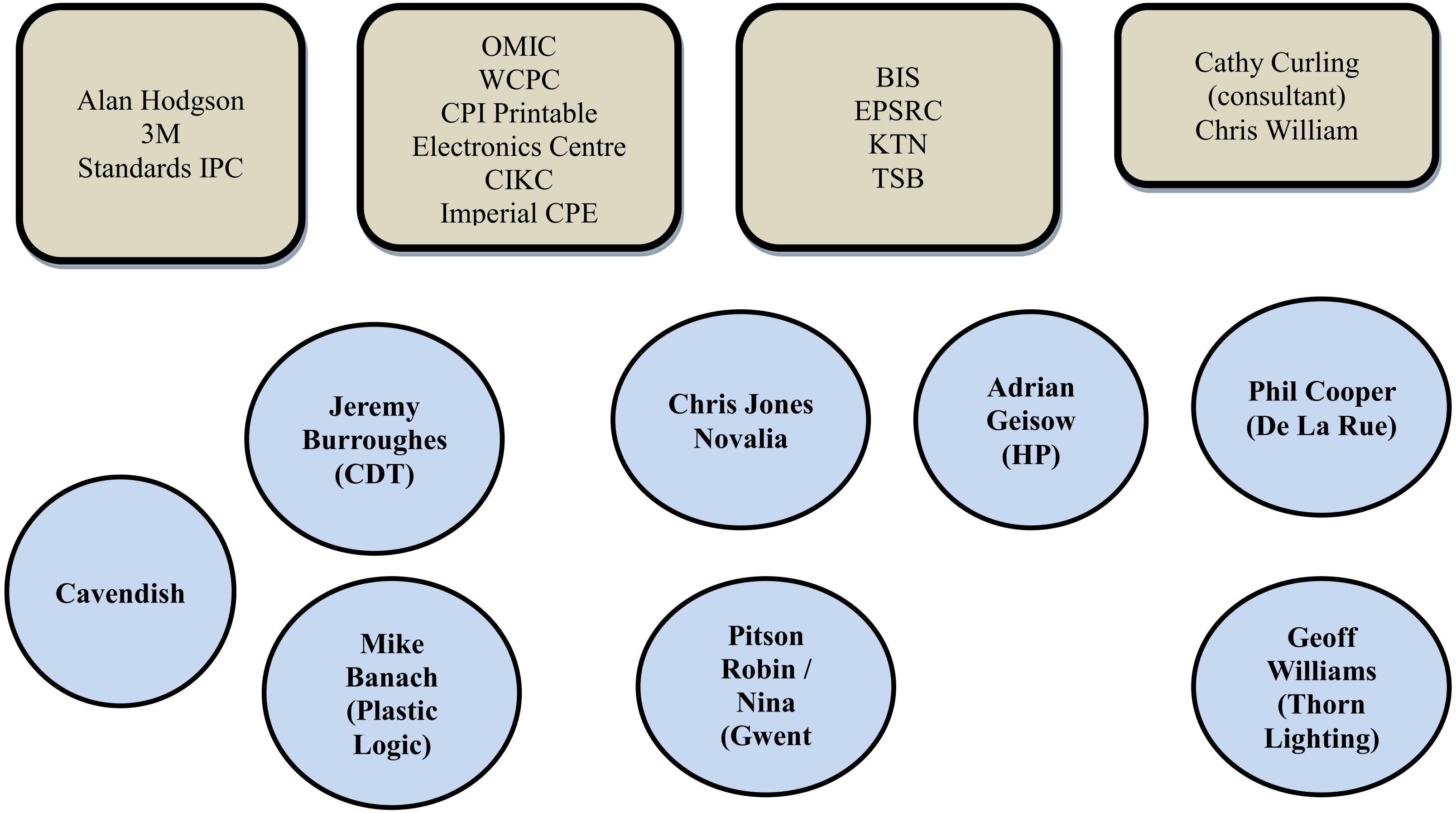
In addition to all these formal arrangements, a voluntary group named Plastic Electronics Leadership Group (PELG) was formed as a result of a strategy group recommendation to create the necessary market pull. As Figure 5.8 shows, it represents the active UK printed electronics community and is comprised of 30 members. The group members include major players from the supply chain that are well connected both through formal and informal relationships, and aims at improving coordination among UK stakeholders, identifying collaboration opportunities, applying for grants and also identifying market sectors where OPE can offer unique propositions.

> So if you look at the PELG, technology is not discussed there. It is all about, can that group shape the environment, which makes it easier and more fruitful for everyone to succeed in. Making sure the external world knows it is exciting edge we are funding or why should we be funding it. (Respondent SYO)

> …They are trying to engage with potential end user community to pull through some ideas and some demonstrators which those of us if you like who are pushing the technology might not have seen but there is a solution here. (Respondent MHO)

Membership within PELG is voluntary; members belong to different types of organisations (universities, small and big organisations within the supply chain, consultants, and government officials) and share an identity, a passion and a vision for printed electronics within the UK. The working practices of the PELG bear close resemblance to a "Community of Practice" (Wenger and Snyder, 2000) whereby the group explores how to generate value for the UK and look into the possibilities of exploiting available financial support, engages with end user communities, and participates in standard-setting activities. Communities of practice are characterised by mutual engagement, a shared repertoire, a joint knowledge domain that facilitates knowledge exchanges and alignment between actors that belong to different organisations.

Figure 5-8 Plastic Electronics Leadership Group



Source: Adapted from Plastic Electronics Leadership Group Website (http://www.ukplasticelectronics.com/pelg/)

“They are a group of people informally bound together by shared expertise and passion for a joint enterprise” (Wenger and Snyder, 2000).

“Communities that we discern are, by contrast, often non-canonical and not recognised by the organisation. They are more fluid and interpenetrative than bounded, often crossing the restrictive boundaries of the organisation to incorporate people from outside” (Brown and Duguid, 1991, p.49). These tend to be important drivers in the exploration phases of disruptive technologies (Delemarle and Laredo, 2008). They help facilitate developing an ecosystem, build momentum, provide opportunities of joint learning and create expectations and visions about the nascent technology. The expectations thus created result in mobilising resources and attracting investments at national level.

> There's active engagement, and some of it is by identifying groups where an interaction and discussion can be facilitated, and the other is participation in events and exhibitions as a way of reaching people who don't have particular knowledge of printed electronics. So the PELG will go to the… Manufacturing and Automating exhibition in the NEC, 7 and 8 November, as a way to engage with a community and try to help them understand the potential, at least, of printed electronics. (Respondent MHO)

> […] you’ve got some potential commercial conflicts of interest but at the moment organisations are choosing to sit at the table because their view must be they can gain more by participating. (Respondent MHO)

> And what we’re doing there is we’ve picked ten areas that we think… ten markets that we think have excellent growth potential, and we’re collecting data in each of these areas on what are their problems: what is the problem space? And having identified what their problems are, how do the capabilities of plastic electronics match up to those problems? What are the problems for which we can provide solutions? (Respondent JHP)

However, the question that arises when seeing the Plastic Electronics Leadership Group is how the organisational boundaries are bridged that often hinder collaborating and sharing. It was found from the interviews and personal participation at one of the PELG meetings that inter-organisational boundaries in practice did not influence working towards the vision of developing a thriving printed electronics community within the UK. One explanation for the free flow of information lies in the industry’s being in a ferment stage and the need to leverage and learn from each other rather than operating in silos. The challenges at present are more from the incumbent technologies and regime pressure that have influenced commercialisation and delayed its adoption.

> So we have to almost sort of put our organisational hat to one side and try and think of it as a total […] a lot of the stuff I’m trying for 98%, 99% of it will have no impact or benefit to [organisation name] at all apart from the fact that the bigger the plastic

> electronics base is in the UK, the better from a perception point of view. (Respondent JBC)

5.6.1.5.4 The Northern Way Project

In addition to the collaborative projects at the national level, the UK Regional Development Agencies (RDA)[29] – viz. One North East, Yorkshire Forward and Northwest Development Agency – funded in 2010 a £5.7 million Northern Way Innovation Project. Headed by CPI Printable Electronics Technology Centre, it aimed to raise awareness of the technology, bridge the gap between research and commercialisation by envisioning new product ideas, and stimulate the regional supply chain by bringing diverse partners from the print, packaging, electronics and chemical sectors. The programme manager, Bela Green, commented on the usefulness of the project:

> What's really encouraging is that, just a few months ago, most of the participating firms hadn't even heard of printable electronics. Now they are using their existing skills base, infrastructure and expertise to form collaborative partnerships with other complementary businesses to create completely new printable electronics products.[30]

The Northern Way Project's success in bringing together the diverse and specialised partners that in future could play a role in the emergent value chain of OPE attracted the attention of the Technology Strategy Board and resulted in the replication of "Demonstrator Project" at national level. Government interventions in the form of demonstration projects not only reduce the uncertainties but also stimulate learning, facilitate supply chain development and shorten time to market (Hendry et al., 2010). According to the industry expert and advisor to CPI Printable Electronics Centre, Bev Brown:

> The North has a fantastic chemicals industry comprised of highly proficient companies who are expert at making small quantities of materials to the same exacting specification, again and again. We are simply playing to their strengths: helping them to supply probably the most valuable component in the display supply chain: the formulated inks.[31]

The Northern Way project has resulted in engaging with specialist chemical and printing companies who had not been previously involved with printed electronics, leveraging the existing diverse research base in the UK universities of Manchester, Leeds and Liverpool and finally producing demonstrators that were presented to display manufacturers in Korea and Taiwan.

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[29] RDAs were abolished in 2010
[30] http://www.stevecalder.com/wp-content/uploads/2012/11/pdf/Case%20Study%20-20Printable%20Electronics.pdf
[31] http://www.stevecalder.com/wp-content/uploads/2012/11/pdf/Case%20Study%20-20Printable%20Electronics.pdf

> It raised awareness across a broader number of sectors. It also helped with the potential scale-up routes because, again, as we've said, the science base inside universities in terms of making new materials etc. is very good. How you scale them up so that you have enough material for prototyping was a challenge. (Respondent MHO)

The Northern Way Project was able to bridge the gap that existed between academia, start-ups and the printing industry. The next section will discuss how the printing industry within the UK is trying to capture the opportunities offered by OPE.

5.6.1.6 Identifying Opportunity—How the Printing Industry Got Involved

Printed electronics is about bringing diverse industries—chemical, electronics, printing, and packaging—together. The main proposition offered by printed electronics is its ability to offer functionality at a lower price point by using conventional printing methods. The section below discusses how the print industry responded to the opportunity provided by printed electronics and participated in the Northern Way initiative. It is based on an in-depth interview with the manager of Print Yorkshire. Print Yorkshire is a network of print houses and print users and contributes around £1.35 billion to the region's economy (Ver-Bruggen, 2010, p.22).

At present, Print Yorkshire are working in close collaboration with CPI to create awareness of the potential of plastic electronics via events and exhibitions, to push the printing industry and bridge the gap that exists between science and industry.

> The print industry doesn't speak the same language as the plastic electronics industry. Far from it. This is why we're working with a partner who's linked to the print industry. This partner has capability in plastic electronics and capability in print. It's almost like they're our translator, and they can help us to target the right places in the print industry. (Respondent JHP)

The vignette below describes the initial interaction and awareness of the printing industry for OPE.

Ric Allott and I first met at an event in London—it was probably one of the forerunners of Innovate [...] probably two, three years ago, now. *And they had lots of workshop sessions, and I attended one of them and he was one of the speakers. And it seemed like every other word was 'printed this', 'printable that'. And so at end it was "Any questions?" and I just stood up and said, "I haven't counted the number of times you've mentioned the word 'printing' but I'm from the printing industry and, to the best of my knowledge, you have not engaged with the printing industry, and if you want a printable electronics industry you have to do that.*

And he said afterwards, "Yes, fair point." And since then the scientific and academic industry of printable electronics has realised it needs the printing industry if it is to commercialise and industrialise the processes.

There's only so much you can do in a laboratory, and if the printable electronics industry has a future then it must industrialise the processes. And it's better to use what's already in existence, i.e. the printing industry, with whatever adaptations are necessary, to industrialise the production, to make it cost effective. (Respondent MH)

The UK print industry comprises small entrepreneurial companies employing on an average less than 15 people. The industry can be described as highly competitive, keen to invest in new equipment and technology and therefore runs on overcapacity. Narrating how they got involved in the Northern Way project to produce an interactive poster with Cambridge start-up Novalia, considered to be one of the first successful demonstrators, Respondent MH said:

> We went to a presentation at Leeds University […] and they were launching a competition… And from that meeting at Leeds University I was thinking, well, what can the printing industry do with that overcapacity?
>
> […] We invited any printing company in the area to come to this room and learn about it, talk about it […] Something sparked off up here with them and we ended up with a small consortium of normal printing companies. We had a litho printing company which is the traditional printing methodology. We had a screen printing company. We had a graphic design company.

These partnerships that were established via the Northern Way project still exist, however, the printing industry still lacks motivation and requires resources for exploitation and to move from demonstration to commercialisation. There have been attempts to reduce this gap through government intervention like CPI (Centre for Process Innovation). These challenges were highlighted during an interview with the manager of Print Yorkshire:

> So development is going on, in little pockets, but it's going on because people are curious. They're interested in it. They're innovators. They're entrepreneurs. But is that the way to run an industry? I don't know.

The OPE industry is still growing and evolving; however, it still remains to be seen whether the UK will be able to grasp the opportunity. In August 2013 Chris Williams, the co-founding director of the UK Displays and Lighting Knowledge Transfer Network, lamented on the lack of integrated approach of the UK Government to fund demonstration projects that could result in commercial exploitation:

> Once again, the UK Government and its partner agencies show it can mentor the scientific goose, and encourage it to research and develop its golden egg up to the point where it is almost ready to be laid, but then Government funding is taken away and focused on newer areas that seem to be sexier and more sound-bite worthy. It happened in the past with composite materials, and it is happening now with plastic electronics. (Williams, 2013)

Having presented and discussed the emergence of the OPE industry in the UK, the next section will discuss the German landscape.

5.6.2 Emergence of Ecosystem in Germany

Germany is considered to be the hot spot for nurturing Organic and Printed Electronics activities, owing to the presence of leading chemical companies such as BASF, Merck and Evonik as well as start-ups such as Novaled. Optimisation of organic materials is an important driver for the progress within OPE. However, to realise the opportunities offered by OPE, maintaining position upstream as a material supplier is not sufficient. In this regard, competencies need to be developed for device and processes development as well as for production and integration. The emergence of OPE requires assemblages and coordination of various specialised actors and institutional arrangements. Within Germany there are many regional level initiatives and clusters such as Forum Organic Electronics around Heidelberg and Organic Electronics Saxony (OES) in Dresden. OES is considered one of the largest organic electronics clusters in Europe, provides interactions and brings together competencies around materials, devices and process development. The next section will discuss OES and is followed by policy level initiatives.

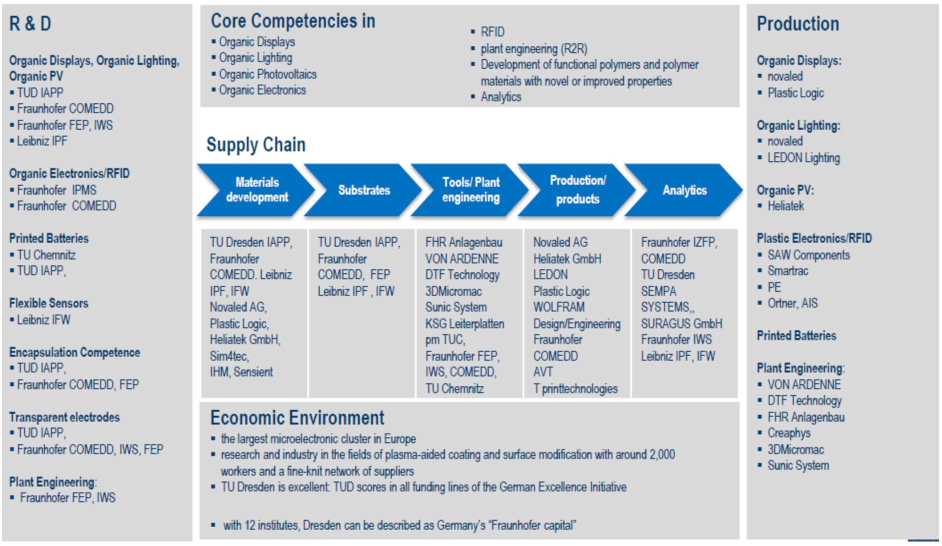
5.6.2.1 Organic Electronics Saxony (OES)

Organic Electronics Saxony (OES) in Dresden is the most thriving cluster for Organic and Printed Electronics within Germany, known for its established silicon semiconductor-manufacturing base (Silicon Saxony).

> Dresden… is known as Silicon Saxony. And so you've got AMD and other companies. So you had highly skilled workforce to kind of recruit from. (Respondent JMP)

The Dresden cluster includes 39 companies and 17 research institutes, employs 1000 people and is considered the largest cluster in Europe having competencies in OLED displays and lighting, OPV and components, as evident from Figure 5.9. Owing to the rich presence of skills and competencies in Saxony, Dresden has been able to attract investments in Organic and Printed Electronics. Plastic Logic, a spin-off from Cambridge University, established its production facilities for $100 million for the first plastic e-readers.

Figure 5-9 Organic Electronics Saxony



Source: Dresden 2014 [32]

[32] http://www.dresden.de/media/pdf/wirtschaft_extern/dresden-flexible-electronics-2013.pdf

The emergence and growth of the cluster can be attributed to Professor Karl Leo, head of the Institute of Applied Photo-Physics (IAPP) at Technical University (TU) Dresden. Karl Leo has been in the field for 20 years and is associated with successful spin-offs active within the field of organic electronics.

> Karl Leo is described as visionary: 'I think without Leo, we would not have this field in Dresden. He is the nucleus, around which this industry is developing.' (Ver-Bruggen, 2007)

> Due to the situation of the established classical semiconductor industry on one hand and on the other hand new companies from Karl Leo, many more companies within Saxony came to this topic or decided to make a vocation in Saxony […] because of the knowledge and people. (Respondent DGS)

CreaPhys was the first to spin off from IAPP in 1999. It provides a solution for purification of organic compounds and supplies the OLED display and lighting industry with thermal evaporators and sublimation units. In 2001, *Novaled* spun out based on the work done by Jan Blochwitz Nimoth on doping technology during his PhD. The founding members of Novaled are Prof. Karl Leo, Jan Blochwitz Nimoth, Martin Pfeiffer (founder of Heliatek) and Jörg Amelung (from IPMS, also founder of LEDON). Novaled is one of the leading material and technology developers in OLED with around 500 patents granted or waiting worldwide. Novaled was acquired by Samsung in 2013 for €260 million ($347 million).

Heliatek is another success story associated with Professor Karl Leo's group and is a leading global player within OPV. It spun off in 2006 from Technical University of Dresden and University of Ulm. Big players such as BASF (chemical company), Bosch (electronics company) and RWE (a major electricity provider in Germany) have been major investors in the start-up. These investments not only improved the basic technology, but also enabled Heliatek to install a first production line, somewhere between a pilot line and a small-scale production line for vacuum roll-to-roll deposition of organic solar cells. Heliatek's ongoing collaboration with Prof. Karl's group for physics in TU Dresden and Prof. Boyle's group for chemistry in University of Ulm enabled it to achieve the record-breaking efficiencies of 12%.

LEDON OLED Lighting was founded in 2009 as a joint venture of the Zumtobel Group and the Fraunhofer-Gesellschaft as well as some employees of the Fraunhofer Institute for Photonic Microsystems (IPMS). Its main focus was on OLED lighting solutions.

Furthermore, to facilitate the technology move from lab to fab an established applied research centre *COMEDD* (Centre for Organic Materials and Electronic Devices Dresden) was also established in 2008 within the Fraunhofer Institute for Photonic Microsystems (IPMS). Within COMEDD three pilot fabrication lines have been installed to support work on OLED lighting, signage and roll-to-roll manufacturing. Further details of this institute will be presented and discussed in Chapter 8.

To coordinate, and to provide support and training to the organics community within the region, liaison at project levels and interfaces at the government level, a formal representative network, Organic Electronics Saxony E.V. (OES), was established in 2008 by seven companies and three research institutes. OES represents the Dresden organic electronics community at various trade fairs and exhibitions.

Germany has achieved a leadership position in different application areas of OPE and has competencies in materials, devices, equipment and printing technologies owing to the presence of both large players and start-ups. However, it faces serious competition from the US and Asia that necessitates developing policy initiatives and funding mechanisms that can support implementation of research results. The next section will discuss some of the successful promoting mechanisms.

5.6.2.2 Policy Level Initiatives

The Federal Ministry for Education and Research (Bundesministerium für Bildung und Forschung, BMBF) has been actively promoting the development of organic electronics. Organisation of a Cluster of Excellence and Innovation Alliances are some of the instruments introduced under the 'High Tech Strategy' for promoting organic technology.

5.6.2.2.1 Innovation Alliance

The objective of Innovation Alliance is to mobilise industry participation and investments whereby "one Euro of the Federation moves five Euros of economy" (Acatech, 2011). Two major projects that were included under the Innovation Alliance instrument are:

1. **OLED Alliance 2015** started in 2006 with the aim of improving OLED technology for display and lighting. The Alliance comprised 33 partners and received €100 million from government whereas €500 was contributed by industry. The Alliance was made up of small sub-projects that were further pursued by industry partners in follow-up projects and resulted in major advancement within the field. Amongst the

successes was the opening of the OSRAM OLED lighting pilot production facility in Regensburg and the Philips pilot production facility in Aachen.

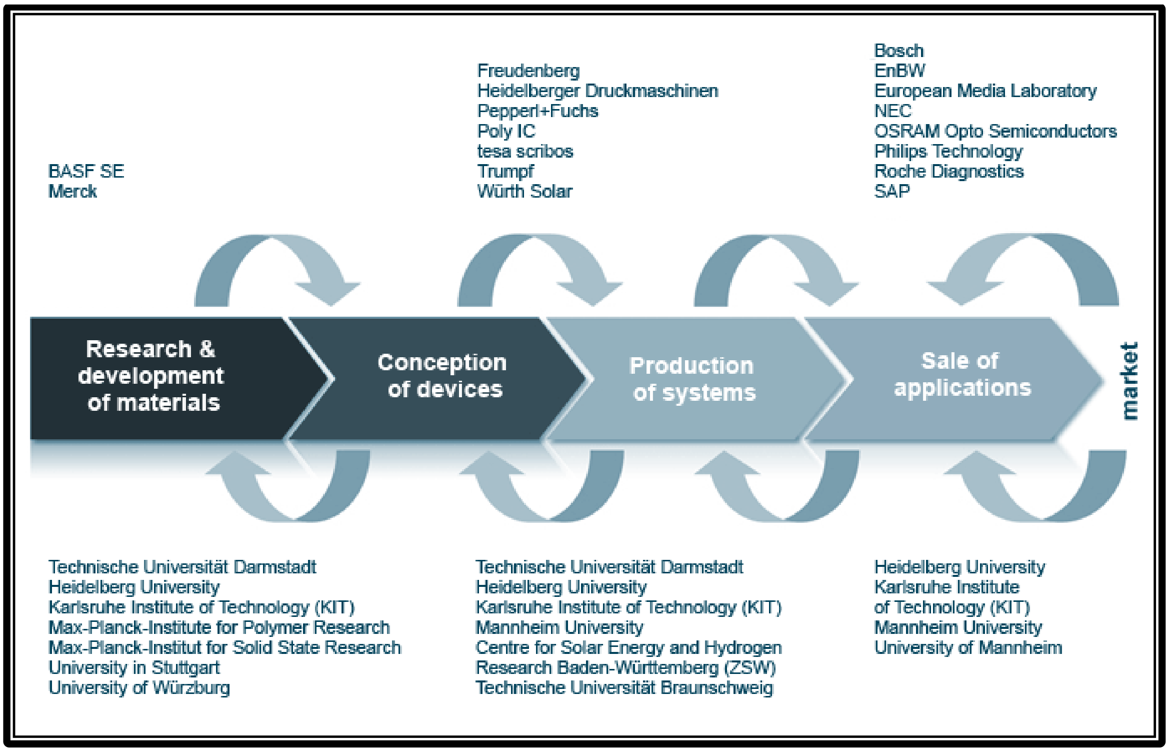
2. **OPV Alliance** was initiated in 2008 to accelerate the development of organic photovoltaic technology. It was comprised of 15 joint projects and received €60 million in funding from BMBF. The Alliance received tremendous support from the big industrial players such as BASF, Merck and Bosch. Projects such as “OPEG” improved the efficiency of an organic solar cell from 5% to 8.3% and proved instrumental in the success of Heliatek.

5.6.2.2.2 Cluster of Excellence

Another initiative that was taken under the High-Tech Strategy 2007 was the launch of a leading-edge cluster competition. Among the winners was the Forum Organic Electronics.

The “**Forum Organic Electronics-Innovation Lab”** cluster in Rhine-Neckar metropolitan region received €40 million in funding from BMBF for the five years 2008-2013. Another €40 million was contributed by industry players. Additionally, another €5.5 million was provided by Ministry of Science, Research and the Arts Baden-Württemberg. Forum Organic Electronics in Heidelberg combines the expertise of 25 industrial as well as academic partners along the value chain and includes Merck, BASF, SAP, Heidelberg, University of Heidelberg, Technische Universität Darmstadt and Karlsruhe Institute of Technology among others (see Figure 5.10). The partners’ competencies span from material development to the development of devices and components, production of systems to the marketing of products and applications as shown in Figure 5.10. At present around 100 scientists are involved in various projects around four major areas: OPV, OLED, Organic Sensor Applications and Organic Circuits and Memory.

Figure 5-10 Competencies of Forum Organic Electronics Lab



Source: Innovation Lab[33]

5.7 Discussion

Printed Electronics, though considered to have high potential for numerous applications (displays, lighting, photovoltaic, memory, sensors, batteries, RFID), is still in its ferment phase and faces challenges as the emerging value chain is fragmented, unbalanced and fluid with many possible entry points. According to Sheats (2004, 1985), "as sophisticated as our knowledge of organic electronic materials is, the industry appears more like silicon in the 1960s than silicon today, and a shorter development time should not be expected." According to IDTechEx (2011), "97% of the companies… are materials, equipment or component providers. Only 3% make products or do integration." This has been the topic of discussion in initiatives at both UK and European level (for instance, in PELG and Organic Electronics Association meetings) in which the researcher has been an active participant.

[33] http://www.innovationlab.de/en/cluster-foe/leading-edge-cluster-forum-organic-electronics/leading-edge-cluster-forum-organic-electronics-background/

> What is delaying the introduction of flex-many products? The answer is almost everything. Not only must the display itself (including the backplane and barrier film) be flexible and not deteriorate over many flexing cycles, but so must the other components of the device, including the touch screen, circuit boards and battery. Hard switches and buttons must either be eliminated or designed to work with a flexing substrate and, perhaps [...] None of this is easy, but solving the problems are where the product and investment opportunities lie. (Werner, 2013 cited in Siegal and Shivakumar, 2014)

5.7.1 Sailing Ship Effect

One of the challenges that has been faced by fledgling Organic and Printed Electronics industry is the continuous improvements of the incumbent technology, even sometimes at an accelerated pace. The phenomenon is referred to as the "sailing ship effect" and is defined as an "acceleration of innovation in the old technology in response to the threat of innovation in the new technology" (Howells, 2002, p.887). Emerging technologies are characterised by a longer period of development and this has been seen in the development of OLED that took around 32 years from the first publication in 1981 by Kodak scientist Professor Ching Tang to its penetration in 2013 for smart phones. During this long period of experimentation and development, the incumbent technology liquid crystal displays (LCD) incrementally improved and the initial performance differential that existed between LCD and OLED on certain attributes such as colours and viewing angle narrowed. This, dynamics coupled with high manufacturing cost, lower yields and shorter lifetime associated with OLED, contributed to decreased adoption of the new technology. According to Lawrence Gasman of NanoMarkets:

> OLEDs have made market inroads, but their success has mainly been on the supply side where Samsung – a force to be reckoned with in the mobile phone space – has adopted OLEDs as its primary mobile display technology. NanoMarkets can, however, find little evidence that consumers themselves are jumping up and down with excitement about OLEDs.[34]

The sailing ship effect has been prominent in the Plastic Logic e-readers case that faced challenges in the development of its nascent technology that resulted in its losing the battle against incumbents like Amazon's Kindle and Apple's iPad. The development of flexible display based on organic thin film transistor technology though being novel took several years to develop owing to the absence of ecosystem. However, the existing technology based on inorganic materials, pioneered by incumbents, developed faster and therefore offered the

[34] http://nanomarkets.net/articles/article/how-oled-lighting-could-save-the-oled-industry

traditional glass based e-reader with feature better than plastic e- reader at much lower prices. This ultimately forced Plastic Logic to exit e-reader market in 2012.

Chris Rider, Director of EPSRC Centre for Innovative Manufacturing in Large Area Electronics (CIMLAE), commented on the challenges during the journey of Plastic Logic as, "When it all started out, it looked like a revolution was about to happen. It was very exciting, with the possibility of doing things which couldn't be done in other ways but what we've found out in the last ten years is that it wasn't quite that simple."

5.7.2 Changing Macro Environment

The third generation of photovoltaic that included organic photovoltaic (OPV) and dye sensitised solar cell (DSSC) faced tremendous pressures from the existing first and second generation solar technologies due to the massive drop in silicon module prices between 2007 and 2011, resulting in shakeouts such as that of Konarka, spun out of University of Massachusetts, in 2012, and G24i going into administration late in 2012. Konarka received around $200 million (€154 million) in funding for commercialising of its breakthrough technology. These challenges point towards the stable regime pressures that result in failure for path-breaking innovation. According to the leading industry magazine "+Plastic Electronics":

> In Europe over supply, plummeting prices for crystalline silicon PV modules and reductions in feed-in tariffs (FIT) for PV modules and building-integrated PV (BIPV) products have all contributed to the contraction within the industry, especially the thin film PV segment.[35]
>
> The window of opportunity on OPV is closing. With investment failing to recover from its 2008 high and recent failures, investors are losing interest in OPV, closing off opportunity and funding avenues for emerging developers. (Plastic Electronics Magazine, 2013)

5.7.3 Keeping Value Chain Local

The main challenge for the UK, as well as for Europe, wishing to derive economic benefits from the opportunities presented by printed electronics, is to keep the "value chain local" through development of high value manufacturing processes and capitalize on lessons learned

[35] http://www.plusplasticelectronics.com/energy/global-solar-closes-german manufacturing-operation-58264.aspx

from the missed opportunity in exploiting liquid crystal display technology. These concerns are also shared within the US as is evident from recent reports by National Science Foundation (NSF). This also necessitates accelerating the pace of development within OLED lighting, OPV and smart integration systems where Europe has a strong R&D presence and in finding applications other than displays where East Asia holds prominence. Following the acquisition of Kodak's OLED business by LG in 2010, UK-based Cambridge Display Technology by Sumitomo in 2007, and Novaled by Samsung in 2013, most of the patents for OLED are now held by Asian companies. According to Mr Hannah, CEO of Plextronics, "analysis of patent shows that about 5,000 patents in organic electronics have been awarded in the United States, 4,000 in Europe and 25,000 in Asia. So where's the activity? ...in Asia" (Shivakumar,2013).

5.8 Conclusions

Emerging technologies are considered fundamental for the economy but they face great challenges when it comes to commercialisation. OPE can be considered as an example of pervasive emerging technology.

> The mere fact that an innovation can be applied in several areas of production (pervasiveness) does not mean that it will be used. In order for society to employ the technology pervasively, its adoption must be convenient from a cost-consideration point of view, that is, it must reach a certain level of efficiency (scope for improvement), and it must lead to the development of new 'secondary' or 'complementary' technologies (innovation spawning). (Youtie et al., 2008, p.317)

OPE is considered to be growing slowly and there has been less progress than expected when it comes to commercialisation. There are large numbers of heterogeneous players that are involved in the development of OPE; and this includes universities but also government bodies, consultants, and intermediaries such as technological and research institutes. Furthermore, there are dedicated quasi-public spaces or " hybrid forums" (Callon et al., 2002) where technology is discussed and debated as witnessed in the case of the emergence of the UK ecosystem; this will be elaborated in following chapters where the role of association will be discussed.

The discussion of the emergence of the technology has identified certain dynamics:

Technology Push and Demand Pull - Technology progress necessitates both supply push and demand pull perspectives (Di Stefano, Gambardella and Verona, 2012). The initial phase of emergence of OPE can be considered more of a technology push, dominated by efforts of inventors, dedicated technology developers and large firms and supported by government funds. Early efforts of scientists and engineers resulted in creating necessary mass around the technology and enrolled other heterogeneous actors also from other industries resulting in evolution of the space. According to Woolley (2010), technology is not developed within a single industry but initiates development across an interdependent population. The early phase of technological emergence can be attributed to the entrepreneurial efforts of upstream players, notably material providers such as Cambridge Display Technology in the UK, Novaled in Germany and Universal Display Corporation (spin-off from Princeton University) in the USA and large organisations such as Kodak and Merck, to name a few. These upstream players established relationships with other suppliers and customers that resulted in technological spillovers and further development of nascent technology. However, recently there has been evidence of small entrepreneurial firms such as Thin Film Electronics, a Swedish start-up, and PragmatIC Printing, a UK-based start-up, adopting an ecosystem approach in order to create a market pull to the industry, thereby initiating a change in initial strategy mainly focused on developing the technology and moving further down the value chain.

Globalisation and Internationalisation - Knowledge-based industries are driven by both international competition and international collaboration (Murtha et al., 2001). Proximity and clustering generally facilitate rapid diffusion of knowledge that tends to be otherwise sticky. But new technologies activities often bubble in parallel in different countries before creating critical mass in any one of them; organisations create their affiliates or subsidiaries in areas where knowledge hubs are located, as has been witnessed in the case of OPE. This resonates with Murtha et al.'s (2001, p.31) observation in the case of flat panel displays (FPD): "It is impossible to predict the exact timing and location in the world where any given technology will commercialize and a global industry emerge. But it is possible for companies to design management process that positively affect their probabilities of taking part." Organisations had the trend of maintaining the presence of management teams in Japan, Korea, China and the US rather than just maintaining the presence close to home. Thus they were able to leverage from the knowledge and capabilities present in international hubs. For example, Plastic Logic had its R&D hub in Cambridge while the manufacturing was established in Dresden close to Silicon Saxony in order to benefit from the competencies in the region.

Similarly, Thin Film Electronics (TFE), as we will see in the micro case in a later chapter, maintained their presence in the USA and Japan as well as Sweden.

Dedicated Network Builders - In order to develop momentum in new technologies, the creation of new networks around heterogeneous players is of paramount importance. Elzen, Enserink and Smit (1996) pointed towards the presence of one or more actors "who have to work against the odds", referred to as "dedicated network builders" or system-builders (Hughes, 1979). Network builders enrol other actors in the network and create variety within the emerging network. "The presence of dedicated network builders is an important factor influencing the chances of new technology" (Hoogma, 2000, p.84). Our case also identifies these network builders such as the role of Richard Friend in the UK and Karl Leo in Germany. The pioneering start-ups in both regions and their evangelising efforts resulted in creating critical mass and building up of networks around the technology.

Having discussed the emergence of the OPE industry at macro level the next chapters will focus on micro and meso levels.

Chapter 6: Creation of an Ecosystem: The Case of Thin Film Electronics

6.1 Introduction

The previous chapters highlighted the importance of Organic and Printed Electronics (OPE) as a breakthrough technology and discussed its application potential, such as in OLED lighting, third generation photovoltaics (OPV and DSSC), electronics and components (memory, transistors, batteries) and integrated smart systems (such as RFID, sensors, and smart textiles). The emerging industry based on OPE technology is demonstrating an organic growth as the products are slowly making their way into diverse industries, such as OLED displays in mobile phones and televisions and OLED lighting in automobiles. Another area of promising growth and disruptive potential is in electronics and components where the recent implementation of printed memory devices for brand protection, along with developments in other components such as batteries, transistors (logic) and sensors, is paving the path for the realisation of the emerging megatrend that is the "Internet of Everything".[36]

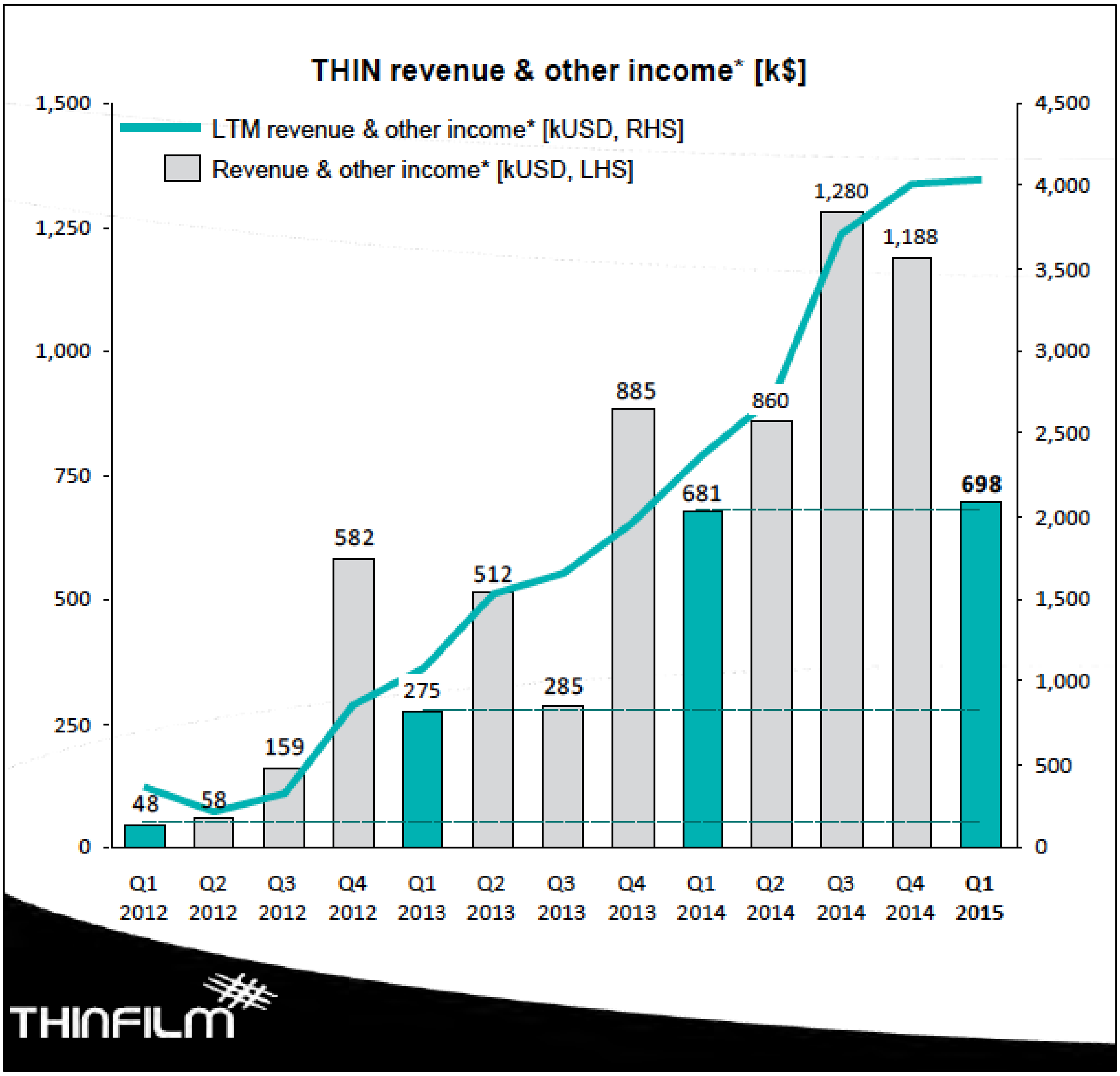
The ubiquity associated with OPE as compared to silicon and its potential for lower production costs offer unique opportunities for adding intelligence to low-cost, high-volume disposable items. However, one of the major challenges associated with the realisation of this vision and OPE's commercialisation is lack of integrator firms and systems, as elaborated in the previous chapter. There are many promising start-ups developing individual components such as batteries, sensors and transistors; however, the adoption of printed electronics by large users in certain applications such as smart packaging and counterfeiting labels necessitates integrating the components, bringing the technology to the market and demonstrating that the whole system can work.

This chapter discusses in depth a case study of an entrepreneurial start-up firm, Thin Film Electronics (TFE, or Thinfilm), a leader in the development of printed memories and integrated systems. TFE is a Norwegian public listed company headquartered in Oslo and has

[36] A world in which low-cost wireless sensors are integrated into packaging ad products, providing real time information that helps business and consumers make more informed decisions (Thin Film Electronics, 2015).

global operations with research and product development based in Linköping, Sweden; production, product development and business development in San Jose, California; and a sales office in Tokyo. Thinfilm currently (2015) has 90-100 employees. Figure 6.1 provides revenues for the period 2012 to the first quarter of 2015. In the first quarter of 2015 revenues of $698 million were reported as compared to $48 million within the same period for 2012 indicating strong and progressive company growth over the years. Thin Film Electronics is among the few companies within the OPE space that are acting as an integrator with major strides in commercial product development, thus creating the necessary market pull long awaited by the industry.

Figure 6-1 TFE Revenues (2012-2015)



Source: Thin Film Electronics[37]

TFE's core competency is in printable rewritable non-volatile memory, for which they hold major patents, and their vision is to "bring electronics to even the most cost-sensitive applications". To realise the vision of low-cost printing and the "Internet of Everything" they believe that orchestrating an ***ecosystem*** is a key. TFE's strategy is one of the few success stories within the OPE space as they have demonstrated high growth, attracted investments

[37] AGM Presentation: The presentation was held by CEO Davor Sutija and CFO John Afzelius-Jenevall, May 7, 2015, Oslo, Norway (accessed May 2015).

and also established commercial relationships with high growth Fortune 500 companies. However, this success is the result of continuous innovation effort, entrepreneurial orientation and the CEO's cognition and vision.

The chapter discusses how ecosystem creation can facilitate commercialisation in the case of breakthrough technologies that are characterised by uncertainty and low initial performance and face challenges from incumbent technologies. The case study offers uniqueness and richness to the growing academic debates on entrepreneurial ecosystem (Overholm, 2015). Small entrepreneurial firms, though considered as instrumental for Schumpeter's creative destruction, suffer from the liability of newness and face challenges for commercialisation of breakthrough technologies (Song et al., 2008). The case illustrates TFE's keystone strategies for shaping and constructing new markets based on disruptive technology.

TFE consciously orchestrated the development of the ecosystem and created value through symbiosis, interdependencies and co-creation. However, enrolling actors and defining boundaries are a necessary but not sufficient condition for creating value in ecosystems, as the case demonstrates. Value creation within an ecosystem requires developing routines at both the intra-organisational and inter-organisational level.

The chapter begins with the historical background of TFE and its evolution; it discusses interdependencies between TFE and its partners that led to value creation within the ecosystem; it discusses in detail the creation, evolution and stabilisation of an ecosystem; and finally it elaborates on intra-organisational and inter-organisational routines created by TFE for value creation, and draws some conclusions.

6.2 Historical Developments

Thinfilm started in 1997 as a subsidiary and Swedish research arm of Opticom, with the vision to provide plastic memory. Founded in 1994 by Hans Gude Gudesen, Opticom had been active in researching polymer-based multi-layer memory, which had the potential to disrupt the flash memory market[38]. During 1995-1998, Opticom concentrated on developing printed roll-to-roll memory and developed prototypes with collaborative partners (100

[38]http://www.geek.com/chips/plastic-memory-545237/

scientists and 30 institutes)[39] that included star scientists such as Richard Friend of Cavendish Lab in Cambridge, Professor Alan Heeger, Professor Dr Olle Inganäs of the University of Linköping, Dr Robert Birge of Syracuse University, and Bell Labs (AT&T/Lucent Technology R&D), to name a few. Memory technology progress and its business potential created lofty expectations resulting in a joint development research agreement and attracting investments from Intel in 1999 and the formation of Thin Film Electronics ASA (Intel's initial investment was 6%). In 2001 Intel increased its investment to 13% and also entered into a licensing and production agreement. The technological developments during that phase were focused mainly on hybrid memories (polymer on silicon).

> Intel researchers were intrigued with the possibility that polymeric non-volatile memory could be a replacement for flash memory.[40]
>
> It was 70 people at Thin Film Electronics and maybe around 50 people at Intel trying to develop this memory, at the time. (Respondent GGA)
>
> So the company that we have today has the IP that was created at that time. But it was a hype curve; they were saying that they were going to use ferroelectric memory materials to replace all of silicon, in every application known to man: all memories would be made in plastic. And in many cases that created a downside because it creates this kind of… Gartner… the disillusionment portion of the cycle, when you get down here—if you have very lofty expectations. (Respondent DST)

In 2003, Opticom hybrid memories were hit by manufacturing problems and technological hurdles (Clarke, 2003)[41] and this resulted in the cancelling of the collaboration between Intel and Opticom in 2005. Many reasons are given for Intel not continuing with the collaboration and one of the most important is the incremental improvement in existing memory technology at that time, as hinted by the respondent:

> It is that when we started Thinfilm, no one had heard about the memories. But during these five or seven years, the awareness of how important portable memory, or flash memory […] just grew…. And all of a sudden the whole silicon industry just shifted from processes and D-RAM and memories to flash memories […]
>
> […]because when we started, they said it's impossible to make memories more than a few megabytes with flash. It doesn't work. It can't work. They had theoretical models and so on that it could never, never work.
>
> So the technology we had was the only one, and it was probably 100 times more efficient than the other memories, but then… the whole semiconductor industry started to work on memories, flash memories. (Respondent GGA)

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[39] http://www.cwu.edu/~borisk/312/018.html
[40] http://www.eetimes.com/electronics-news/4059847/Plastic-electronics-group-reforms-prints-memory
[41] http://www.eetimes.com/electronics-news/4092559/Opticom-plastic-memory-hits-volume-manufacturing-hurdle

The end of the collaboration lost momentum for Opticom activities and led to its acquisition by FAST (Fast Search and Transfer) in 2006 and transfer of the old business (Thin Film ASA) to a new incorporated company Thinfilm, with the concentration of their efforts on organic printed electronics (OPE). Non-volatile memories held a considerable potential for emerging printed electronics applications, however the business model adopted by Thinfilm at that time was licensing. Thinfilm was listed on the Oslo exchange in 2008.

Thinfilm's history can be divided into three phases:

- 1997-2006, when the focus was on developing non-flash memory;
- 2006-2010, during which time efforts were devoted to developing the non-volatile fully printed ferroelectric memory, and
- The third phase, from 2010 onwards, where the focus has been to move from merely a licensing company to a product company. This period could also be regarded as a transition for the organic printed electronics industry.

6.2.1 Industry Dynamics

Flash memory appeared in 1980 and was approximately 0.3% of the total memory market. However, by 2006 it rapidly diffused into the market with penetration of 34.4% (see Table 6.1) owing to the rising demand in the consumer electronics market for portability, miniaturisation and non-volatility.

Table 6-1 The Rise of the Flash Memory Market

	Flash memory market (USD Million)	Flash memory market annual percentage growth	Flash memory as percentage of total semiconductor market	Flash memory as percentage of total memory market
1990	35		0.1	0.3
1991	135	286	0.3	1.0
1992	270	130	0.5	1.8
1993	640	106	0.8	3.0
1994	865	35	0.9	2.7
1995	1,860	115	1.3	3.5
1996	2,611	40	2.0	7.2
1997	2,702	3	2.0	9.2
1998	2,493	-8	2.0	10.8
1999	4,561	83	3.1	14.1
2000	10,637	133	5.2	21.6
2001	7,595	-29	5.5	30.5
2002	7,767	2	5.5	28.7
2003	11,739	51	7.1	36.1
2004	15,611	33	7.3	33.1
2005	18,569	19	8.2	38.3
2006	20,275	9	8.1	34.4

Source: WSTS and IC Insights

Source: Yinug, 2007[42]

Intel was the first company to introduce flash memory in 1988 and was looking at the possibilities of a new generation of non-volatile memory technologies to follow NOR and NAND variants in 1990, working on two-option phase change memory and ferroelectric polymer memory (Clarke, 2004)[43]. At that time the common belief among the industry players was that there would be a limit to flash memory, as discussed by Stefan Lai, VP of the technology and manufacturing group at Intel, in an interview:

> Flash memory, in its EPROM tunnel oxide (ETOX) and NAND variants, still has more than five years as the key mainstream non-volatile memory, but the race is on to find the memory technology that can scale to sub-45nm manufacturing processes. (Clarke, 2004)[44]
>
> The opinion is spreading that Flash will be "just good enough" in the near future, but in the medium term will have to be replaced. At least, that is the industry line. (Gruener, 2004)[45]

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[42] http://www.usitc.gov/publications/332/journals/rise_flash_memory_market.pdf
[43] http://eetimes.com/electronics-news/4120949/-b-Interview--b-on-non-volatile-memory-with-Intel-s-Stefan-Lai
[44] http://www.eetasia.com/ART_8800331765_499486_NT_315cc567.HTM

> But there is a limit to how far flash technology can be pushed. The hunt is therefore on for other forms of non-volatile memories that are also fast and cheap. Four promising technologies—magnetic RAM (MRAM), ferroelectric memory (FeRAM), polymer memory, and chalcogenides—are emerging from semiconductor laboratories around the world. (Economist, 2002)[46]

In addition to the research and development efforts in alternative memory technology around the globe by different universities, noteworthy corporate efforts were those by Hewlett-Packard Laboratories (H-P Labs) in collaboration with Stephan Forrest at Princeton University, Coatue (bought by AMD) and Philips Research in collaboration with University of Groningen.

6.3 Organic Printed Electronics—Growth Potential of Memory

As discussed in Chapter 2, logic and memory were the two areas with tremendous growth potential, as highlighted by the leading industry consultant IDTechEx (2011) (see Figure 6.2 and Table 6.2).

> The biggest opportunities for printed electronics include displays, printed transistor circuits, RFID and sensor networks. Of course, these overlap […]. One thing is missing as we seek to print all of them and it is non-volatile, preferably large memory. There may be 100 hundred companies developing OLEDs and thirty developing thin film transistor circuits yet compatible printed memory - needed for almost everything we have mentioned - is being tackled only by a handful of organisations, most of them at the university - write a scientific paper - stage and with no chance of being ready on time. (IDTechEx, 2005)[47]

According to IDTechEx (2011), the main players within the area of large capacity printed memory are AMD, Thin Film Electronics, Princeton University/Hewlett Packard, the University of California Los Angeles (UCLA), the University of Groningen and the University of Sheffield. The increased interest in the organic- and polymer-based memories is based on the emergence of markets for applications such as smart packaging, branding and security, games and toys, greeting cards, tagging and smart cards where conventional silicon-based technology would not be able to reach the desired high-volume/low-cost production target (see Figure 6.3).

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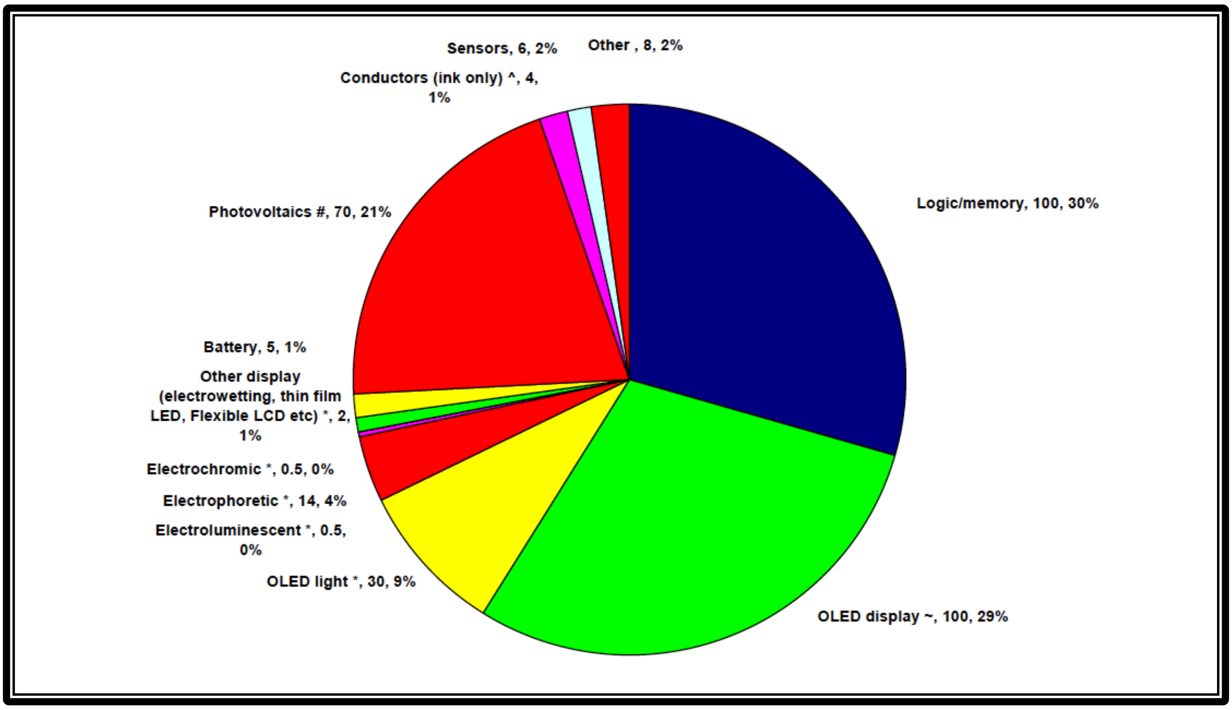
[45] http://www.tomshardware.co.uk/is-flash-heading-for-retirement, review-14150.html
[46] http://www.economist.com/node/1176222/print
[47]http://www.printedelectronicsworld.com/articles/shortage-of-memory-technologies-00000173.asp

Organic transistors and memories will create new classes of products ranging from multifunction smartcards to pharmaceutical packaging and will also breathe new life into games, toys and greeting card business. Technologies now exist to print electronics that enable games, toys and other novelties to interface directly with the Internet thus expanding the boundaries of the gaming business. By 2015, the values of "games, gadgets and gizmos" using printed or organic electronics will be $1.2 billion. (packagePRINTING, 2007)[48]

Figure 6-2 Thinfilm Addressable Market: 30%-40% of Printed Electronics Market in 2030



Source: IDTechEx, 2011

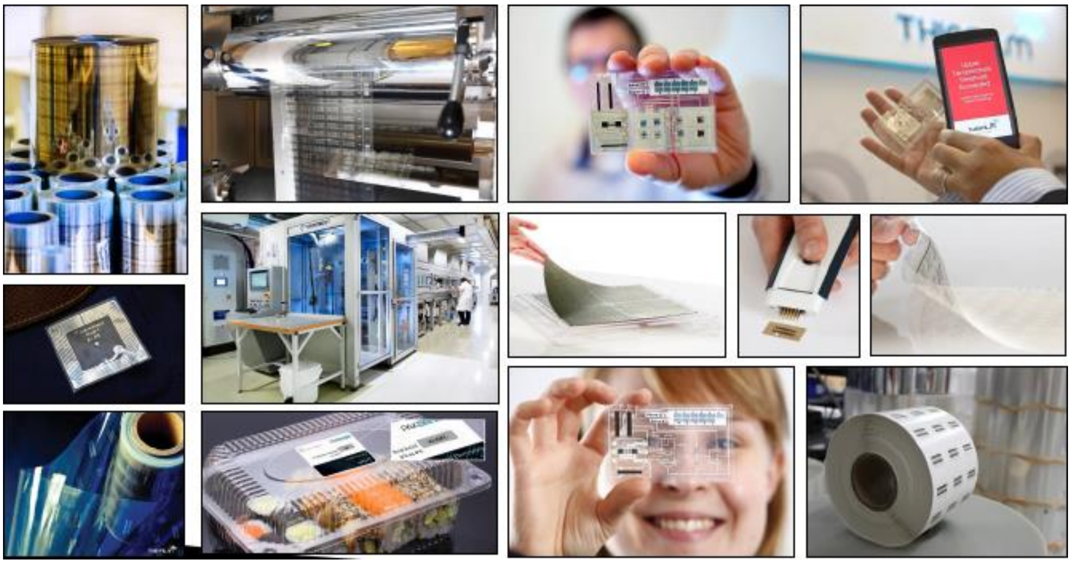
Table 6-2 Market Potential for Printed Electronics Logic and Memory 2011-2021

	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Logic/memory US$ Bn	0.002	0.005	0.01	0.02	0.03	0.1	0.5	1	2	3	4
Logic/memory % Printed	65	75	80	82	84	86	88	90	90	90	90
Logic/memory % Flexible	80	80	80	80	82	84	85	86	87	90	90

Source: IDTechEx, 2011

48 http://www.packageprinting.com/article/nanomarkets-projects-262-billion-disposable-electronics-market-2015-83929/1#

Figure 6-3 Printed Memories



Source: Thin Film Electronics, 2014

6.4 Thinfilm Collaborations

6.4.1 Year 2006-2010

During 2006-2010, TFE, having realised the opportunity focused on organic printed electronics, adopted licensing as their business model.

> And that was because my colleague from FAST, who is the CEO of FAST, John Markus Lervik […] he in 2009 invested in Thinfilm because we had done a due diligence and we saw that there was a transition point in the printed electronics industry; we believe it's going to be a major wave, technological wave, in the next few years. (Respondent DST)

During this phase, several collaborations were initiated, aimed towards the development of a technology ecosystem and value chain around printed memories considered to be a crucial and driving component for the printed electronics industry.

In 2006 Thinfilm and its partner, UK-based inkjet print head manufacturer Xaar, were able to demonstrate the first printed ferroelectric memory. Later, in 2007, TFE signed joint development agreements to strengthen its relationship with Xaar. The collaboration aimed at developing inkjet processes for printed memories at a commercial scale. At the same time a collaboration was also established with Soligie (a printed electronics manufacturer and integrator) to develop a low-cost volume manufacturing process for the production of polymer memory. Other partnerships (Figure 6.4) during that period included:

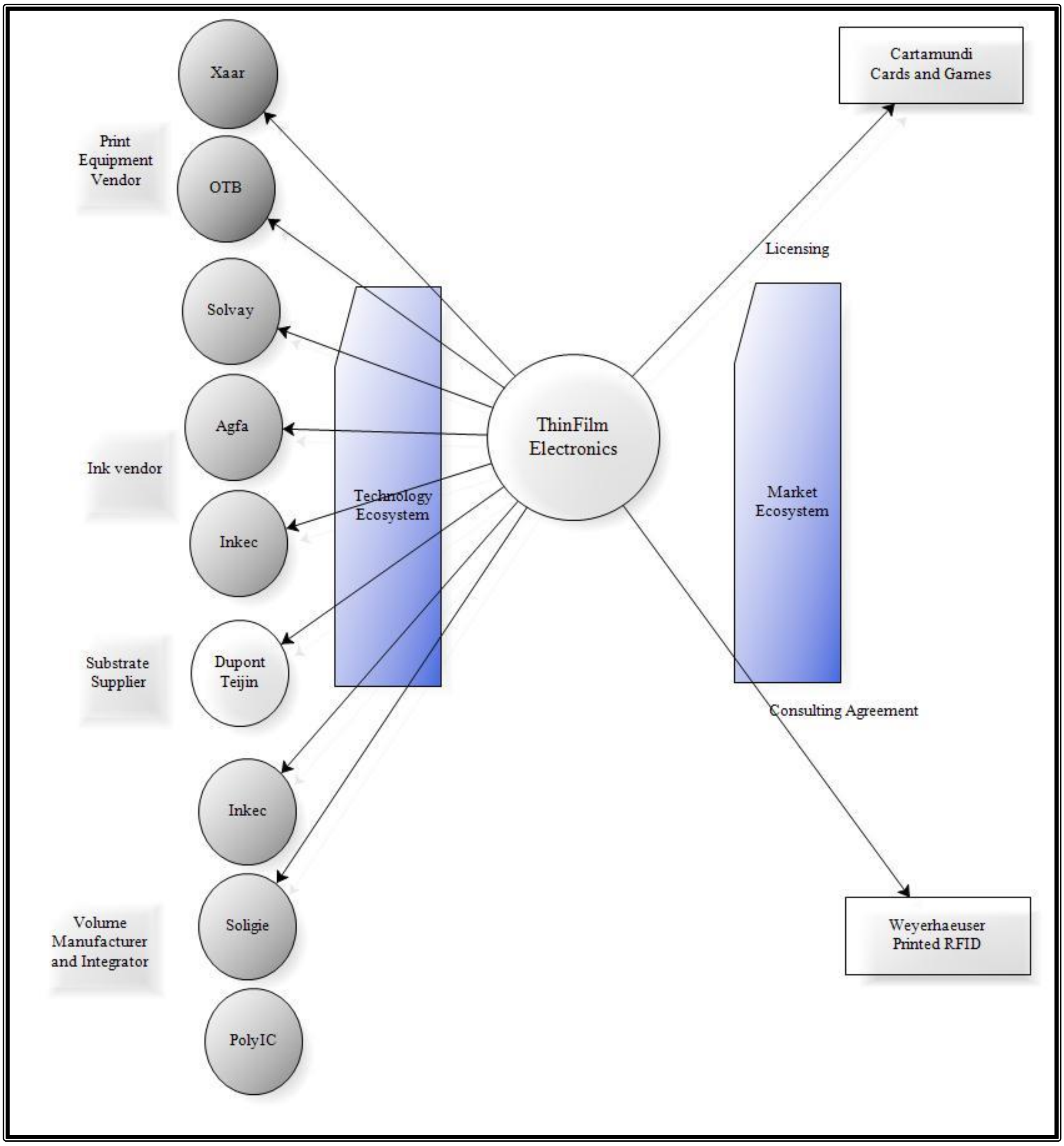
- A joint development programme with equipment vendor OTB (Netherlands) to develop in-line manufacturing processes;
- A collaboration with material supplier Solvay Solexis to enhance the performance of its memory and optimise the ferroelectric material;
- A joint development agreement with conductive ink vendor Agfa to increase the performance of material; and
- A Memorandum of Understanding (MoU) signed with substrate vendor DuPont Teijin.

Thinfilm also developed a strong and continuing relationship with InkTec, headquartered in Kyungki-do, Korea and a leader in manufacturing printed electronics. The collaboration aimed to optimise TFE memory based on InkTec silver inks for memory cell electrodes and in 2009 they were able to demonstrate a fully roll-to-roll (R2R)[49] manufacturing process for their printed memory. Another important collaboration worth mentioning during 2009 was between PolyIC and Thinfilm that resulted in R2R manufacturing of rewritable polymer memory. PolyIC was a joint venture between Siemens and Leonhard Kurz with expertise in roll-to-roll production processes and was involved in the development of RFID (radio frequency identification) tags.

In addition to these partnerships that aimed at building a supply chain and technology ecosystem for ferroelectric memory, TFE also worked on establishing relationships with end customers to enable commercialisation. The first targeted application during that period was a platform for toys and games. In this regard, a licensing agreement worth €20,000 was signed with Cartamundi NV, the leader in 2007 for collectible cards and games. A consulting agreement was also signed with Weyerhaeuser to develop printed ferroelectric memory to be integrated with Weyerhaeuser 13.56 MHz printed RFID devices. In 2009, the agreement with Cartamundi was deepened and resulted in the opportunity to cater for the broader market of toys in addition to the use of Thinfilm technology for collectible cards and games.

[49] R2R is a manufacturing technique involving processing of flexible substrate.

Figure 6-4 Collaborations 2006-2010



Source: Author

6.4.2 Year 2010: Journey from Licensing to a Product Company

In 2010 TFE changed its orientation from a licensing to a product company. The main factor was a change of leadership that resulted in the adoption of an entrepreneurial approach. The role of CEO and top management, and their prior experience, is instrumental in defining boundaries (Santos and Eisenhardt, 2009) and developing strategic direction, and in new product development. Davor Sutija, the newly appointed CEO, with his track record of successes for previous entrepreneurial ventures, identified the opportunity within the printed electronics sector and saw a value proposition that Thin Film Electronics could deliver.

> In 2006, 2007 and 2008 the focus was on creating patents, creating IP, and finding somebody like Intel to take it to market.
>
> That is one strategic direction. That is having a partner with muscle—I mean, resources and technical capabilities and access to market—to create products for you. Then you essentially become an IP factory. You're essentially licensing.
>
> And we thought that there was really a unique opportunity to create a product company. So Thinfilm had previously been an IP company; John Markus bought 10% of the company […]; and changed the direction of the company to be product-oriented. He asked me to join the team, first in business development and then, from July 1 last year (2010), as the CEO. (Respondent Davor Sutija)

Thinfilm initially engaged in exploitative R&D focused on improving its printed memory and lowering the cost of the memory. With these aims, it adopted an exploratory market strategy to target cost-sensitive market segments and flanks. Flanks are defined as opportunities unnoticed and underexploited by established companies. Such 'Trojan horse' moves are considered performance enhancing for entrepreneurial firms (Katila et al., 2012). TFE first decided to enter the toy and games markets with its standalone 20-bit memory. The TFE strategy was one of "innovation from below" and finding out sweet spots in existing markets where the technology can be disruptive.

> […] People have been working on things for 10 to 12, 15 years; and people are becoming more realistic—they're not saying, "We're going to do an entire RFID tag immediately." They're dividing the different addressable markets into segments and saying, "We're going to go after the easy ones first, then the next ones, and so forth.
>
> That's why we're starting with toys and games. That's why, you know, this is what we make, because this is doable with today's technology. (Respondent DST)

The toys and games platform, and the ambition to be product oriented, resulted in the necessary customer interaction required to improve the rewriteable memory. This provided the initial impetus to bring printed electronics products to the market. However, OPE, though having high growth expectations is characterised by technology push dynamics rather than market pull, with only a few applications in the market. Most of the active organisations tend to be more science based rather than engineering based (Autio, 1997) with greater emphasis on enhancing technological competencies within the components rather than on integration and products.

> What we think is great about toys and games are that in spite of it being on one level a niche market, it's very demanding. Nobody will abuse your technology more than children; and nobody has to be treated more safely than children. And that combination is really tough. (Respondent DST)

6.4.3 The Journey from Components to Integrated Systems

From 2010 onwards TFE worked towards the development of the ecosystem for smart integrated systems. The ecosystem analogy drawn from biology provides a rich and dynamic picture of complexity associated with loosely connected participants (Iansiti and Levin, 2002). Ecosystems are characterised by value co-creation, shared logic, symbiosis, co-evolution and increased interdependencies (Adner, 2012; Thomas, 2013). Reducing risks and uncertainty drives the creation of an ecosystem.

TFE, being a listed company and financed by shareholders, focused on reducing time to market as this is the fundamental risk for emerging technologies.

> The fundamental risk is that the technology either doesn't succeed or that another technology replaces it, or that intended application goes away because of something […] So a delay in getting a product to market increases risk. (Respondent DST)

Transistor and logic tend to be the important drivers for OPE applications, along with memory, so Thinfilm, recognising the gap, embarked on the development of a transistor, an important step towards the vision of the Internet of Things (IoT). Such an entrepreneurial orientation and strategic intent demonstrates TFE's dynamic capability.

Cisco believes that there will be 50 billion devices connected to the Internet by 2020. According to the report by McKinsey Global, 2013, "Internet of Things has a potential to create an economic impact of $2.7 trillion to $6.2 trillion annually by 2025."[50]

> IoT is simply the point in time when more "things or objects" were connected to the Internet than people. (Evans, 2011)[51]

[50] http://www.mckinsey.com/insights/business_technology/disruptive_technologies

In this regard collaborations were deemed important, as TFE did not possess the competency internally for developing transistors and logic. One of the significant collaborations announced was with PARC, a Xerox company with 15 years of experience and the world leader in developing TFT (thin film transistors). The collaboration that was initiated in 2010 has been able to achieve fundamental milestones such as demonstration of Thinfilm's addressable memory. According to Raghu Das, CEO of IDTechEx:

> This announcement is a significant step forward for the printed electronics industry. Having both printed memory and printed transistors to address the memory is a fundamental 'building block' that has applicability to, and enables an enormous number of applications across a myriad of markets. (TFE, 2010)

TFE's vision is to move towards IoT and bring electronics into disposable items. After due diligence and market analysis, TFE selected three families or potential systems where printed electronics offers unique advantages compared to silicon technology. This includes temperature sensor tags, display tags and an open system that would enable communication with device by radio frequency (RF). To achieve these goals strategic collaborations were established with component providers such as Acreo (electrochromic displays), PST Sensors (thermistor), Imprint Energy (batteries) and Polyera (n-type semiconductors) and an undisclosed collaborator (p-type semiconductor). In addition to that, existing relationships with InkTec and Solvay were further strengthened and deepened. The approach taken by TFE now differs from earlier announced partnerships. The present focus is on developing a complete system and identifying niche markets for possible applications rather than developing components alone and acting as a licensing company. Their unique value proposition is driven by cost per functionality rather than cost alone as that is not a differentiating and competitive factor in the targeted markets. As a result of these collaborations TFE was able to demonstrate proof of concept for temperature sensors enabling quantitative monitoring of perishable goods and pharmaceuticals.

> What if you have the wrong technologies? […] How do you know you have the right technologies? You bring people with other technologies into your system so that you're always level pegging against the best. You're creating a champions' league of technologists. (Respondent DST)

In January 2014, Thinfilm completed the acquisition of the Silicon Valley industry leader Kovio with its NFC (Near Field Communication) technology. The strategic move enabled TFE to expand its IP assets and ensured rapid progress towards its vision of an Internet of

[51] http://www.cisco.com/web/about/ac79/docs/innov/IoT_IBSG_0411FINAL.pdf

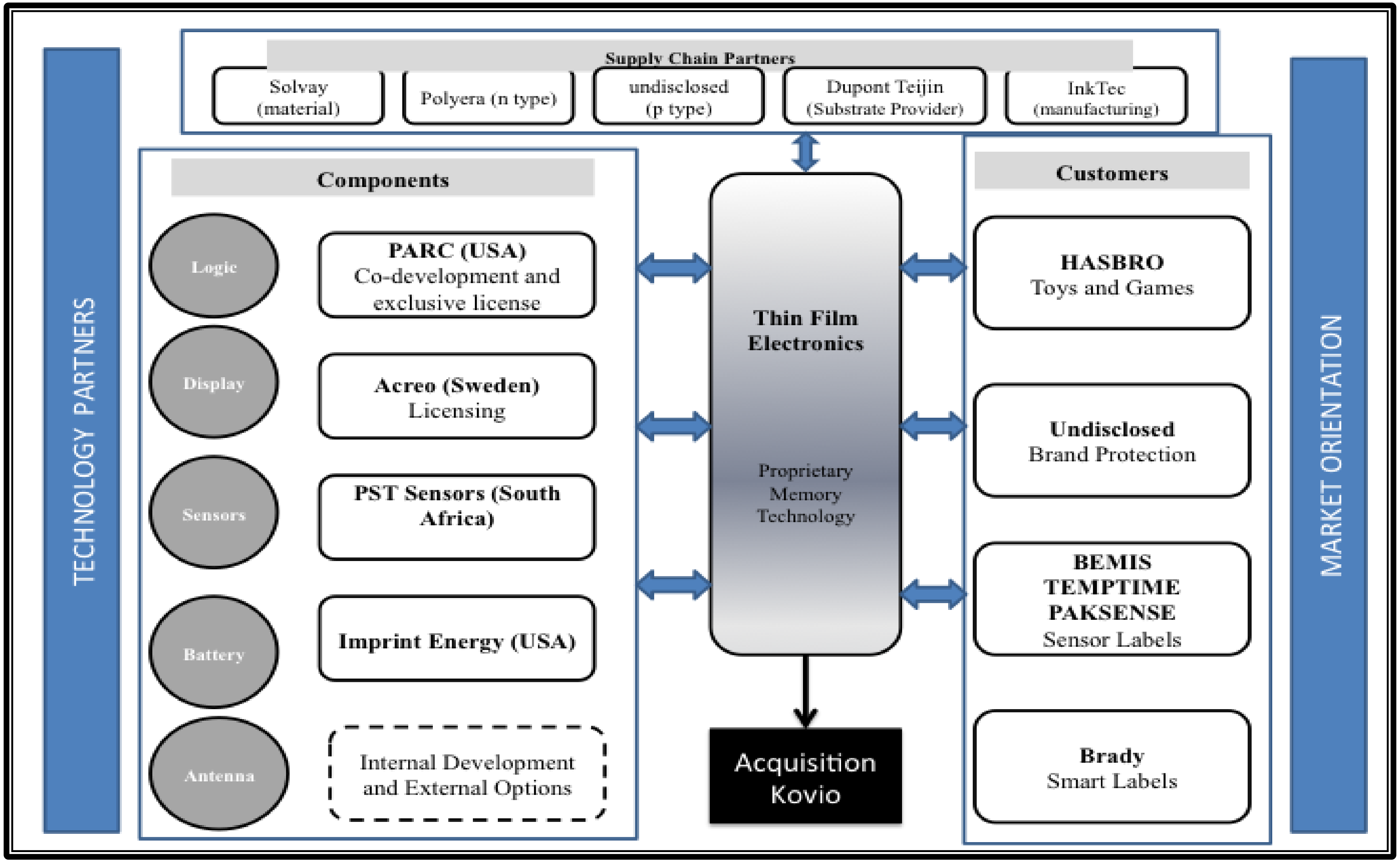
Things by adding functionality to everyday objects. In addition, the NFC Innovation Centre was established in Kovio's facilities at San Jose and joined by more than 20 Kovio team members.

Success for disruptive technologies depends on crossing the chasm from lab to market. These early technological achievements resulted in demonstrating the potential of the technology to brand owners and created the required traction. TFE pursued not only technological partnership, as is the case with most of the technology and component developers in the OPE space, but is also working towards the development of a broad range of commercial opportunities. TFE has established strategic relationships with Fortune 500 companies such as Bemis, Brady and Hasbro to enable commercialisation and reduce the speed to market. Figure 6.5 demonstrates the TFE ecosystem approach as of 2013 and shows technology and upstream material partners as well downstream commercial partners.

Commenting on the new approach of TFE, one of the respondents, while comparing TFE's current strategy with the previous one, commented:

> […] that was the case with Thinfilm a year ago: they didn't have kind of the clear path to the market. It was more: let's develop the base technology and see what happens, and see what type of markets that potentially can pop up.
>
> That is the wrong approach when you're working with the technology development process that has a lead time of a couple of years: you need to know exactly kind of the markets you want to compete in, understand the cost functionality spec… and develop kind of a targeted milestone plan in order to deliver those products at a certain cost and functionality points in the future.
>
> And I think that has been a very constructive and helpful exercise for the company. And… I'm not saying that we have all the answers, no—it might be that next year we need to… yes, strand a couple of technology processes related to certain application markets… hopefully a couple of new ones will have popped up. (Respondent TTT)

Figure 6-5 Thin Film Electronics Ecosystem

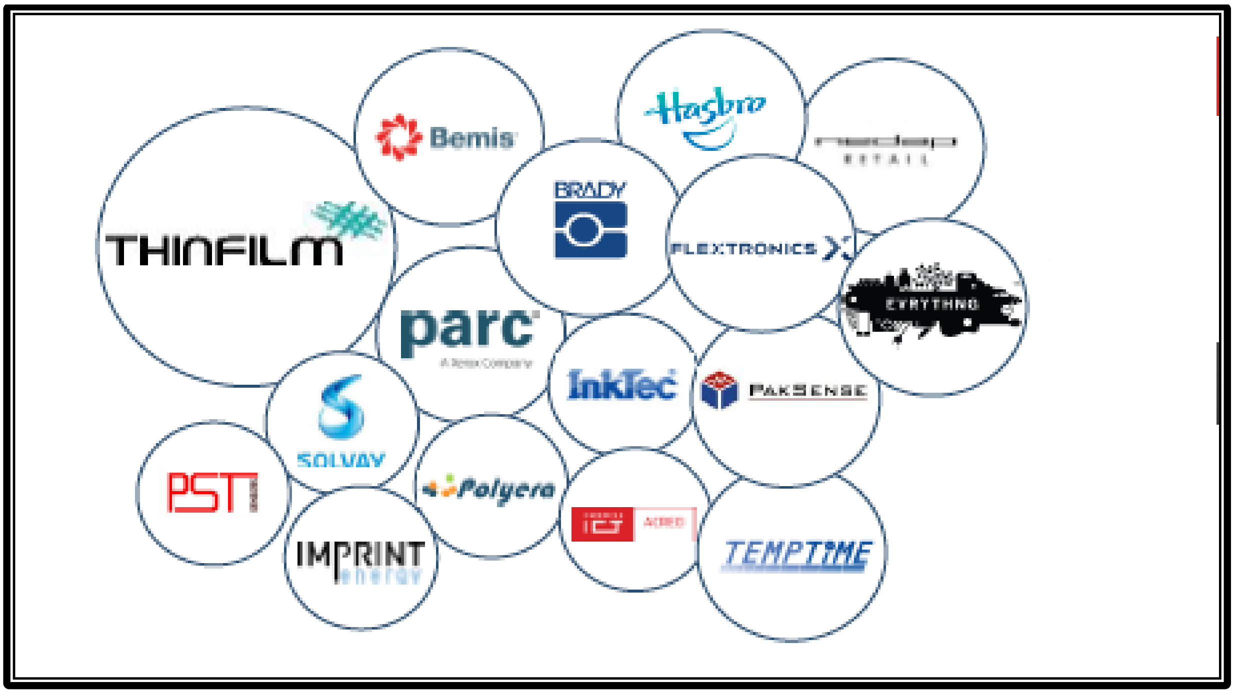


Source: Author

6.4.4 Current Status of Collaborations and Milestones Reached

The figure below describes the current status of collaborations as at December 2014. TFE has expanded its commercial partners and includes Flextronics, a leading supply chain solution company; TempTime, a leading provider of time temperature indicators to the health sector; and Evrythng, a Web of Things software company.

Figure 6.6 Current Status of Collaboration



Source: Thin Film Electronics, 2014

6.5 Drivers for Ecosystem Creation

In this case study, the focus is on the small venture that is providing the necessary orchestration and keystone advantage to develop an ecosystem for OPE. TFE in the case study acts as a hub and platform provider and therefore the health of the ecosystem depends on its activities. It is at present acting as a facilitator of niche creation by developing platforms that can deliver value in diverse industries such as smart packaging, brand theft and authentication. Their strategy is considered to be one among very few attempts within the OPE emerging space where the efforts are concentrated on developing not only upstream technology relationships but also downstream commercial relationships.

According to Adner (2012, p.116), “being in the picture is not the same as being in charge of the picture”. Secondly, being the lead firm is not associated with size or resource richness (Williamson and De Meyer, 2012) and leader and follower do not map as winner and loser (Adner, 2012). But what differentiates a leader from a follower is “having a sound strategic vision”, “making up-front investments” and “taking the up-front risks” (Adner, 2012, p.117). TFE, being the hub firm, acts as architect and mobiliser of the ecosystem, thus defining the system level goal and boundary arrangements such as the actors’ enrolment criteria, degree of stratification or tiers of membership, redundancy and exclusivity (Gulati et al., 2012; Nambisan and Baron, 2013).

The industry presently is mostly concentrated around developing individual components rather than an integrated system and in the opinion of experts this has delayed its commercialisation. Developing an emergent technology requires going beyond proof of concept and demonstrators to prototypes that in turn will expedite diffusion and adoption by the end customer.

> We've had many, many different companies trying to live out of individual components.
>
> We had the battery companies. We had display companies and so on and so on. And they started to talk to each other. And then no one knows who is taking the lead, I mean who is doing the integration? Is it we, or the other one?
>
> But I think that that has to mature and you have to find your roles. But that's the only way to get this out on the market, is the collaboration. But I'm not sure we have found the right form of collaborations yet. I mean, it's very often bilateral, that two companies talk to each other and then they try to do something. (Respondent GA)

6.5.1 Value Creation, Reciprocity and Interdependence in an Ecosystem

One of the most important characteristics of ecosystem is its value creation logic (Adner, 2006; Thomas and Autio, 2012). Möller and Rajala (2007, p.898) defined the value system of a business net “as a set of specific activities carried out by the actors constituting the net. […] these activities are based on the resource constellation controlled by the actors”.

Symbiotic, reciprocal and interdependent relationships among the partners facilitate value creation within the ecosystem and differentiate it from other arm’s-length supply chain transactions. By developing complementary relationship among actors, the hub firm facilitates synergies and systemic impact and achieves goal convergence, lock-ins and investment by partners, which results in reducing uncertainty, sharing risks and accelerating time to market. Ecosystem creation thus aims at increasing the size of the pie and creates a win-win situation for all the partners rather than redistributing value (Pitelis and Pitsa, 2012).

> So the idea of ecosystems, the fundamental one, is that anything that shortens your time to market is something you want to do; and anything that guarantees that you have world-best technology, and a way to diffuse that technology into market, are the other pillars of why you want to build an ecosystem.
>
> Building an ecosystem, on the one hand, can save you money because other people do some of the heavy lifting. And publicly I often refer to that as an important asset. Well, in fact, they call it off-balance sheet assets.
>
> So, the entire idea of creating an ecosystem is that allows you to become world class [...] before you make commitments of capital to make a particular product. So, our idea about creating an ecosystem is on the one side to figure out what is technologically possible in printed electronics; we'll learn from our partners and create a win-win business model, and then get business partners. (Respondent DST)

According to an IBM executive brief, "In the ecosystem view, innovation and operations rely on influencing assets that the company does not own." (Wenzek, 2004).[52] Keystone actors provide "operating leverage" through platforms, development of physical, intellectual and financial resources, mobilising and sharing knowledge (Iansiti and Levien, 2004; Thomas, 2013).

To sum up, the keystone or hub firm co-creates value by increasing efficiency and productivity within the network, contributes to robustness through continuous technological innovation and facilitates diversity (Iansiti and Levien, 2004).

The next section discusses in more detail some of the TFE collaborations and their tangible and intangible impact. It illustrates how value was created within an ecosystem and how individual offerings from each partner were synergistically combined to co-create value.

6.5.1.1 TFE and Acreo

Thinfilm has had a historic and interpersonal relationship with Acreo since 1997 when it embarked on a journey for roll-to-roll printing under the leadership of Gude Gudesen. Dr Magnus Berggren (presently a member of the Technology Advisory Council at TFE), who was a PhD student of Olle Inganas, teamed up with Goran Gustafsson (presently CTO of Acreo) and some of his colleagues at Linköping University to form TFE.

[52] http://www-935.ibm.com/services/us/imc/pdf/g510-3983-rewiring-electronics.pdf

> Maybe the Silicon Valley thing works there […] we have a research centre that's close by that is a source of employees and a source of, you know, ex-employees and so… It is a part of our ecosystem in many, many different ways. (Respondent DST)

Acreo is a leading research institute in Sweden having strong linkages with Linköping University and that enables TFE to leverage from the new research and interesting technologies that are developed at the university.

> Acreo still is one of the key technology developers for such an ecosystem, and the connection to university that we have, this sort of mini-ecosystem in the university, with us. We have a lot of technologies in the pipeline which will be very important for that kind of ecosystem.
>
> So I think we will definitely be a very good technology provider into their system, and Thin Film Electronics could be one of the companies really taking it to the products by combining it with other technologies, also. (Respondent GA)

Acreo also established a manufacturing greenhouse referred to as the Printed Electronics Arena (PEA) in the Norrköping region in 2008 to reduce the barriers for commercialisation of OPE. The main participants for the PEA initiative other than Acreo include Linköping University and Norrköping Science Park. The facility is equipped with state-of-the-art equipment and is used for making prototypes and developing manufacturing processes. The PEA lab complements the TFE activities and provides opportunities for sharing resources and further adding value to development of their processes.

In addition to the prototyping facilities that TFE is able to leverage, TFE and Acreo have also participated in many consortium projects. TFE led a consortium comprising Acreo and Santa Anna IT Research Institute (PROLOG) which received €1.4 million (£1.128 million)[53] from the Eurostar programme for commercialisation of display driver logic for smart tags. In December 2014, Acreo announced the development of flexible and ultra-thin displays using screen printing technologies. The new form factors allow the replacement of conventional LCD displays in applications such as smart packaging, labels and RFID tags. TFE is one of the licensees of the product (Fletcher, 2014).[54]

> […] We have given a design project to a team at the university; and we work with the national lab, Acreo; and Acreo has clean rooms; and all the work that we do in clean rooms is currently done at Acreo. (Respondent DST)
>
> While Acreo, they have a different set of technologies, some which are useful for us. But then, also, Acreo has sort of used by us on a personnel level, also. We have a girl there

[53] Currency conversion is based on average rates in 2014.
[54] http://www.fespa.com/news/features/acreo-uses-screen-printing-to-develop-ultra-thin-displays.html

> that does processing for us in their facilities, full time. They have a lab that complements ours.
>
> During the survival time we sold a lot of equipment that we had out in our clean room, to Acreo. It's still there. So we have a deal so that we can use it in their clean room, and so forth. (Respondent CKT)

6.5.1.2 TFE and InkTec

InkTec, listed on the Korean Stock Exchange and with a presence in more than 100 countries, has been the production partner for TFE roll-to-roll memories since 2009. The collaboration between InkTec and TFE was initiated in 2007 through a joint development agreement. Over the years the relationship has been deepened as well as broadened. InkTec already had experience and an existing infrastructure for customised mass production of roll-to-roll printing that TFE was able to leverage. InkTec developed transparent silver conductive ink for the printed electronics industry that also proved suitable as memory cell electrodes. In 2011, owing to the success of TFE memory in the toys and games industry, InkTec established a dedicated facility that has the capability to produce 10 million tags of TFE memory every month.

> What's most important is they already had a brownfield site with the roll-to-roll equipment there that was custom designed by InkTec […] And that equipment was competent to make our memories. If you could do a search of the entire world there were probably only four places that we know of that could have built our memories roll-to-roll the way that InkTec does. (Respondent DST)

In addition to these tangible benefits, the collaboration has also resulted in TFE learning and refining its production processes, decreasing time to market, delaying CAPEX and decreasing technology and uncertainty.

> It means two things. We've got world's best technology, and we saved years in bringing that technology in for products—because now that we want to buy a roll-to-roll machine ourselves... but if we had tried to do that three years ago, we would have bought the wrong machine.
>
> There's no way that three years ago we could have bought the right machine. Number one, it didn't exist, so we would have had to design it; and we had no competence to design it. With the 2½ years of experience with InkTec, now we are in a position to order a roll-to-roll machine for further developments. (Respondent DST)

6.5.1.3 TFE and PARC

TFE realised the opportunities and gaps for integrated systems and worked towards the development of the printed transistor and logic. Printed thin film transistors can be regarded as a reverse salient (Hughes, 1983) for the printed electronics industry and though there are many players that include universities, research institutes and firms working on thin film transistors very few players have been able to demonstrate technological progress in terms of printing transistors. Palo Alto Research centre (PARC), a division of Xerox, is considered a leader in printed and novel electronics with more than 15 years of experience in the field.

TFE was introduced to PARC in 2010 on their visit to Silicon Valley as an initiative of Innovation Norway to develop an understanding of printed electronics. TFE initially collaborated with PARC to develop a design for the addressable memory and was able to produce a prototype of printed rewriteable memory addressed with complementary organic circuits. Realising the synergies by combining both the technologies, the two parties extended their engagement to the development of a printed sensor platform and, ultimately, PARC investment in TFE. TFE also holds an exclusive license for nine years on all PARC background IP.

> …relationship with Ana (Manager of the Printed Electronics Device Area at Xerox), she believed in us. She said, "What you're trying to do is not too complicated. Most people are trying to make products that are too complicated. I believe that you have a commercialisable memory. I believe that 20 bits is the first starting point; I think we can create a project together, for small amounts of money, that could design a memory plus transistors."
>
> They did the design. And then after the design we then did a negotiation in order to do the actual prototyping; and as part of the negotiation they saw that Thinfilm was a unique company.
>
> So instead of just doing a prototype and getting a fee for service, they decided that we will be their commercialisation partner for all their technology, in… for printed electronics, with regard to logic and memory.
>
> First time they ever invested in a public company; first time they ever invested in a foreign company; and first time they ever gave an exclusive licence to background IP for something that wasn't commissioned work. First time in 40 years. (Respondent DST)
>
> PARC is foremost as a rapid prototyping house for us. They've been in printed electronics for ten years. They have a printed process up and running. It is digital, it is relatively fast. They have experience in doing design and fabrication.
>
> So it's very useful to do early rapid process, in my opinion, evaluating what can be done, and not. (Respondent CKT)

However, what differentiates the keystone approach from others such as dominators, landlords and niches is their ability to create as well as share value thus ensuring symbiosis with member participants (Iansiti and Levien, 2004). The following quote illustrates how PARC was able to leverage from the Thinfilm platform around systems. Thinfilm also collaborated with PARC and University of Berkeley under the project funded by FlexTech Alliance.

> "There are lots of efforts in academia and research where they play with printing electronics," says Janos Veres, who manages the printed electronics team at PARC. What's new is "somebody trying to do it commercially and figuring out what are the first things you can make with 10 or 20 bits of memory and a simple battery," he says. "We need a library of different building blocks that are made by the same standard manufacturing process to get this ecosystem working." (Talbot, 2012)[55]

> Working with Thinfilm in a particular physical dimension, as it's been, is important. They have a view of the future we think makes the most sense, that also, when you start working on the real-life problems to get from where the research is in the world to getting a product out, it helped us identify which were those difficult problems which sometimes are not obvious until you really start grinding down to make a product. (Respondent RBP)

In September 2014, Xerox PARC increased its stake in Thin Film Electronics. PARC will receive 334,702 new shares worth 1,549,000 Norwegian kroner (£150,000) through a private placement.

In Jan 2015, the relationship between PARC and TFE was further strengthened. TFE memory labels will now be printed on a commercial scale at a Xerox manufacturing site that has the annual capacity to produce more than a billion labels. This is a massive achievement not only for TFE but for the entire OPE industry as it marks an important step towards exploitation and mass production.

> And so scaling up in the printed electronics is something that's not happening in very many places at all, yet, I think. (Respondent RBP)

> We think it's important because the whole Thin Film Electronics business is there's something to get out there that gets into the market because… printed electronics has been through the hype cycle a bit, right? It was five years ago, particularly in the UK, actually, I think, and Europe to a less extent, was seen as a huge new possibility to create a new electronics industry that would not be necessarily in Asia. (Respondent RBP)

[55] http://www.technologyreview.com/news/426731/printed-stickers-designed-to-monitor-food-temperatures/

6.5.1.4 TFE and Imprint Energy

Imprint Energy is a start-up founded in 2010 by Dr Christine Ho and Brooks Kincaid and at present is working on the commercialisation of zinc-based rechargeable batteries, technology developed at University of California Berkeley. The company received its initial seed funding from Dow Chemical Ventures and now employs eight people. These batteries can be printed using low-cost capital equipment and conventional screen printing processes, and customised into different shapes as per customer requirement, thus enabling the design of the power source around the device and lifting the barrier of design constraints.

The energy source is an important component for the early applications TFE are envisioning. Imprint Energy are acting as a component provider for the TFE Ecosystem. The partnership is a win-win solution for both the partners: TFE are able to analyse the potential of a new technology that may prove better than the earlier tried and tested one and achieve their product specification target, especially for the temperature sensor (targeted to achieve a price point of 30 cents or less); on the other hand, Imprint Energy are able to explore the opportunities for applications of their technology in printed electronics outside their expertise of consumer electronics and wearable electronics and gain leverage from other partners of TFE in the ecosystem.

Commenting on the importance of the relationship with Imprint Energy, TFE CEO Davor Sutija said:

> We will be working with Imprint Energy to develop and test samples for low-power, ultra-high-volume applications like temperature tags and small-scale displays. Imprint's technology requires very little packaging, making it cost effective to scale the battery to the requirements of a given application. (Clarke, 2012)[56]

> Thin Film […], they're one of several partners, customers that we're working with to develop technology basically determining specs and matrix that make sense for both parties, determining a financing situation that makes sense for both parties and leveraging that type of collaboration as a means towards developing technology towards market entry as opposed to developing technology for technology's sake. That's a customer oriented partnership example.

> It has been very beneficial in really getting the right hand to talk with the left hand. Because we have not been directly been talking with Acreo and I don't think Acreo really cares on a day to day basis of what we've been up to, but in having Thin Film communicated on what we can do and what we expect we can do, that help both parties because we don't plan to make displays, but it's really helpful to know that if we wanted

[56] http://www.edn.com/electronics-news/4368912/Plastic-memory-firm-signs-partners-for-printed-systems-item-2

> to make a device that included a display we know that we could work with this technology. So that is benefit of ecosystem. (Respondent BKI)

6.5.1.5 TFE and Bemis

TFE not only focused on developing technological partnerships, as is the case with most of the technology and component developers in the PE space, but are also working towards the development of customer partnerships. Highlighting the importance of these market oriented partnerships, a respondent commented:

> But the most important thing is they give you talent. So, in the case of Bemis, the chief technology officer of Bemis, a $5.2 billion company, every single week spends between one and three hours on the telephone with our chief technology officer discussing what they're going to do next week.
>
> So it's a great partnership because they bring something to us, which is the ability to scale. Bemis is a company that prints 200 billion packages per year. That number is absolutely mind boggling.
>
> So if I want to talk to a company that would need hundreds of millions of our devices for their product lines, having a partner like Bemis is a significant step up in credibility. (Respondent JET)

6.6 Findings

The TFE case provides a unique opportunity to discuss the emergence of a new organisational design for an emerging industry characterised by complexity and uncertainty. In such a context where the future is not only unknown but also unpredictable the traditional means of collaborating would result in delays and inflexibility.

The findings are divided into two broad areas. Section 6.6.1 discusses the creation, evolution and stabilisation of an ecosystem. The discussion on design elements of an ecosystem is important before moving to section 6.6.2 that focuses on orchestration and management of an entrepreneurial ecosystem using a process perspective and elaborates on intra-organisational and inter-organisational routines that enable value capture.

6.6.1 Creation of an Ecosystem: Dynamics of an Entrepreneurial Ecosystem

6.6.1.1 Creation of an Ecosystem

An emerging inter-organisational design, such as an ecosystem, differs to a large extent from a traditional hierarchical design based on control and coordination that suffers from delays among internal and external collaboration partners (Fjeldstad et al., 2012; Ritala et al, 2013). The main differentiating factors between the traditional hierarchical organisational design and the new emerging design of ecosystems are the decision-making processes and the mode of sharing resources and appropriating benefits. These are more lateral and reciprocal with long-term orientation (Fjeldstad et al., 2012; Ritala et al., 2013). However, "any new theoretical construct begs the question of its boundary conditions" (Fjeldstad et al., 2012, p.745). Strategic decisions regarding the boundaries, though important in the context of ecosystem creation, are mostly dealt with conceptually and include aspects such as enrolment decision, stratification, exclusivity and redundancy (Gulati et al., 2012). The next section will discuss the creation of the TFE ecosystem, its enrolment criteria and stratification strategies.

6.6.1.1.1 Selection of Partners: Enrolment Criteria

> "You need to have a club where membership is a virtue*."* (Respondent DST)

Motivations for alliance formation and selection of partners for established firms in a stable environment have been researched thoroughly compared to the factors that drive alliance formation in a complex and dynamic technological environment for new ventures (Rothaermel and Boeker, 2008). Hub firm enrolment strategies impact the structure, size and diversity of an ecosystem (Dhanaraj and Parkhe, 2006). According to Parmigiani and Howard-Grenville (2011) inter-organisational relationships (IOR), which encompass a broad range of collaborative arrangements from strategic alliances to consortia, combine both exploration and exploitation form, that thus suggests "the most significant feature of an IOR is not its form but, rather, the intent of the relationship." In the case of TFE, the collaboration forms vary and can include licensing, research agreement, consortia and supplier-buyer relationship but, analysing them from the perspective of intent, the focus is more towards exploitation and commercialisation. This has also resulted in a reduced emphasis on collaborations with universities, which focus more on the research side, and more on collaborations with Fortune 500 companies who not only understand their market space but also possess ultra-high scale manufacturing capabilities. Thus the change in business models from licensing to product mix also resulted in a change in the relationship mix and the type of ties that TFE pursued.

"Resource alignment" has been identified as an important factor in alliance innovative performance by Das and Teng (2000) and is broadly categorised as either supplementary or complementary. Supplementary resources refer to the situation when partners contribute to similar and performing resources. Similarity of the resources refers to the degree to which two partners' resource contribution is comparable in "terms of both type and amount" whereas complementary resources refers to the extent to which partners' resources are "non-redundant and distinctive" (Das and Teng, 2000, p.49). For TFE, other than the intent that formed the initial membership criteria, other important factors influencing the tie formation are the need for complementary resources (manufacturing, complementary technology) and amount of leverage the partnership offers, that is, to what extent the resources brought by different partners are comparable when measured in terms of commitment.

TFE's approach to enrolment of partners within the ecosystem is a closed partnership arrangement, rather than the open membership that is more common within IT platforms. Closed membership allows better coordination and diversity but requires careful selection of partners (Gulati et al., 2012). TFE preferred a manufacturing partner such as InkTec over earlier production partners like PolyIC and Soligie who were more research oriented. The selection criteria were not just InkTec's size, visibility and reputation, as is considered to be vital for enhancing the legitimacy of new firms (Lechner and Dowling, 2003), but also its expertise with production of other similar technologies. Selection of **brownfield sites** is an important theme that emerged from the interviews; that is, collaborating with partners who bring with them relevant experiences because that tends to reduce uncertainty when developing new processes, decrease the development times for new products and also contribute to capability development by improvisation.

> So there's a lot of technologies out there, right? […] when I look at the history, when we created Renewable Energy Corporation we went to brownfield sites, not greenfield sites. We went to sites where the building's already where they are, where the piping infrastructure was already there; and then you create a new process and a new product.

> We're doing the same in printed electronics. We're going and leveraging… we're standing on the shoulders of giants. We're going to InkTec that already has a production line, that already has inks, that already has PET, and we're saying, "Modify this a bit to create a new product." (Respondent DST)

In addition to the preference for brownfield sites that reduced the uncertainty associated with manufacturing partner selection, patenting was considered as a signal of a partner's technological expertise and its commitment. Thus, whereas TFE looked for complementary alignment in technical knowledge, it also considered supplementary alignment in resources crucial for the success of the ecosystem. Complementarities resulting from non-overlapping niches contributed to higher strategic interdependency and a propensity for alliance formation (Gulati, 1995; Rothaermel and Boeker, 2008) while supplementary alignment contributed to risk sharing.

> We're going to Polyera who has worked on n-type semiconductors for many years and we're saying, "Modify your inks for gravure printing."
>
> Best partnerships are where they leverage our effort 5 to 1 or 10 to 1. (Respondent DST)

Since the TFE vision is to develop an ecosystem, co-development, transparency, openness and trust are more important in partnership and also influence the criteria for selection of partners.

> I think that each company should bring something important to the table. What we bring to the table is $100 million of investment in printed memory technology. And the patent family is all across the globe that protects… and the initiative to make product, and the DNA that is associated with that.
>
> But one without the other is not enough. What we want from our partners is the same DNA and their own IP that complements ours.
>
> Polyera, with IP on the n-type semiconductor; PARC, IP that we now have an exclusive licence on, background IP in printed transistors; InkTec, unique IP in silver inks and a DNA to make printed products. (Respondent DST)

6.6.1.1.2 Stratification in the Ecosystem—Tie Heterogeneity, Exclusivity and Redundancy

TFE's ecosystem demonstrated some degree of stratification. Stratification refers to tiering of partners within an ecosystem (Gulati et al., 2012). It can be introduced intentionally based on the relevant technological priorities. In the TFE case, heterogeneity of ties and assigned exclusivity resulted in stratification. What is evident from the case is that the significance of the collaborations varies between what is core or peripheral for technological platform development and commercialisation by the hub company. Core collaborations tend to be more intense, transparent, reciprocal and multiplex thus creating higher interdependencies. They tend to act as "glue", maintaining the stability of an ecosystem as a result of partner iteration, while for peripheral collaborations, replacements can take place if partners are unable to meet the system's expectation. Owing to the interdependencies, both the scenarios offer challenges for the stability and robustness of the ecosystem.

> But the difficulty that's going to happen, when we get to a position where we actually are making a specific product and one of our existing partners doesn't cut it anymore and we have to switch them out, that'll be hard.
>
> It'll be hard on two fronts. Kicking them out will be just… you know, it'll be a hard half hour, but it'll be done. The harder part is finding somebody else to bring on-board instead, because all of a sudden we're signalling we need somebody new.
>
> Well, that gives them a bunch of aces in their cards that they hold in their hand, because they know that we need them. When we built the original ecosystem that wasn't the case. (Respondent DST)

Granovetter's (1973) notion of strong and weak ties has been explored in great depth within the network literature and provides rich understanding of network structural properties and their implications. Extant research on networks highlights three important themes: those that suggest that close and embedded ties facilitate tacit knowledge transfer; a second stream of research advocates the importance of structural holes (Burt, 1992); while a third is based on recombination of both strong and weak ties. Mariotti and Delbridge (2012) in their analysis of the motorsport industry provided the rich dynamics of evolution of ties and further contributed to the literature on network ties in dynamic environments and elaborated on potential and latent ties. Relationships where knowledge transfer has not been initiated are called potential while those relationships that, though established, are inactive are referred to as latent.

The nature of ties created by TFE with collaborating partners within the ecosystem is heterogeneous and evolving. They may be classified as strong, weak, potential and latent (Mariotti and Delbridge, 2012). For instance, the collaboration with PARC can be described as strong or intense with frequent interactions and close coordination resulting in co-developments and participation in multiple projects, while that with Solvay (TFE's material provider collaborator) is marked by periods of intense to latent interaction as the quote below suggests. The nature of ties (strong, weak or latent) is often dictated by the organisational strategy and complexity of the technological development rather than by technological capabilities or interpersonal relationship alone. For instance, technological developments within the space of transistor logic (PARC) are more radical from the TFE perspective and require intense and deep interactions as compared to memory (Solvay) where the interactions are aimed at refinement. Nevertheless both partners can be classified as leaders within their respective technological field. However, relationships with suppliers that provide more generic and readily available components can be characterised as more infrequent and therefore weak.

> We have a design, polymer, making polymer analysis evaluation phase. Then we select something, then, in order to fully evaluate it in a roll-to-roll line typically takes a while, like several months. So, then, that is more on and off. (Respondent CKT)

Players in the context of emerging industries constantly search for new potential ideas and markets for technological applications. This active search pattern contributes to identification of potential ties. These ties can be initiated at field-configuring events such as those organised by OE-A or FlexTech Alliance and may involve informal exchanges, visiting the premises and doing preliminary evaluation. They may evolve into weak or strong ties or may not be developed further.

> Based on the board interactions in my first two board meetings, a materials company […] contacted us—and this week […] we will have a team at that company to evaluate their materials.
>
> So that was based on an informal conversation that I had in November at one of the OE-A board meetings, based on an earlier conversation, a couple of months earlier. (Respondent DST)

Owing to the experience and expertise of the collaborating partner within the technological field, TFE has also established exclusivity with some partners such as PARC and Polyera. Exclusivity as elaborated by Gulati et al. (2012, p.577) "characterizes the degree to which member organizations make specific contributions exclusive to a focal organization and not to others." In a dynamic environment, exclusivity is a differentiator, reduces the free rider problem (Wijen and Ansari, 2007) and points towards partner commitment to the hub firm vision thus contributing to the ecosystem's stability (Thomas, 2013). In the context of TFE, exclusivity is mainly driven by partners' technological capabilities, reliability and investments.

> And then, with each of the other technology partners, we looked at their state of maturity. If they looked mature […] we wanted exclusivity for something. (Respondent DST)

> What we get in return is exclusivity so that we're not just a system integrator, we're the only people that you can get the platform from. (Respondent DST)

Another important boundary decision for ecosystem creation, and closely related to tie heterogeneity and exclusivity, is that of redundancy. Redundancy as argued by Mariotti and Delbridge (2012, p.521) represents the "duplication of resources and knowledge and the reduction in relevance of the knowledge obtained from existing ties". Higher redundancy in an ecosystem decreases interdependence and allows parallel processing and lower co-innovation risks in circumstances when a member organisation fails to innovate. It also ultimately results in providing the hub firm more bargaining power. However, achieving high redundancy may not be possible in all areas where the focal company is searching for potential partners, even though it may be desirable for countering risk. One possible explanation lies in the context of new emerging fields where the technology is still developing and rudimentary and finding more than one partner with similar skill sets would be difficult.

> We did our cost analysis. We then looked at what are all the vendor options available to us, and then what were the criteria that were important – so for the display technology we definitely had to think about supply chain, because we were seeing companies go broke in the space.
>
> In the case of the sensor, we looked at the sensing technologies, for both their cost competitiveness… there wasn't really a great match. To be honest, we didn't find exactly what we were looking for. (Respondent JET)
>
> If you could do a search of the entire world there were probably only four places that we know of that could have built our memories roll-to-roll the way that InkTec does. (Respondent DST)

Maintaining higher redundancy may be discouraging for some partners as they may see themselves not valued or replaceable and therefore they may be hesitant to co-invest. Furthermore, redundancies may also result in overloading and tie latency for new ventures (Mariotti and Delbridge, 2012).

6.6.1.2 Evolution of an Ecosystem: Iterative and Staged Expansion

The evolution of an ecosystem may be based on self-organisation and serendipity or it can be strategically facilitated by hub firm or keystone (Williamson and De Meyer, 2012). Adner (2012) suggests three principles for ecosystem sequencing and building: (1) Minimum viable footprint (MVF); (2) staged expansion; and (3) ecosystem carryover. MVF refers to the smallest configuration that comes together and still offers a unique value proposition; staged expansion refers to the additional elements that are brought to MVF and further enhances the value potential of the existing elements; ecosystem carryover refers to leveraging the effects of one ecosystem to another. These three sequences in turn suggest that ecosystem development and scaling require time and clear direction and are done gradually. Iterative and stepwise building of an ecosystem enhances its chances of success and further expansion (Adner, 2012; Sharapov et al., 2013; Walrave et al., 2013). TFE followed an iterative and staged model for the ecosystem expansion, thus moving from MVF to expansion.

The TFE case illustrates that during the initial stages of ecosystem creation initiated by the CEO, Davor Sutija, the organisation focused on developing a memory platform and established a relationship with InkTec as a manufacturing partner. Instead of building a complex endeavour in the initial stages they started with few partners and followed the strategy of building a minimum viable footprint (MVF). Their first target market was that of toys and games. The goal was to demonstrate the technological possibilities based on a simple value proposition. This gradual building of an ecosystem facilitated the identification of the initial stages of execution, co-innovation and adoption challenges as well as helping to build TFE internally.

> And we've then built the company step by step. We were four employees at the beginning of 2010, four or five employees; now we're 16: we've added many technical staff members but, just as importantly; we recruited a CFO from McKinsey, Torgrim.
>
> And we recruited Jennifer Ernst, from our partner PARC; she had spent 20 years at Xerox PARC… (Respondent DST)

Success with a minimum viable footprint (MVF) reduces challenges, is cumulative and is extendable. It helps in achieving alignment within the ecosystem and gains commitment from partners (Adner, 2012; Walrave et al., 2013), as also commented by one of the TFE ecosystem partners:

> […] the sort of things that Thinfilm is talking about, which is sensors and small circuits, is what we believed was going to be the way forward for this technology.
>
> And so they said, "We are really pushing that part of the market." So we think that's exactly the right place to go.
>
> So that's why we've worked very closely with them from very early on because basically our view of how this was going to play out was pretty aligned. (Respondent RBP)

In 2010, when TFE decided to approach the toy and games industry, they had to learn the rules for playing the game within this industry. The initial screening or filtering of ideas through the inventor relations department requires a demonstrator that looks like the final toy. Thinfilm at that time only had the technology, not a product.

> So our first shock was we didn't have a complete toy. And so the toy company says, "Well, we're not used to dealing with technology […] we don't go to Intel and specify a chip; we just go to an inventor and the inventor buys some chips and makes a toy and we either like it or we don't. (Respondent DST)

TFE came up with the idea of a "toy development kit" and reduced the bill of materials to $5 from the previous $12.

> We came up with the 'toy development kit' idea. And so that's why first we made the chip, the ASIC chip that costs about 50c to 70c; and that ASIC chip replaces $4 of electronics in the former thing; and we also made other cost savings, so that you can actually have a contacting system for about $1. (Respondent DST)

The prototype was made available to the world's top toy companies' engineering teams for evaluation. Close interaction, feedback and incremental improvements enabled an accelerated learning curve and offered a unique value proposition for printed electronics as compared to that of silicon. To be considered as an acceptable product, the prototype was also evaluated as to whether it could meet certain specifications and standards pertinent to the toy industry that included tape test, scratch test, safety test and EN71-3 regulations for chemical substances in children's toys.

> […] so we now have our standard spec sheet of what our 20 bit memory does. And that took several months to develop, that standard spec sheet […] We wouldn't have known what tests to do if we didn't have these interactions with the engineering team. (Respondent DST)

At the same time the toy development kit was made available online at TFE's website and to the electronics designers' community through inventables.

> But then we thought, well, you know, we actually want to sell this. We want inventors to use it—maybe they'll come up with a cool game. (Respondent DST)

> Because the whole point of having a demo like this is you go to a toy company and you tell them, "Listen, this is the cheapest way of getting electronic memory today. There is no other way that you can have permanent memory for 5c. (Respondent DST)

The desired customer pull proved to be an important milestone in TFE's success and established their identity as a product company, increased their perceived value to stakeholders, attracted attention from specialised and general media and finally established cognitive legitimacy. TFE's efforts to establish their identity as a product company, matching market demand with technological possibilities, signalled their quality and leadership, further paved the way for integrated systems, and established a strong relationship with PARC. Enrolling other actors within the ecosystem resulted in a gain in momentum (Gawer and Phillips, 2013) and attracted end customers like Bemis.

> They've dived into printed electronics […] they'll […] spend time with us, because we will be their guide as to what is reasonable—and the only way we can be their guide is because we created the ecosystem which means that we're the most knowledgeable in the entire printed electronics universe. We're the McKinseys of printed electronics. (Respondent DST)

After establishing the MVF and the initial success with toys and games companies, TFE was able to demonstrate the potential for the technology and moved on to a staged expansion of the ecosystem, establishing relationships with other component providers. According to Adner (2012, p.203), "by establishing a base of consumers, the MVF reduces demand uncertainty for partners and lowers the hurdles to bringing them on board."

Previous research highlights the significance of prior established alliances for facilitating the formation of direct and indirect ties (Gulati, 1995). However, within a new venture context that lacks resources and established organisational ties, founders' prior interpersonal, direct as well as indirect ties and founding team human capital, such as knowledge, signals the quality of new ventures to potential partners. In addition to the founders' ties and human capital that are bounded by particular context and therefore limited in predictability, organisational accomplishments such as awards and successful product launches are other powerful positional attributes. They provide evidence of organisational progress and its potential in meeting technological and market uncertainty (Hallen, 2008).

> Convincing the people who invented laser printing and the mouse to choose us as their commercialisation partner in the entire field of printed electronics was a challenge.
>
> And how did we meet that challenge? Because we already then were customer focused. We already were talking to toy and game customers about specific problems, specific products, and we told PARC, "We know building real systems is hard. We want to take baby steps. And the first baby step is to just have a better stand-alone memory tag for toys and games."
>
> They said, "Wow, you guys are really realistic. We could probably do that." (Respondent DST)

6.6.2 Orchestrating an Ecosystem: A Routine-Based Model

The orchestration of an ecosystem has been defined as "deliberate, purposeful actions undertaken by the hub firm as it seeks to create value (expand the pie) and extract value (gain a larger slice of the pie) from the network" (Dhanaraj and Parkhe, 2006). How this happens in practice is still an underresearched theme as the research has been focused on structures and relations rather than processes within the network theories (Nambisan and Sawhney, 2011). According to Fjeldstad et al. (2012), the exploitation of accrued benefits from the design of new organisational forms necessitates the development of organisational capabilities and processes. Thus, in the context of an ecosystem that is characterised by knowledge heterogeneity of its members, the hub firm needs to develop processes and practices such as those for knowledge mobility, innovation appropriability, innovation coherence, innovation leverage and ecosystem stability (Dhanaraj and Parkhe, 2006; Nambisan and Sawhney, 2011).

The analysis builds on the routine-based model proposed by Lewin et al. (2011) to discuss the orchestration processes. Rather than focusing on mechanism only at the ecosystem level or at the hub firm level, two sets of meta-routines in the context of ecosystem were identified: inter-organisational and intra-organisational routines. Inter-organisational routines can be further divided between those developed in dyadic relationships between the ecosystem hub firm and other partners and which are aimed at achieving coordination and knowledge mobility, and those developed at the collective level in the ecosystem for achieving shared logic, cognitive and sociopolitical legitimacy and finally ecosystem stability. Inter-organisational coordination routines include practised routines such as ongoing communication, modular communication, and tacit coordination and facilitate knowledge sharing, assimilation, and transformation between the hub firm and its ecosystem partner, while those aimed at developing shared vision and legitimacy at industry level proved instrumental for ecosystem stability.

Intra-organisational routines focus more at the hub level and comprise a variety of practices such as those for identification of new knowledge from external sources, creating new knowledge internally via variation; developing prototypes and sharing knowledge inside the hub firm for assimilation and transformation. In addition, an iterative and closed loop exists between inter-organisational and intra-organisational routines that enable TFE to further assimilate and transform the knowledge obtained from external partners.

Table 6.3 reports the routines developed by TFE to coordinate and leverage the ecosystem. In the following sections first *inter-organisational* routines that facilitated the development of shared vision and cognitive and sociopolitical legitimacy around TFE integrating activities at the ecosystem level are analysed before moving to the analysis of *intra-organisational* routines for internal knowledge creation processes related to the ecosystem.

Table 6-3 Orchestration of an Ecosystem – A Routine-Based Model

Meta-routines	Practiced routines
Inter-organisational routines	
Coordination routines (bilateral level)	• Ongoing communication • Modular communication • Tacit coordination mechanism
Shared logic, legitimacy (collective level)	• Shaping the conference at the level of industry associations
⇕ ⇕	⇕ ⇕
Intra-organisational routines	
Identifying external technical and market knowledge	• Technical advisory council • Participation in international networks such as industry associations OE-A, FlexTech Alliance and relying on weak signals • Scouting • Internationalisation • Attending conferences related to printed electronics as well as other divergent markets such as smart packaging, mobile communication
Facilitating variation, selection and retention	• Top management team diversity and experiences
Assimilation and transformation	• Prototype development • Sharing knowledge across organisation
Establishing legitimacy	• Sense giving activities (diverse and intense)

Source: Author

6.6.2.1 Inter-organisational Routines

6.6.2.1.1 Bilateral Level—Knowledge Mobility and Coordination

Increased interdependencies between the hub firm and partners requires developing coordinating mechanisms within an ecosystem. Coordination in an ecosystem, characterised by increased specialisation among partners, requires aligning actions of specialised partners and recombining distant scientific knowledge. Failure to coordinate distributed tasks is common when the partners are interdependent, distant and may lack "common ground" or mutual knowledge that restricts synchronisation in joint efforts (Kotha et al., 2013). This may hamper technology commercialisation and demotivates an ecosystem's partners even in the circumstance where the appropriability strategies such as contracting and IP issues are clearly defined and non-conflicting. Both formal and informal communication channels ensure knowledge mobility within the ecosystem and thus enhance trust and commitment and ensure reciprocity (Blomqvist and Levy, 2006; Dhanaraj and Parkhe, 2006; Ritala et al., 2009). They also enable the development of a shared space for exchanges among partners and ensure alignment, development of a common understanding and uniformity in meanings. In addition to the ongoing communication mechanisms discussed extensively in the literature, modularisation (designing standardised interfaces) as well as tacit communication mechanisms such as visiting each other's sites are identified as an important coordination mechanism (Srikanth and Puranam, 2011). Tacit communication mechanisms enhance the visibility of each other's context and processes, increase the formation of common knowledge in the situation of complex interdependencies and enable interpretation of anomalies, as has been identified in the TFE case.

Ongoing Communication is necessary within an ecosystem owing to the increased geographic separation, location in different time zones and diversity in nationalities and culture. Diverse organisational groups have different beliefs regarding expectations (Srikanth et al., 2014). Use of ICT communication tools such as email, telephonic conversation, Skype and video conferencing enable continuous feedback and ensure knowledge sharing; these were a norm in TFE.

Modular Communication through Copy Exact: TFE replicated routines from their past partnership with Intel. One of these was Copy Exact (Burgelman, 2002), a routine that was dominant in Intel and became part of TFE. Every experiment is documented at TFE; they have developed a standard way to record the results and also implemented the same ‘process of records’ (POR) at their partners’ premises. Copying exact ensures alignment with partners. Developing standard interfaces such as POR or employing similar testing mechanisms helps coordinate when partners are geographically separated and tasks are more modular and interdependent (Srikanth and Puranam, 2011). The use of POR points towards the performativity aspect of the routines and the roles of intermediaries in coordinating and shaping interaction. According to D’Adderio (2008, p.774) “they *(standard operating procedures)* structure work, extend interactions, increase visibility of knowledge and actions, create a common platform for the accumulation of common knowledge, constrain the ability of practitioners to alter the results of another, regulate who has access to making changes, track progress of changes, link multiple sites in different time and geographical locations, facilitate data sharing and the reception of feedback”. In the case study, acquiring a partner’s knowledge was not the objective when interacting with component providers but at the same time TFE needed to ensure that the component could be integrated with core as well as with other components thus avoiding inconsistent results and performance deterioration.

> Meaning where we did things, and we were happy, Intel tried to make copy-exact, meaning everything in detail should be the same – meaning equipment, materials, temperature, relative humidity, what have you.
>
> So that we also try to do, so during initial phases, for example with Imprint Energy, battery testing, we bought a tester that was as identical to theirs—so first thing I asked was what type of tester they had—so that we actually have the same baseline, and then used the same script.
>
> Particularly evaluation protocols, test protocols, they should be copy-exact. Even a tiny change in a measurement protocol typically results in quite different results coming out on a measurement. (Respondent CKT)

Tacit coordination mechanism: In complex task environments such as that of radical innovations, where the pattern of interdependent changes are difficult to anticipate ex ante, coordination through ongoing communications and modularisation may not be sufficient (Srikanth and Puranam, 2014). In such situations, tacit coordination mechanisms are used to achieve common ground. “Common ground is this shared information that allows participants to anticipate each other’s actions and correctly interpret their communication” (Srikanth, 2007, p.46). However, Srikanth and Puranam (2014) found that creation of common processes and technologies, though they may be useful, are not a norm when projects are spatially distributed and require coordination among firms. The possible explanation may be the absence of a central authority and the time consuming and expensive nature of tacit coordination mechanisms.

The case study, in contrast, provides evidence that TFE stresses the importance of co-development in an ecosystem, therefore visiting other members’ sites in addition to the frequent face-to-face communication is a norm. The close engagement with members is necessary due to the tacit nature of the knowledge and the repeated iterations and experiments required for technology development in the technological niches.

> InkTec and Thinfilm have an excellent relationship in that context. They are so transparent, and we are that, too. So, actually, key to make a memory work was that we spent enormous amounts of time over there, with them, doing trials together, in a totally transparent fashion. (Respondent CKT)

> But we work closely with people; [...] we are in Korea once a month. And their staff have been at Linköping and they’ve gotten training on how to test the memories; and we have delivered equipment to them; and we have made joint investments in upgrading their line—we are partners. (Respondent JET)

In addition to the early experiments that resulted in knowledge exchanges with technology partners, TFE’s active participation in forums such as those organised by PARC, IDTechEx, OE-A and FlexTech Alliance facilitated further socialisation, informal exchanges and knowledge mobility among partners.

6.6.2.1.2 Collective Level—Shared Vision, Legitimacy and Ecosystem stability

An ecosystem aims at collective value creation among the partners and is characterised by symbiosis and interdependencies which in turn suggest shared fate (Thomas and Autio, 2013). “The world of innovation ecosystems often requires a different approach. Here, the challenge is that delivering your value proposition requires multiple partners to agree, align and commit" (Adner, 2012, p.194). The prevalent logic within an ecosystem is that of multiplication. Therefore, in addition to the legitimacy building, hub organisations also actively develop shared logic that is mutual understanding of the meanings and goals among the ecosystem participants through industry-wide initiatives (Thomas, 2013). For instance, TFE adopted certain "external work practices" to change the prevalent logic within the industry. External work practices refers to "a form of institutional work through which the focal organization creates and disseminates new practices to other organizations in the field with the intention of influencing the institutional logic" (Gawer and Phillips, 2013, p.1046). The CEO of TFE believed in the replication of their previous success in "Fast" whereby they were able to transform the new venture to a $1.3 billion (£0.83 billion) company that was bought by Microsoft.

> And if we took anything from the experience of FAST to Thinfilm, it was obviously related to the reasons Microsoft bought FAST. We would like to replicate that. Not necessarily that we want to be bought, but it's what makes us valuable; it makes us compelling as a company. […] What was unique about FAST is that they had a value proposition for their search because it was more scalable than any others.
>
> And that's what then we learned that, and that's where we decided that printed electronics will never beat silicon on the checklist. The only thing they can do is have a unique value proposition that silicon can't match. (Respondent DST)

OPE was initially considered the domain of large area electronics and therefore the focus was on displays, lighting and OPV. TFE's vision for OPE was the Internet of Things (IoT) and innovation from below. To enrol actors and influence the institutional logic (Gawer and Phillips, 2013), TFE ensured its leadership position with the industry associations such as Organic and Printed Electronics Association (OE-A) and FlexTech Alliance and made significant changes at the institutional level, thus acting as the institutional entrepreneur (Battilana et al., 2009). Being at the board level position at OE-A and the FlexTech Alliance enabled TFE to actively participate in the standardisation efforts, shaping the conference or events organised so that the topics, such as memory or smart packaging, most relevant for progress and resolving challenges associated with TFE platforms, were included in the conference programmes. These active interventions resulted in legitimizing TFE's vision and enhanced ecosystem stability. Ecosystem stability is crucial for value creation and can be achieved through several ways such as building reputation, enhancing the shadows of the future and creating trust (Dhanaraj and Parkhe, 2006; Poppo et al., 2008; Thomas, 2013). For instance, the focus of LOPEC[57] was modified to include a business conference in addition to the technical and scientific sessions, which brought practitioners and researchers/academics together. The overall driver for these initiatives was to catalyse the TFE ecosystem building, create interest and momentum among the wider ecosystem players such as academia, government and venture capital, establish legitimacy of its venture and vision and enrol more actors.

> I mean, until we started being active there was no session on memory and logic. So Jennifer is organising a session at FlexTech in Phoenix on memory and logic. There was no session on that last year.
>
> So how are we going to get funding or awareness of our product markets unless we lead that? Nobody's going to do that for us. And in order to get the opportunity to do that leadership you have to be part of the organisation that has the conferences. So I was elected to the OE-A; Jennifer was elected to FlexTech; we're the only company in the world that has board members in both organisations. And we have 16 employees. And both have been chosen to organise a symposium, a session, based on their own strategic intent. So if you're in charge of the business conference you can influence the strategy of the entire organisation, in my opinion—in a positive way, to become more business focused and less academic, as we evolve. (Respondent DST)
>
> But it's much more than that: it's the work on standards, getting the IEC to create printed electronics standards that are favourable to the OE-A; figuring out how to have the right mix of programme material at LOPEC is very important. (Respondent DST)

Trust, reciprocity and goodwill have been identified extensively as social control mechanisms for coordination and governance within network settings in addition to the formal contractual agreements that drive collaborative relationships (Larson, 1992). The case study finds support for the synergistic impact of both shadows of the past and expectation of continuity as an important determinant for developing trust in entrepreneurial ventures within emerging industries. Both dimensions were present in the case of TFE's partnerships with big names like PARC and InkTec as is evident from the quotes below from PARC respondents:

> […] When we first talked with Thinfilm was just trying to understand whether there was something that made sense for both of us to do together and started off with one version of what was happening and it's sort of grown into a much stronger relationship. This relationship has grown and strengthened over the years is what I meant.

[57] Large Area Organic and Printed Electronics Convention organised yearly by OE-A

> So when we started out, it wasn't, "Are we going to put all our eggs in the Thinfilm basket in this technology?" It was, "We think these are very interesting people to work with." We put together a deal that we think works well for both of us.
>
> Thinfilm is more special of our clients because they really are trying to get this whole thing out themselves. So most of the people we work with are wanting to be part of the value chain.
>
> They have a view of the future we think makes the most sense. […]I think in this case they had the roadmap pretty well… they spent a lot of time on their own roadmap and… we can sort of talk to them about it and they ask us if we've heard anything new and so on, but really they take the responsibility and the credit for the roadmap. That's really theirs. (Respondent RBP)

6.6.2.2 Intra-organisational Routines

The TFE case demonstrates that in addition to the inter-organisational routines it also employed a repertoire of intra-organisational routines mainly aimed at identifying external technical and market knowledge or developing knowledge internally, knowledge assimilation, and transformation.

6.6.2.2.1 Recognising the Value of New External Technical and Market Knowledge

In technology intensive industries, the core capability of an organisation is based on accessing external sources of knowledge and complementing these with internal knowledge to facilitate innovation and obtain competitive advantage. In general, entrepreneurial firms are constrained by limited resources, small size and the liability of newness and therefore external sources of knowledge, both formal and informal, such as collaboration, mobility of workers and geographical co-location, tend to be vital for their growth (Almeida et al., 2003). According to Katila and Ahuja (2002) heterogeneity in a firm's search strategy is a differentiating factor in its innovative performance.

Due to the complexity, modularity and dynamism associated with OPE, TFE realised the importance of searching broad and deep for outside sources of knowledge to enhance their existing technological competencies related to memory, increase diversity and acquire knowledge in other domains (such as printed transistor) important for systemic innovation. In addition to technological knowledge, scanning the trends and opportunities in targeted market segments was also deemed necessary. According to Lubik et al. (2013) the selection of markets is one of the critical challenges faced by entrepreneurial firms, as the wrong choice often results in ultimate failure and losing financial investment.

TFE's external routines aimed at both scanning the technological environment and identifying commercialisation opportunities and "sweet spots" where ubiquity associated with printed electronics offered advantage as compared to silicon. They relied on weak signals and developed elaborate mechanisms and processes such as the appointment of a technical advisory council and participation in divergent conferences (those in packaging and cold supply chains) and international networks.

Thin Film Electronics established a Technical Advisory Council (TAC) that acts as an external consultant. It includes four members with varying competencies in different technologies.

> …we're trying to fill gaps and potentially there are gaps we fill in areas that are non-core to Thinfilm… So there is the idea that here is a nucleus, a core technical strength of the company, and the TAC is an outer ring that has a broader set of experiences. (Respondent DLT)

> Then they brought in competence in areas where Thinfilm didn't have it, like TFTs, LEDs, what have you. So, very useful now, particularly when it comes to… on a high level, giving some direction and selecting a technology. Not so much when it comes to details, of course, or detail roadmapping and stuff like that. So, more partner finding – OK, we need a display technology; who is out there? Some feedback… (Respondent CKT)

From the data it can be ascertained that the use of an advisory council contributes to developing absorptive capacity within the firm, enabling TFE to capitalise on their social capital as well as providing a fresh perspective and critical feedback on their technological roadmaps. The use of specialist knowledge providers such as advisors is instrumental for radical innovation and complement rather than substitute firms' internal knowledge (Tether and Tajar, 2008).

The advisory council members that were appointed by TFE were highly respected in the industry and their expertise in relevant processes deemed important for commercialisation of TFE products, thus enhancing legitimacy of TFE's vision and robustness of their approach (Sturdy et al., 2009).

> The reason is that we wanted to get input for the team, the development team in Linköping, a fresh set of eyes on the milestone plan that we develop.
>
> But after we've drafted that (milestone), the technical advisory council was called in to critique the milestone plan, to give feedback on the feasibility and about the technical risk and about any opportunities they saw from modifying the plan to improve either the efficiency or reduce the risk—so, really, a technical critique of the milestones themselves and the plans, the work scope, to be able to meet those milestones. (Respondent DST)

Identifying promising avenues of technological development in the case of an emerging industry based on breakthrough technologies is particularly challenging and also relies on weak signals (Ansoff, 1975; Doering and Parayre, 2000; Mendonça et al., 2004) and scanning the uncertain environment. "Weak signals of technological emergence are those more subtle indicators that a scientific discovery has commercial potential and that independent analysis has recognized this potential" (Doering and Parayre, 2000, p.84). The best way to look for these technologies is either in literature or in conferences and presentations, as discussed by Brenner (1996). TFE's top management relied on weak signals to identify the promising markets, technology partners and potential customers.

> What I mean by that is, when you're in large companies there's a tendency to have to prove that something is a market or to prove that something is a good idea. I don't have enough data to be able to do that, but what we can do is we go to the conferences, we see… you look at the people that register – is it the same…? There are always a few packaging people at the conferences, there are always a few security printing people, there are a few of the labelling people, there's always Avery Dennison.
>
> So you start seeing some patterns about… the people that are paying attention to printed electronics are in certain blocs, and out of that you can begin feeling through what is it that really resonates? What is it that they're looking for? Why are they here? There's something that brings these same kinds of people back to these conferences year after year. So what is it that's the essence of what they're looking for...? (Respondent JET)

One of the ecosystem partners, Imprint Energy, while hinting at how the relationship with TFE was initiated, said:

> We got connected with Jennifer Ernst pretty early on and that was when we were just kind of getting off the ground we got connected to her because she had formally been at PARC she was located in the Bay area, she was coming over to Berkley pretty frequently to look at new technologies and meet with people, so we got connected with her and just kind of started talking generally about printed electronics but not with any particular motivation in mind, then after we got some seed investment we were progressing along we were actually going to become a

> legitimate company and then Devin came on board, we sort of re-engaged in those discussions. (Respondent BKI)

At TFE, the internationalisation and the location of the business development offices in San Francisco and Japan supported the routines for technological scouting and tracking of technological and market opportunities in a turbulent environment, thus enabling them to respond to weak signals quite early in the absence of complete information.

TFE participates actively in conferences not only within the technological domain of OPE but in divergent and unrelated areas where they are looking for early commercialisation such as in toys and games, temperature sensor markets or brand authentication.

> One of the things is it gives me access to a really large knowledge base. So it's not just the reports that they have out there, but the network […] we see proposals from all sorts of organisations. So I now know about people who are starting to do things at the edges or who are coming up with some new, interesting stuff that I would never have seen if I were just heads-down, working, my day job in Thinfilm. So it's really about building up that network. (Respondent JET)

The process for identifying the target market is iterative and involves analysing trends through market reports such as Frost and Sullivan, IDC and Gartner, probing customers, and discussion with leaders of conventional technology or industry experts. Commenting on the process, Respondent TTT said:

> So there you need to do both some proprietary data gathering, meaning you need to talk to industry experts, kind of existing silicon players that provide the products… to actually get the level of granularity you need in order to say, "Well, if we develop kind of this with certain kind of price functionality, we will be able to compete in kind of this and that segment of the market.
>
> So, I mean, there are kind of top-down type of analysis, just reading existing reports on markets; and then you need to do the… bottom-up analysis in terms of speaking to potential customers, speaking to existing manufacturers of the products, and so forth.

6.6.2.2.2 Routines for Generating New Knowledge Internally

Individuals serve as the microfoundation for organisational routines and processes (Felin et al., 2012) and the individuals' heterogeneity contributes towards organisational performance differences. Salvato (2009) contributed to the prevailing view of organisational capabilities by studying the mindful acts of individuals. He argued:

> …Understanding a firm's ability to systematically renew its strategies and underlying capabilities requires an in-depth understanding of the microprocesses that make up an organizational capability […] day-to-day events that […] induce mindful alterations […] and of the role of managerial intentionality has in leveraging such alterations with the aim of achieving systematic improvement in capabilities. (Salvato, 2009, p.385)

Variation is a source of internal idea generation and can be achieved in a variety of formalised and informalised ways. TFE, being a resource-constrained organisation, does not have the provision of slack resources or playfulness at the institutionalised level but benefits from the top management that brings to the table diverse experience, knowledge sets and capabilities. Jennifer Ernst, VP in the USA, has a rich 15 years' experience of working in PARC; the CTO has been with the company since the time of Intel and therefore is aware of developments in memory. The CEO brings with him entrepreneurial experience that sets TFE apart from other academic start-ups.

> What's really interesting about Thinfilm is we have experience from other industries. Torgrim, from management consulting […] he knows a lot about technology acquisition, you know, the consolidation of industries.
>
> So we think that we bring to the table different industry experiences. Because we have different industry experiences, our view on how to organise a business conference, our view on how to organise a roadmap, may be different than somebody who's worked in a large company for 40 years. (Respondent DST)

6.6.2.2.3 Routines for Assimilation and Transformation

TFE, being an integrator and a product-oriented company, differs from other players and academic start-ups. They have established engagement with market players such as Bemis, Hasbro, Brady and others. These early interactions with customers and development of prototypes and not limiting themselves to demonstrators served as a vehicle to learn about potential market segments and their requirements that later translated into technological specification and were incorporated into TFE's organisational roadmaps. Those requirements are further trickled down to organisational milestone plans. Thus there is a continuous feedback loop at both inter-organisational as well as intra-organisational level that is mandatory for assimilation and integration. Assimilation refers to the routines that enable the firm to understand and interpret the new knowledge from external sources while transformation facilitates combining existing knowledge with newly assimilated knowledge (Zahra and George, 2002).

> A lot of the performance requirements do not come from research organisations. They come from products. So they are developed together with design and product thinking rather than technical research-oriented.
>
> Then… when you develop a roadmap that includes design rules such as line width, spacing, registration accuracy, we […] also consider all our input we have from equipment vendors, and what is possible to do within a given time frame when it comes to printing processes.
>
> So, equally important as just coming up with ad-hoc or product-inspired requirements is knowing the practical limitations of the processes and equipment you intend to use. (Respondent CKT)
>
> It's had a significant impact on requirements that we give our technical ecosystem. So it allows us to say, "Here are the things that matter, there things that don't."
>
> When we talk about the battery, do we care more about it being really small, and it can be thick? Or do we care more about it being thin? And those kinds of decisions are significantly informed by having a customer engagement.
>
> And that's actually why the early adopters, early customers, are so critically important to a technology company. We can design in a void, but the chances… if we don't have a customer with whom we are co-developing the spec, the specification, it's far too easy to get to market, say, "I've got a device – it's all ready to produce" – and nobody wants it because if you'd made a different design decision 12 months earlier you'd have ended up in a better spot. (Respondent JET)

While working with customers in the toy and game industry for commercialisation of their memory TFE were able to get input from the toy industry about its working practices, standards, bill of materials and technical requirements and assimilate and transform that knowledge to produce a working prototype of their product, a game. The prototype was distributed among major customers to get the required feedback and thus improve further. Though artefacts such as these prototypes are not routines in general they are critical in evolution of routines (D'Adderio, 2008). These prototypes in turn facilitated assimilation of new knowledge from customers.

> So if you ask about what is best practice for the toy and game industry, first you have to understand the structure of the industry; you have to understand the cost dynamics of the industry; and then you have to have a platform that you can use as a starting point for exchanging information with the engineering teams.
>
> They give us feedback. I mean, when they say, "This prototype failed"—that's the first thing they say. And then we work on those few items that they think need improvement.

> Some people were worried about electrostatic discharge; some people were worried about tape testing; some people were worrying about a ballpoint pen—you know, what is known as scratch testing or indentation testing. So we now have our standard spec sheet of what our 20 bit memory does. (Respondent DST)

Prototypes thus provided an iterative cycle of framing: overflowing and reframing that enabled improvement in the product and technology through mutual adaptation and adjusting of the procedures and processes. In addition to developing prototypes, other sources for assimilation and transformation of external knowledge was sharing knowledge within the growing organisation.

6.6.2.2.4 Routines for establishing legitimacy

Creating market pull for OPE has been a challenge for both large as well as entrepreneurial firms. Early adopters and brand owners do adopt a wait-and-see strategy in areas of breakthrough technology because investing early in such context can be risky and may result in sunk costs.

> Some of that is about market position. And some of that is about willingness and ability to commit. So not every company we've talked to have the fortitude to be an innovator.
>
> Not everybody wants to spend time in that early space. So we needed to find people that… we needed to find both companies that felt that desire, that burning in the gut, had that kind of culture, that they saw purpose to being at the innovation edge. (Respondent JET)

Increased legitimacy facilitates identity creation for entrepreneurs in nascent markets (Santos and Eisenhardt, 2009). Different perspectives on legitimation offered by institutional, cultural, ecological, impression management, and social movements converge on the need for new ventures to acquire, maintain, or restore legitimacy and this tends to be even more important in the context of new industries characterised by high velocity environments. “NVs *(new ventures)* are believed to lack legitimacy if they enter a nascent context with limited density, while they have legitimacy when they enter a more established context with somewhat higher density” (Überbacher, 2014, p.672).

For new industries, legitimacy has to be established at both the macro and micro levels as opposed to the dominant themes in established literature that have adopted an either/or perspective: (1) at the institutional and collective level the association mainly aims at establishing the future potential of the technology while (2) at the strategic and organisational level an entrepreneurial firm has to establish the legitimacy of its vision to attract financial investments and recruit potential members in the ecosystem. This is particularly relevant for the case study.

Prior to gaining credibility, entrepreneurial ventures seek to attract attention and indulge in sense giving activities, i.e., “the process of attempting to influence the sensemaking and meaning construction of other toward a preferred redefinition of organizational reality” (Gioia and Chittipeddi, 1991, p.442), for example through broad communication process related to the new emerging field. “Being considered, therefore precedes being evaluated favourably” as argued by Petkova et al. (2013, p.866). The TFE sense giving activities can be characterised as both intense and diverse (Petkova et al., 2013). They aimed at establishing legitimacy for heterogeneous audiences such as investors and shareholders and ecosystem partners, both technological and commercial. “Intensity” refers to the frequency of communication activities whereas “diversity” is related to the use of different types of communication channels. They participated and presented at a large number of conferences and forums that enhanced their visibility and established them as key players in the field that should be followed**.**

> I think it’s exceptionally important […] if we are to apply for funding elsewhere, people have to understand that we are a safe choice, that we are a household name. So the companies that are on the board of the OE-A are in fact Europe’s leaders within printed electronics. That’s one thing. So there’s a matter of recognition. (Respondent DST)

TFE employed impression management tactics and used a variety of communication channels, both generic as well as industry specific, and frequently reported on their achievements via press releases in the general media as well as industry-related media. In addition to the formal media channels they also used social networking sites such as Twitter and LinkedIn to announce their achievements and establish themselves as cognitive referents.

> And what's happening now—it's actually been kind of an interesting shift for us—is we had the first set of partnerships. We have definitely leveraged… we're showing what can be done. We've started to demonstrate that the world is not against us, the laws of physics are possible to make real printed devices.

> And now people are coming to us. So I have more and more people… we basically created a magnet, and we have more and more people coming to us to say, "Have you looked at…?" "I have a novel technique for x, y, and z – would it be of interest to you?" (Respondent JET)

The perception of the young organisation's success and its reliability was also influenced by affiliations and inter-organisational relationship (Stuart et al., 1999). TFE signalled leadership by establishing contacts with reputable organisations very early on, such as with PARC, and disseminated stories of their early success in toys and games. TFE built their identity around bringing intelligence to everyday objects and the Internet of Things (IoT) and adopted motivational framing for their ecosystem vision, comparing it with the success of Apple to make it a compelling proposition (Battilana et al., 2009). *"And then we found that there were two things that were happening: there was the Apple effect and the Walmart effect. And we published this in September 2010. When we raised the money, this was our pitch"* (Respondent DST).

As a result of the intense and diverse sense giving activities, TFE was able to get attention in both the generalised and the specialised press and was nominated for various technology awards. For instance, in 2012 they were the recipient of the most prestigious and esteemed OPE industry awards such as the FlexTech Alliance FLEXI Innovation Award and IDTechEx's Best Product Development Award. TFE together with PARC were named as runners-up for the Wall Street Journal Technology Innovation Awards. Cross-industry and industry-related news and awards further paved the way for mobilising resources, funding and participation in development projects. In addition to these tangible benefits, the increased credibility of TFE contributed to its increased bargaining power. In the absence of formal authority higher status and reputation result in asymmetries and are a source of informal authority for the ecosystem orchestrator (Gulati et al., 2012).

6.7 Discussion and Conclusions

Distributed sources of knowledge and increased specialisation that necessitates close coordination among autonomous organisations demand moving away from traditional hierarchical and contractual thinking and turning attention to develop a different organisational design. Among the modes that have recently gained currency within management literature is that of business or innovation ecosystem. The ecosystem approach, discussed increasingly in the context of digital services firms like Facebook and Google, tends to be instrumental for commercialisation of path-breaking innovation in an emerging industry. Path-breaking technologies are referred to as hopeful monstrosities and their development necessitates protection from mainstream markets (Mokyr, 1990). Innovation ecosystems include a wide range of actors, production, users and intermediaries that are interdependent and co-specialised. Furthermore, they collaborate, co-create, cooperate and co-innovate together to offer a compelling value proposition. Innovation ecosystems can be organised around technology platforms (Cusumano and Gawer, 2002; Gawer and Cusumano, 2002) or around hub firms (Moore, 1993) or keystones (Iansiti and Levien, 2002; Iansiti and Levien, 2004).

The case study has focused on analysing organisational processes and routines for orchestrating an entrepreneurial ecosystem in the context of an emerging breakthrough technology. The contributions of the original case lie in the uniqueness of the small entrepreneurial firm acting as an orchestrator of an ecosystem and industry shaper, rather than a follower or niche player, as discussed often in the literature (Zahra and Nambisan, 2012; Nambisan and Baron, 2013).

The analysis conceptually contributes to the discourse on microfoundation of capabilities by adapting Lewin et al.'s (2011) routine-based framework for developing capabilities in an ecosystem in the context of emerging technologies. It extends the model beyond internal and external routines and provides empirical insights into not only intra-organisational and exploration as has been the focus of the extant studies but also inter-organisational routines adopted by the small hub firm to facilitate innovation and commercialisation of the emerging technology. Entrepreneurial ventures are considered as a source of opportunity creation and discovery. The literature, while acknowledging the importance of processes in value creation, has not discussed in detail or provided a "compelling explanation" for the ability of some young firms as well as a few established companies to "continuously create, define, discover and exploit entrepreneurial opportunities" (Zahra, Sapienza, and Davidsson, 2006, p.917). Exploring the routines in new high technology ventures and in an emerging context provides insights on the underresearched theme of the emergence of capabilities. "A thorough understanding of how routines emerge is necessary to derive the performance benefits they yield for organizations" (Bapuji et al., 2012, p.1).

In general large established firms present innovation routines and processes which have been developed over time and which reflect their experience in managing the innovation process. In contrast, small entrepreneurial firms which do not build on long standing experience need to develop such processes. In new technology-based firms, these routines are not particularly sophisticated but simple processes that can take the form of heuristics or rules of thumb. Simple routines enable managers to make fast and timely decisions in a dynamic and resource-constrained environment where attention is mostly in short supply (Eisenhardt and Martin, 2000). The case firm was able to develop a repertoire of inter-organisational and intra-organisational routines and practices, including a number of routines at the collective, ecosystem level, through mindful selection of routines and strategies of its top management members based on their own prior experience (Aldrich and Yang, 2014). Routines result from learning processes, trial and error, and experience and are considered to be path dependent, so how do they emerge in an entrepreneurial context that does not possess an elaborated history? Miner (2011) identifies the important role of prior experience of the top management team in development and replication of routines through several pathways such as automatic importation from previous organisations, selective importation, redeployment of routines, recombination of routines from team members and external networks. The case study contributes to the role of top management team experience and cognition in developing capabilities in entrepreneurial ventures thus contributing to the recent and growing academic research on microfoundations of organisational capabilities and managerial cognition (Gavetti, 2005; Eggers and Kaplan, 2013). The case also illustrates that whereas CEOs' and top management's previous entrepreneurial experiences contributed to automatic importation of routines, imprinting from earlier interaction with Intel resulted in retaining certain routines and enacting them in a new context. However, an important contributing factor to the variation, selection and replication of routines is the *diversity* among top management team members. TFE's top management team in the early days was comprised of CEO, CTO, VP and CFO who brought with them heterogeneous backgrounds and industry experiences. Managerial cognition contributed to encoding of the heterogeneity of experiences into routines, differential interpretation of the environment, opportunity recognition and finally mindful selection, recombination and deployment of routines in a new context. According to Winter (2013, p.124), routines in the organisation “bear traces of the influence of many individuals back along the historical track, including many who never were part of the organization but nevertheless had a historical encounter with the routine”.

It also enjoyed the benefits of complementarities among those routines, which, in turn, resulted in competitive advantage and innovative performance (Lewin et al., 2011). The intra-organisational routines enabled the ecosystem orchestrator to explore markets and develop internal practices for variation, assimilation and transformation of internal knowledge. In addition, complementing inter-organisational routines facilitated coordination at the bilateral level, and also established shared identity and legitimacy at the collective level. The case study provides evidence that the bundle of routines and their complementarities contributed to the focal firm’s first mover advantage in the printed electronics industry. TFE identified and developed effective routines that would lead to their ecosystem momentum and success as the industry evolves and competition intensifies with the entry of new ecosystems and imitators into the fray.

One of the most interesting and novel routines that TFE developed that is particularly relevant for the context of ecosystem in breakthrough technologies is creation of legitimacy. Legitimacy is a crucial resource for new ventures (Zimmerman and Zeitz, 2002), which enables entrepreneurial new ventures to overcome their liability of newness through acquisition of resources such as financial capital and trained and skilled human resources. However, building legitimacy in new markets can be extremely challenging (Navis and Glynn, 2010). In the case of new industries devoid of institutional context and characterised by higher uncertainty, entrepreneurs need to build legitimacy not only at organisational level but also at intra-industry, inter-industry and institutional levels (Aldrich and Fiol, 1994) and for heterogeneous stakeholders such as investors, ecosystem partners and policy makers. Diverse and intense sense giving communication strategies, affiliation with and endorsement from high status actors and higher management experience all contributed to achieving legitimacy for TFE, its ecosystem and printed electronics.

The TFE case demonstrates that building of an ecosystem is a gradual and iterative process and “that winning in ecosystems requires winning more than just the execution race" (Adner, 2012, p.193). While the traditional sequencing of scaling up in product-related environments follows a sequence of prototype-pilot and roll out, this creates complexity in ecosystem settings where the co-innovation challenges multiply. Here the suggested sequence is that of MVF, staged sequence and ecosystem carryover. MVF focuses on early commercial success for an initial simple proposition, as shown by TFE's games and toys success. Initial success makes the new firm attractive to the best people—researchers and top managers. They are all crucial for sustaining success. The initial momentum enabled recruitment of potential partners. In such situations the conversation with a potential partner shifts from "after we jointly get this system together, we will go and find customers and then we'll all succeed" to "I have an established customer pool that would appreciate the value proposition even more if you were a part of it" (Adner, 2012, p.203). Furthermore, the shift from a patenting and licensing business model to a product-based orientation has allowed the focal firm to develop routines that put the technology closer to the market and made the whole process of developing an emerging technology more effective. Thus the change in business model from licensing to product mix also resulted in a change in the relationship mix within the ecosystem.

One of the prominent characteristics of TFE's ecosystem is symbiosis that enabled partners to mutually adapt and innovate. Burgelman (2002) highlighted the importance of the symbiotic relationship that existed between Intel and Microsoft for development of the Wintel platform and enabled both collaborating partners to overcome inertia, mutually adapt and successfully innovate. Davis and Eisenhardt (2011) highlighted the role of rotating leadership in facilitating symbiotic partnerships especially for uncertain circumstances. However, in the context of entrepreneurial ecosystems, such as that of TFE where there was no prior history of partnerships, larger shadows of the future and expectations of continuity enabled collaborating partners to co-evolve and adapt (Doz et al., 2000; Dhanaraj and Parkhe, 2006; Gulati et al., 2012). Unusually, TFE, building on prior organisational routines and the individual experience of top management members, showed both valuable shadows of past and future expectation of continuity. Initial stages of collaboration were more cautious, surrounded by uncertainties regarding other partners' capabilities. However, over a period of time, the ecosystem partners developed inter-organisational routines for coordination, joint problem solving and sharing information. According to Poppo et al. (2008, p.43), “building these expectations is both complex and costly, expectations of continuity must exist” as it is a motivating factor for parties to continue collaboration and invest time and resources on developing routines and practices for cooperation.

Another factor contributing to the activation of the relevant capabilities of collaborating partners that facilitated innovation within the TFE ecosystem is the reduction of tensions that mostly originated from intellectual property (IP) rights issues (Dhanaraj and Parkhe, 2006; Ritala et al., 2013). Creating contracts and identification of IP boundaries to ensure that cost and benefits are equally shared among the partners reduces opportunistic behaviours and increases transparency among the ecosystem partners. The case illustrates TFE’s contracting mechanisms that facilitated moderation in the value appropriation as instrumental for value creation within the ecosystem. Designing contracts and clarifying the appropriating mechanisms at the start of collaboration sets realistic expectations among partners, as also proposed by Fjeldstad et al. (2012). According to Zahra and Nambisan (2007, p.225), “Strategic thinking about the way to build and maintain partners’ loyalty is essential for long term success of the ecosystem”.

The case study further makes an empirical contribution and provides rich understanding on the structure of an ecosystem and the strategic role of a hub firm in developing inter-organisational ties. Ties within the context of dynamic environments are heterogeneous and continuously evolving. The temporal aspect of ties provides rich dynamics on the role of orchestrator as well as change of relationships over a period of time as industry evolves (Mariotti and Delbridge, 2012). There are not only strong and weak ties, as the rich literature suggests, but also potential and latent ties that the hub firm managed. Broad search and exploration activities are considered instrumental for generating new ideas in the context of both dynamic and stable environments. However, for emerging industries, whereby the technology is still embryonic and developing, market applications are unclear and actors are in flux, there is strong evidence of evolution of ties. Strong ties may become weaker and inactive while new potential ties may develop to explore new options. Potential ties refer to a “temporary condition from which a tie may further develop or die” (Mariotti and Delbridge, 2012, p.515). This was facilitated within TFE through a variety of proactive initiatives such as personal relationship, creation of a technical advisory council or through intermediaries and field-configuring events (these are discussed in more detail in Chapter 8). Similarly latency is also a temporary condition and over time the inactive and latent tie may be reactivated, alleviating overload and redundancy in the entrepreneurial context. There is increased evidence of latent ties within OPE and the pattern is demonstrated increasingly by small and medium sized firms. Among the factors motivating the renewal of existing collaborations rather than forging new ties is changed technological priorities that may require renewing existing collaboration owing to the prior increased investments in R&D, reliability of the partner and its unique technical competency.

The study was conducted in real time in a dynamic environment and there have been substantial changes in the focal firm and its ecosystem as the PhD progressed. The TFE ecosystem has evolved and moved from nascent and early stage into the momentum phase. There has been the inclusion of a large number of new commercial partners, along with changing position of some of the ecosystem partners, including some changing from being a collaborator to a competitor. The early success of TFE has also resulted in imitation dynamics and increased adoption of an innovation ecosystem model in the broader OPE industry. These recent events indicate the need for a follow-up study on the TFE ecosystem to explore how the late stage routines differ from the early stage routines (Peeters, Lewin and Massini, 2014).

The study has managerial implications as it identified that the change in the business model, from licensing to commercialisation, impacted the position of the firm from upstream to downstream, affected the configuration of partners and overall competitive advantage. The findings of the effective strategies could be further tested using large samples for generalisability.

Chapter 7: Reconfiguration of Routines: The Case of Solvay

7.1 Introduction

The previous chapter discussed the dynamics of a small entrepreneurial firm, Thin Film Electronics (TFE), that orchestrated an innovation ecosystem and developed inter-organisational as well as a large number of classical intra-organisational routines to facilitate commercialisation. Extant literature supports the notion that radical, breakthrough, discontinuous and architectural innovation requires building new capabilities and working out of the box (Bessant et al., 2005). Schumpeter entrepreneurial firms are considered to be more proactive and better equipped when it comes to breakthrough technologies owing to their flexibility contrasted to that of large incumbent firms that tend to suffer from organisational inertia, path dependencies and inflexibility (Christensen, 1997). Christensen contended that incumbents fail to recognise the threat from disruptive technologies and referred to it as the “innovator’s dilemma”.

Routines have been long recognised as defining patterns of behaviour which result in establishing processes, procedures and norms within organizations (e.g., Nelson and Winter, 1982; Feldman and Pentland, 2003). They provide stability when the environment is unstable, especially for established firms, which tend to have developed routines over time. This may be particularly challenging in the case of emerging technologies, often characterised by creative destruction, the potential of disrupting an existing industry, and the decline of incumbent firms. This may due to the incumbents’ inflexibility and delays, a preference for continuous investing in incremental innovations with certain payoffs rather than developing radical more uncertain innovations, and fear of cannibalising existing sales (Christensen and Rosenbloom, 1995); however, some outlier incumbent organisations can adapt, survive and even regain their supremacy when confronted with breakthrough technologies (Hill and Rothaermel, 2003; Lavie, 2006; Ansari and Krop, 2012).

Incumbents can develop varied responses – “capability branching” (Helfat and Peteraf, 2003) – to opportunities arising from technological change that involve recombination, redeployment, renewal or reconfiguration of capabilities (Lavie, 2006).

Organic and Printed Electronics (OPE) can be categorised as a general-purpose radical technology that has the potential for a broad range of applications in various sectors. General-purpose radical technologies, owing to their potential for value creation in diverse industries, are attractive both for large incumbents as well as new ventures; see for example the advanced material sector (Maine and Garnsey, 2006; Maine, 2008). Shane (2004) argues that start-ups have a distinct advantage when it comes to commercialising general-purpose technologies as compared to incumbents. However, Maine and Garnsey (2006) elaborated on the commercialisation challenges faced by entrepreneurial ventures in the advanced material sector that require both product and process innovation. The present research study further contributes to this line of research and identifies challenges as being similar for both new ventures and incumbents.

At this emerging phase of the technological development within the OPE space, we find evidence of the presence of heterogeneous players like universities, research institutes, small firms, start-ups and big organisations. Many of the upstream[58] material companies, such as chemical companies and substrate providers, have the R&D programme to track the progress and develop the internal competencies required to gain advantage when the technology matures and dominant design emerges. Incumbent organisations have adopted various mechanisms to overcome the gale of creative destruction such as the formation of strategic alliances, licensing arrangements or R&D partnerships with start-ups. These arrangements resonate with those in biotechnology where incumbent pharmaceutical companies were able to form alliances with start-ups that proved mutually beneficial for both. Large firms were thus able to retain their strategic position and ensure their survival while start-ups were

[58] When firms are described as occupying an upstream or downstream position on an industry value chain, this refers to the distance from the activity performed to the consumer, with downstream being closer to the consumer.

able to get access to their complementary assets (Hill and Rothaermel, 2003; Rothaermel and Thursby, 2007).

This chapter provides an in-depth analysis of how a large incumbent Belgian material company – Solvay – is responding to the challenges associated with the creative destruction of a breakthrough technology, Organic and Printed Electronics (OPE), currently in the emergence phase. It proposes that incumbents have strong incentive to experiment during this early emergent phase, despite the challenges and uncertainty characterising the period before the emergence of dominant design. Proactive and early investments in emerging domains are necessary for knowledge accumulation and enhancing absorptive capacity and preventing technological lock-out (Cohen and Levinthal, 1990; Hill and Rothaermel, 1993; Schilling, 1998). The empirical evidence suggests that large firms' response to emerging technologies in the emergence phase can be categorised as transformational rather than one of substitution or evolution. The analysis uses routine-based model (Lewin et al., 2011) to investigate the mechanisms for reconfiguring Solvay's capabilities. The case study illustrates the transformation mechanisms adopted by an upstream incumbent to develop new competencies in response to environmental changes. It contributes to research on capability reconfigurations by incumbent firms by providing empirical support to the theoretical framework proposed by Lavie (2006).

The case study is neither prescriptive nor ex ante any successes or failures associated with the firm's attempt to develop second order technological capabilities for exploration (Danneels, 2008). Section 7.2 discusses the contextual factors in the advanced material sector and upstream positioning. Section 7.3 provides a brief history of Solvay and this is followed by a detailed discussion of mechanisms for reconfiguration and intra- and inter-organisational routines for absorptive capacity. Section 7.6 discusses the findings and concludes the case study.

7.2 Contextual Factors

OPE, as discussed in Chapters 4 and 5, is a new way of making electronics through innovation in new materials and manufacturing processes. It cannot be neatly categorised as either the product or the process innovation. Upstream material firms, new ventures and incumbents within OPE face high technological as well as market uncertainty. For commercialisation, both the technological and the market challenges need to be synchronised or matched (Maine and Garnsey, 2006, p.379) and that tends to be complex "as it involves high cost product and process development, complementary innovation, vertical integration or alliance formation, long time horizons, financial investment, and tolerance of sustained technology and market uncertainty."

As OPE is a generic radical technology, the basic scientific R&D innovations are followed by customised process innovation for each targeted market sector, thus requiring continuous product and process innovation in the form of prototypes and pilot lines. OPE is characterised by a long gestation period, high product and process innovation cost, complementary innovations and distributed knowledge that necessitates collaboration among diverse technological partners thus spanning disciplinary, geographical and sectoral boundaries.

> A prerequisite to the formation of collaborations and alliances is a flow of communication that spans industries… Chemical companies are needed to synthesize the raw materials, printing industry players to apply their skills to low-cost manufacture, and […] electronics and display firms to push ahead with new devices and systems. (Moore, 2002)[59]

7.3 Solvay

Solvay, founded in 1863, is one of the oldest chemical companies in the world. Over the years it carried through a strategy of being a commodity chemical company and also created, as did many chemical companies, a pharmaceutical arm. In 2009, a decision was taken to sell the pharmaceutical arm and a deal was reached with Abbott. Solvay has a dominant position in fluorinated polymers following the acquisition of Ausimont. Its operations are divided into plastics, chemicals, specialty chemicals, new business development and corporate and business support.

Solvay is unique in being a family owned business. This is an important aspect of the structural difference when compared with other similar chemical companies, such as ICI (Imperial Chemicals Industry). It implies they can make quite long-term decisions and stick to them. Their operational excellence and top management control enabled Solvay to survive even in the difficult times of the 1980s and 1990s when other

[59] http://spectrum.ieee.org/semiconductors/materials/just-one-wordplastics

chemical companies that had been household names were vanishing. According to their website, “The family nature of its share ownership structure, which is still clearly evident today, facilitates a long-term corporate vision and reduces dependence on the financial markets.”[60]

According to Alois Michelsen, the first non-family chairman of the board, “If you are born with the shares in your cradle, you are more tolerant to losses and the stability is then higher” (Bertrams et al., 2013, p.533).

However, it has been argued that Solvay’s efficient production processes for commodity chemicals were based on economies of scale rather than being innovation intensive (Bertrams, 2007). This aspect was clearly highlighted during interviews:

> So they were able to articulate “Our strategy has worked very well, but what next? We’re running out of… we’re number one in these areas…” The only way, really, is down, if you’re bluntly honest about it. So you can expand geographically. And it’s a very Eurocentric company so there’s the rest of the planet to go at, and that will keep you going for a while. But ultimately you’ve got a problem, a strategic problem. What’s the answer? We must be more innovative. (Respondent anonymous)

In 1993, Solvay’s CEO Daniel Janseen proposed restructuring the company from a function-oriented matrix organisation to a product-oriented strategic business unit (SBU). This decision was taken as a result of the recession and aftermath impacts of the Gulf War in 1990 that shook the chemical industry. The industry witnessed low growth and revenues and the 1980s strategy of diversification was replaced by a process of consolidation of competitive advantage in core businesses and divestment of peripheral activities.

Prahalad and Bettis (1986), while discussing the dominant logic, also emphasised the hampering role that management dominant schemas play in filtering out and divesting projects that do not fit firm core competencies or those that introduce strategic variety. In these circumstances the management response is either untimely or inappropriate. The dominant logic and existing routines played a central role in Solvay as creative and divergent projects that did not fit the organisation’s existing strategy were divested or sold out leaving behind some orphan projects.

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http://www.solvay.com/en/binaries/HistoryFINAL%20GB-137483.pdf

> The dominant top management logic in a diversified firm tends to be influenced by the largest business or the 'core business', which has the historical basis for the firm's growth. (*ibid*., p.490)

Reflecting on the strategy of formation of SBU and the need to move into new business development, Bertrams et al. (2013, p.500) commented:

> Looking back on the introduction of the SBUs at Solvay, one can conclude that they were successful in giving the company a strategic focus and a leaner organization… But there was also a negative side… it was more difficult to start new businesses outside the strategic domains of SBUs. When these flaws in the new organization were discovered remedies such as competence centre… and New Business Development were introduced.

The tension and challenges that prevailed within Solvay as a result of the restructuring were also pointed out by a respondent:

> We just ended up a process of 10 years of structuring the company in business units and creative activities were left out of them. I strongly pushed… that if people don't need it and if we believe there is value in it first thing to do is to sell that outside. So they said Oh! Selling that outside you cannot do that there can be value for competition there, no if there is value for competition take it for you. If there is none let us sell it. It was a kind of difficult battle. People saying I don't want that, I don't want to pay for that and in the end if you want to sell it, they say oh that's very important, personnel knowledge there, we can leverage that, if you can leverage that, take it and so at the end we started to sell outside, small activities of around 10 people working on the subject. Catalyst research, plastic processing there were quite a few there and adhesive manufacturing. We had 4-5 different projects there and we started to sell it we succeeded to do it at the end, always with kind of internal struggle. (Respondent LDS)

> We did that with several pieces, but doing that we asked ourselves also, […] if we do that after 2, 3, 4 years everything will be sold out and then what we will do. We decided to allocate the sum of money to try create at that time activities out of the boundaries of what we did. (Respondent LDS)

The above quotes reflect the inherent tensions such as mental rigidity and under-allocation of resources arising from dominant coalitions prevalent in the incumbent organisation when faced with technological discontinuities (Kotha et al., 2011). The Solvay business model had been to produce tons of materials rather than the processing of mere kilograms, and restructuring the company in business units created an approach that was more short-term and profit oriented rather than long-term and innovative. Furthermore, restructuring the company in business units resulted in creating silos rather than promoting cross-fertilisation of ideas and mobility that would enable recombination and nurture creativity. To address these inherent tensions, a more ambidextrous approach of establishing new business development units was initiated. However, it could be argued that Solvay has been a follower in introducing these initiatives, and the introduction of separate units for pursuing long-term radical projects was already prevalent in other firms within the chemical industry such as BASF.

7.3.1 New Business Development (NBD)

In 1998, to overcome the problems of narrow focusing, Alfred Hofaait, Head of Research, established New Business Development (NBD) and innovation became the buzzword within Solvay. NBD activities initially encompassed many areas and were broadly defined as evident from the objectives and vision mentioned in the Solvay Annual Report of 2001 that referred to NBD as "a veritable hive of projects" and comprised projects at different stages of maturity. Bertrams et al. (2013, p.543) also mentioned the initial diversity of the pursued projects:

> When the NBD plan started in 1998, it first developed in all directions: biodegradable polymers, plastics recycling, fluorine chemistry for optical fibres and lithium batteries, peroxide chemistry and catalysts, water treatment, and membranes for fuel cells, to mention some examples.

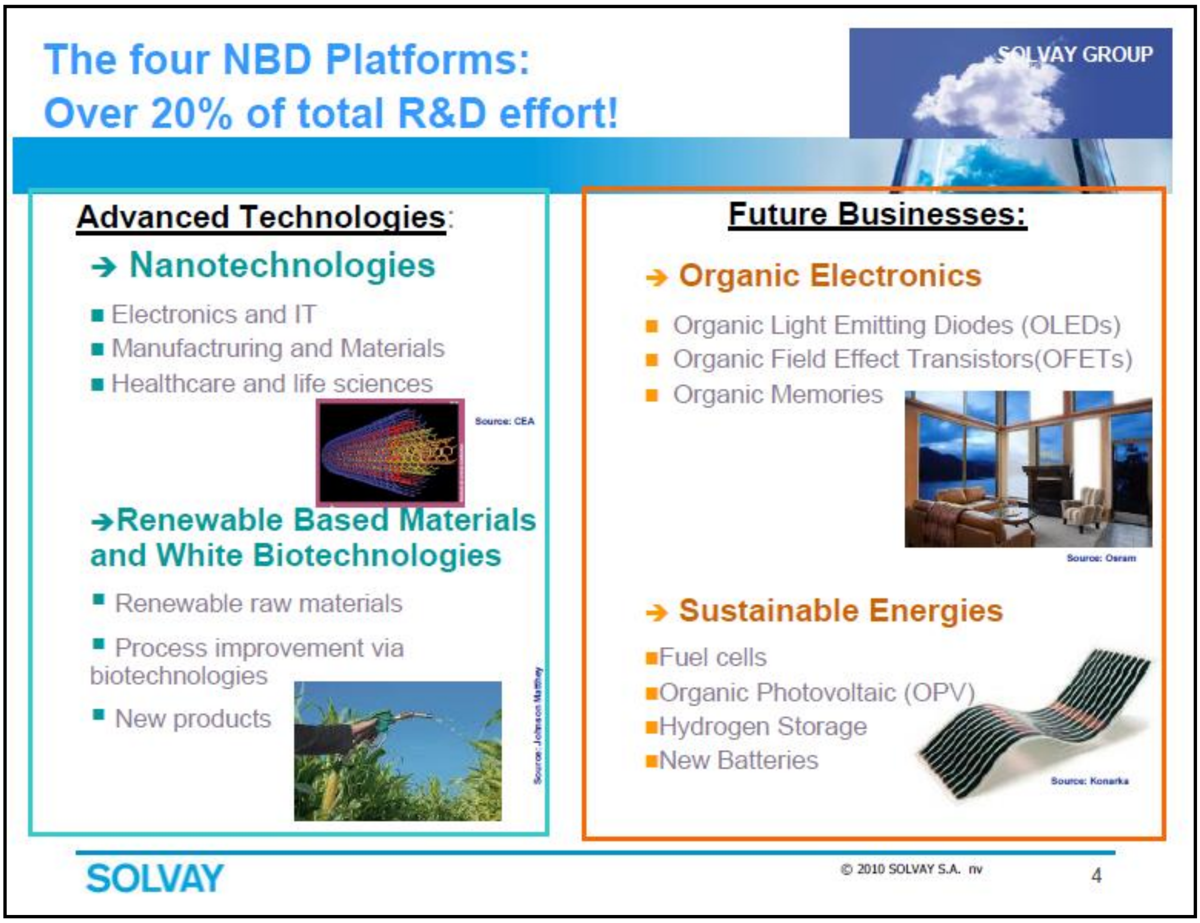
The move of Solvay to establish NBD is an example of structural ambidexterity; it creates dual structures, separate subunits for exploration and exploitation, so facilitating organisational renewal (Duncan, 1976). Organisational ambidexterity enables firms to manage exploitation through incremental innovation and exploration nurturing breakthrough innovation (March, 1991; Tushman and O'Reilly, 1996; O'Reilly & Tushman, 2008), thus striking an intricate balance between firms' dual orientation of adaptation and alignment (Birkinshaw and Gibson, 2004).

The New Business Board was created in 2004 and the projects were redefined and aligned according to the megatrends in society such as ageing population, water shortages, energy issues and scarcity of resources, to name a few. Based on these identified megatrends and considering market needs two strategic platforms were created in NBD (for details see Figure 7.1):

- Advanced Technologies (nanotechnologies, renewable chemistry) headed by Francois Monnet mainly working on the spread of new technologies inside the existing business, leveraging internal networks of existing competencies within Solvay with the aim of pushing them further.

- Future Businesses (Organic Electronics and sustainable energy), the brainchild of Leopold Demiddeleer, targeted towards long-term developments and future business, thus looking at opportunities outside the current business scope.

Figure 7-1 New Business Development Platforms



Source: Mesland, 2010[61]

Following the divestment of its pharmaceutical business in 2009, Solvay went for another restructuring under the "Horizon" project following "sustainability" as the key theme and driver shaping the Solvay future. As a result of this initiative, the Innovation Board was established, headed by Jacques van Rijckevorsel. It replaced the

[61] http://www.solvay.com/en/binaries/20101014_RD_Solvay-135308.pdf

previously established New Business Board. Furthermore, NBD and the innovation drive of 1997 were consolidated and merged into "The Innovation Centre" headed by Pierre Jorris reporting directly to the CEO. This was followed in 2011 by the acquisition of Rhodia, a specialty chemical company, thus laying the foundation of New Solvay.

> The Horizon reorganization of the Group ultimately aims to reinforce entrepreneurship within Solvay, bring its businesses closer to the customer, empower employees operating in the field, giving them more leeway to take action, and facilitate strategic thinking and boost innovation as part of Solvay's overall strategy. [62] (Solvay Live, 2011)

Pierre Jorris, the Chief Scientific and Innovation Officer, commented regarding the need for the Innovation Centre:

> What we learned from the survey was that many people had lots of ideas, processes were in place to encourage and reward these ideas, but on one side, management in general was not seen as providing enough attention or focus on the innovation agenda, and on the other side, the ideas or practices being generated were not being transferred or even managed easily across the company.
>
> This lack of `transversality´ was particularly obvious in our Research and Development activities, which are an essential pillar of innovation for an industrial group like ours. R&D was and will remain decentralized within the Business Units (BUs) and corporate activities, each being responsible for its own R&D resources, programs and priorities. But there was almost no review of the consolidated R&D portfolio of the Group to counterbalance these silos, no common vision to ensure coherence and synergies. (Solvay Live, 2011)

7.3.2 Innovation at Solvay

The major function of the Innovation Centre is not limited to identifying synergies in the existing businesses and building additional expertise through grasping outside technologies but also fosters a culture of innovation at Solvay. "*Open innovation is one of the key attributes of Innovation Centre"* (Respondent BLS). However, innovation requires a change in mindset in big, diversified organisations like Solvay going from commodity business to highly specialised business such as special polymers to very exploratory future businesses. The legitimisation and institutionalisation of autonomous ideas through developing processes, culture and

[62] "The New Solvay-Horizon, Rhodia… a new momentum," Solvay Live September 2011

procedures enable commercialisation of radical technologies by incumbents and are necessary to overcome organisational inertia (Hill and Rothaermel, 2003).

> What you see generally in company like us is there are internal silos…. It also relate to Not Invented Here (NIH) Syndrome, people try to protect what they have developed. You want to change internal mindset of people, trying to connect people and make lot of cross fertilisation exercise or initiatives on different topics or different themes…. We are working on building external networks but also building of internal kind of events or platform that people really need to share it… You have to push people to work a little bit differently and that is part of the challenge we see in a lot of companies today… you also have to change internal way of doing thing. (Respondent BLS)

> And therefore if you want to be innovative you have to create the environment for innovation. And you can go to various companies and you can see that that's occurring and you can go to other companies, Solvay being one, 10/12 years ago, where it's not occurring. That doesn't mean that the people aren't extremely capable of running that machine. They're better than anybody else in the world. But if you ask them to build another machine, not only will they not know how to go about it, they won't even be very interested to do it. (Respondent anonymous)

> So the mindset that you get for people who've come up that line is that's what they want to do and that's what they're good at: improving a little bit the thing that we already do quite well. If you take a person with that mindset, however clever they are, and say, "I want you to do something completely different, now, something that we don't do well, and do that," they try to apply the previous thinking. And it's quite frustrating for them because the machine doesn't work very well because it hasn't really been built yet. And they're reluctant, and they also become quite anxious that this isn't going to further their career in Solvay, because they don't know what the right answer is. (Respondent anonymous)

Some of the initiatives that were taken to create an internal culture for innovation include the "Innovation Trophy" in 2004 to recognise contributions towards innovative projects, the establishing of an Innovation Charter in 2003, "Innovation Scorecard", "electronic idea boxes", and setting up a network of Innovation Champions (2004) who acted as catalysts for organisation. The innovation drive was not limited to R&D but was applied to all other areas including Human Resources and Intellectual Property Rights.

7.4 Solvay's Move into Organic Printed Electronics – The Rationale

> Solvay made a kind of intellectual leap to think that we could get into the electronics area. There are a number of things that drove, let's say, that basic thinking: the need for change, to do something with the portfolio; a recognition

> that the electronics industry was a growing industry and very unlike the pharmaceutical industry which had been the main cash driver for Solvay; that it had a long future—electronics wasn't going to go away. (Respondent anonymous)

Major chemical companies in North America, Europe and East Asia as pointed out in IDTechEx report 2011 and shown in Table 7.1 were already involved in the early space of OPE, trying to capture the opportunity. However, to acquire new competencies they opted for different modes. For example, Dow Chemical acquired a Light Emitting Polymer (LEP) material license from Cambridge Display Technology and had venture capital investment in Plastic Logic in 2002; Covion Organic Semiconductors GmbH (Frankfurt, Germany) wanted to position itself as the leading supplier of materials for organic LEDs (OLEDs), both for companies using polymers and for those developing small molecule systems; Avecia also had dreams of building its position in inkjet printing materials and a presence in the emerging organic FET (OFET) industry.[63] In 2005 Merck acquired Avecia's OLED polymer material business that also included Covion Organic Semiconductor and later in 2008 it acquired all the IP of OELD-T (a UK-based company involved in the material development of OLED).

Table 7-1 Giant Material Companies' Involved in OPE

North America	Europe	East Asia
DuPont, Eastman Kodak, Dow Chemical, Dow Corning, Honeywell	BASF, Solvay, Merck Chemical, Henkel, Evonik Industries, Bayer	Nissan Chemical, Sumitomo Chemical, DuPont Teijin, Teijin, Mitsubishi Chemical, Hitachi Chemical

Source: IDTechEx, 2011

Solvay, realising the opportunities within the emerging space of OPE, opted for systematic development and targeted three major areas: OLED (Organic Light Emitting Diode) for lighting, OFET (Organic Field Effect Transistors) for backplanes and OPV (Organic Photovoltaic). However, activities for OPV were on a small scale (scouting) compared to those for OLED and OFET. "*OPV in my understanding at the time was a by-product. We could make it on top of what we already made for OLEDs. If you work on light emission you can also work on light absorption.*" (Respondent LDS). In addition, OLED, OFET and OPV are complementary themes in terms of

[63] http://spectrum.ieee.org/semiconductors/materials/just-one-wordplastics

materials.

> Issues are basically the same in terms of processing. The materials which are similar are also materials used in OLED for specific layers which are similar to the materials that you could use in OPV; have some similarities between semi-conductors used in OPV and the semi-conductors used in OFET. (Respondent PBS)

The portfolio approach for developing materials that could target various application platforms has been a prevalent practice for players in this fledgling industry.

> So for a year or two we're hunting for what should we do? Is it OPV? Is it OLEDs? Is it field effect transistors? Is it lighting applications? Is it white lights? Is it coloured lights? … All sorts of things. And… from where we are now, I think it would look a rather linear progression. But I think there was quite a lot of hunting and trying things and "That's not going to work" and modification of use. And I think that will still continue. (Respondent anonymous)

Solvay's strategy to explore the OPE space in 2005 can be classified as "wait and see" compared to other chemical companies like Merck that in the past dominated the market for flat panel display, had a successful business in liquid crystals and therefore were also looking for a leadership role in the organic area leveraging the existing distributed channels, especially in display industries. Solvay's vision is to be in the value chain and "*take share of a market where the device makers at the end will look for suppliers that are able to provide them the relevant sets of inks"* (Respondent LDS).

> In some ways it seems… I wouldn't say it's completely unique but it's a relatively unusual case that the conceptual move from the idea to the business model is so simple, and in many ways risk-free, because the electronics industry exists, the electronics industry is going that way, they now suddenly need chemists, and they aren't chemists, so we can supply that half of the equation. (Respondent anonymous)

From the field work and discussion with the experts it becomes clear that for chemical companies, being very much upstream and following the traditional business model of being sole supplier of raw material and molecules, this would not be a viable business model. OPE requires the convergence of electronics, chemicals and printing and these three industries would need to be integrated to realise the potential of the field. The question that then arises for the upstream chemical companies is how much they need to move downstream and to what extent they need to understand the other two scientific strands of electronics and printing to be able to offer a unique proposition to the end customer. Moving into the space of Organic Printed Electronics thus requires disrupting the business model for the upstream material supplier from supplying bulk quantities for commodity markets to small quantities for niche applications. Parandian (2012, p.74) hinted at this dilemma and tension as is evident from an interview with Eliav Haskal of Philips:

> Material suppliers hold a key position in the OLAE[64] value chains, but because of that they face challenges. They have to do application specific R&D based on the values placed on features and performances in many different end markets in which demand is not articulated yet. Hence, high investments have to be done in R&D without getting real feedback.

The debate and discussion around a viable model for entering into OPE have also been part of the dynamics within Solvay as is evident from the quote below:

> But the team was very good at thinking through and codifying the fact that we would have to move down the supply chain quite a long way to make our business viable. That's one point. How much of the value chain could we go to? And there was a lot of discussion about: Shall we make inks? Shall we make systems, components? Where would we get to, to connect to let's say Samsung or whoever it is? So that debate was quite active. (Respondent anonymous)

The above discussion provided a rich context to understand the processes developed by Solvay to gain competencies and develop capabilities for a radical and breakthrough technology. These developments are discussed in the following sections.

7.5 Findings

The next section discusses the reconfiguration of intra-organisational and inter-organisational absorptive capacity routines that enabled Solvay to gain relevant competencies within the space of OPE and overcome the lag owing to its late entry in the field as compared to its competitors.

7.5.1 Reconfiguration of Capabilities

According to Lavie (2006), reconfiguration facilitates narrowing the capability gap and refers to the mechanisms employed by the incumbent organisation to change the configuration of their capabilities in response to technological change. Thus it offers

[64] OLAE-Organic Large Area Electronics is another term that is frequently used for Organic and Printed Electronics (OPE)

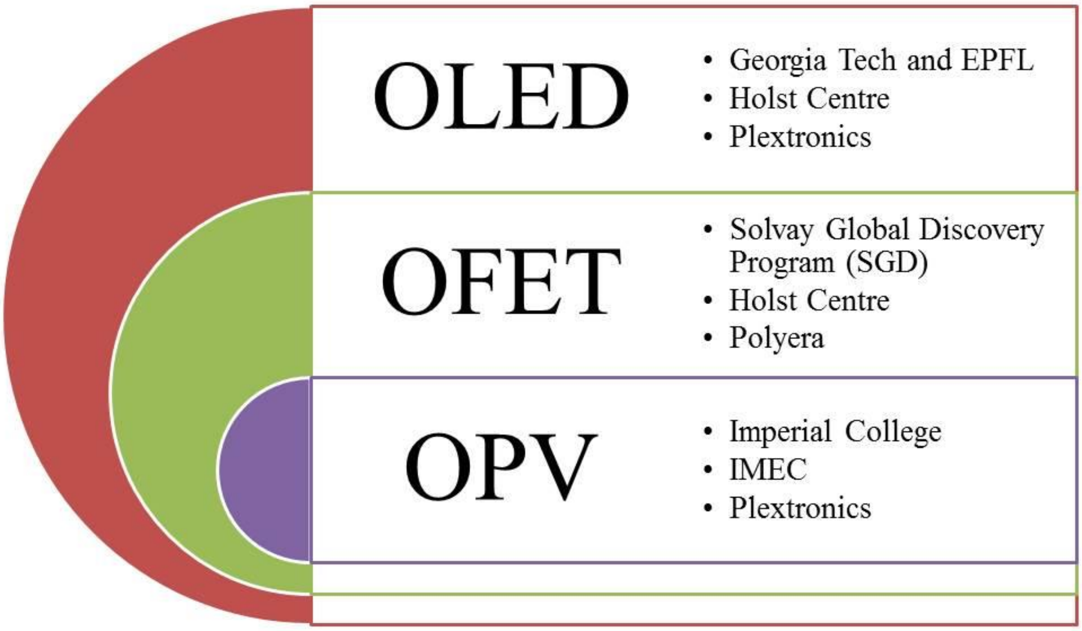
an alternative explanation to that proposed by research on technological discontinuities (Tushman and Anderson, 1986) that associates technological discontinuities with creative destruction of incumbents and that of dynamic capabilities (Teece, 1997) which offers an adaptive explanation of existing competencies. Lavie (2006) suggests three capability reconfiguration mechanisms: substitution, evolution and transformation. Substitution implies that existing capabilities are difficult to change and therefore require either discarding existing capabilities or acquiring new ones when faced with technological change, while capability evolution is an ongoing process that enables adaptation and modification. Transformation, in comparison to substitution and evolution, is an intermediate response to technological change, "in which some routines are modified, others are discarded, and the new ones acquired… it involves learning from a combination of internal sources of knowledge and external resources…" (Lavie, 2006, p.159). Furthermore, reconfiguration necessitates developing absorptive capacity routines such as monitoring and scanning the environment for technological changes, assimilation and integration of the new capabilities and, finally, application.

The following section discusses the routines adopted by Solvay for developing transformation capability to gain competitive advantage within Organic Printed Electronics. The findings indicate that the approach taken by Solvay is exploratory with strong emphasis on practices to identify and access external knowledge that would enable them to build their knowledge base and develop a value proposition in the emerging field of Organic Electronics where chemistry would eventually play a dominant role.

> Exploration is something important […] Problem is the timing also. When are you travelling a new technology and market matrix, in time you start from somewhere and then you travel and you go from lab to industrial scale, prototyping and in market-market exploration, scouting, then you are industrial and you are in good business condition to launch a business. (Respondent LDS)

Identification of external knowledge outside the firm's boundary imposes challenges for established companies (Benson and Ziedonis, 2009). Solvay increasingly relied on three mechanisms to identify, evaluate and access external knowledge that included outsourcing and creating external networks with academia and research institutes, corporate venture capital activities, and finally establishing collaboration and alliances with entrepreneurial technology-based firms. Solvay's mechanism for different technologies is represented in Figure 7.2. In addition to that, Solvay also participated actively and shaped the activities at the association level (more detailed discussion in Chapter 8). Solvay realised that accessing external knowledge and developing inter-organisational collaborations is only a part of the equation and also developed intra-organisational mechanisms for assimilating and integrating the acquired knowledge.

Figure 7-2 Solvay's Approach for OPE



Source: Author

7.5.1.1 Intra-organisational Routines for Identifying and Accessing External Knowledge

7.5.1.1.1 University-Industry Partnerships – Global Discovery Program

Science and technology have been often described as dancing partners (Rip, 1992; Makri et al., 2010) and "enriching a firm's science knowledge domain can enhance its technology domain" (Makri et al., 2010, p.606) and will contribute to an increase in absorptive capacity. Furthermore, scientific complementarities result in exploration and further advances in the technology domain.

The role of university–industry links in innovative performance has been widely recognised in scholarly literature (Perkmann and Walsh, 2007). It is recognised as one of the vital search and screen tools to identify and access external information. The extent of openness, size of the firm and R&D intensity have been identified by Fontana et al. (2006) as important factors that impact the propensity of firms to collaborate with universities and research institutes. However there is not much evidence to support the impact on the type of innovation e.g. product-versus-process. One of the structural factors that has been highly acknowledged and widely studied as influencing the firm's propensity is the size of the firm. Large firms with greater R&D intensity and high absorptive capacity demonstrate a higher level of collaboration with public research organisations (PRO) (Mohnen and Hoareau, 2003; Laursen and Slater, 2004). Panagopoulos (2003) proposed that the propensity for forming research joint ventures with universities tends to be higher for emerging technologies where there are increased spillovers compared to mature industries where opportunity cost is higher. Thus the impact of university links on industrial innovation is heterogeneous and varies with industry.

Cohen et al. (2002) identified various channels that enable flow of information from public research institutes to firms. These include patents, publications, reports, conferences, informal knowledge exchange, contract research, consultants, joint research projects, and hiring of graduates. However, the importance of these channels varies across industries and they tend to be more important for problem solving or project completion rather than for idea generation. That study's empirical research further confirmed the findings of earlier research that the impact of the public sources is less effective compared to downstream sources of knowledge such as suppliers and customers.

Perkmann and Welsh (2007) emphasised the importance of the relationship-based link (research partnership, research services) rather than more generic links such as provision of graduates with required skill sets (and other open science links such as publications, conferences) for open and networked innovation because it facilitates long-term relationship and learning.

Establishing networks with academics and universities was established as an exploratory or knowledge-creating routine in Solvay to access the required external knowledge, improve learning curves, shorten time to market and develop required competencies within OPE. It was research oriented, driven by the rationale to identify and select the technologies that looked promising and to generate new ideas, develop an initial IP position before further prototyping and, finally, for business development, in contrast to Cohen et al.'s (2002) limited view of problem solving. In nascent science-driven industries, university collaborations are a locus of knowledge creation whereas its commercialisation is driven by industry collaboration (Lavie and Drori, 2012). Solvay was a late entrant in the field of OPE compared to other material companies, and did not have an internal R&D programme or competencies in existing businesses that could provide them with initial impetus for entering into the OPE space. Academic collaborations proved crucial to build a strong intellectual property right position. The interviewees also stressed, for following the knowledge-creating and exploratory approach:

> When you start, you have to build your IP base. Without an IP base in industry you are dead and internally you don't have the capacity to develop the big portfolio of original IP […] unless you create a kind of division of 100 people working on something. We cannot pay that, so we have to go through academic partnerships then and indeed at the start it is quite science and research driven because of the fact that you are trying to catch […] (Respondent LDS)

> When I go back seven years or so, when […] we did not know a lot within Organic or Printed Electronics. It was also for us learning because it is very difficult you can talk to your competitors or potential customers because you have nothing in hand. […] so you have to enter progressively, you have to learn over some years and now I think we are in a position that we now have marketing relationship with potential customers and that gives us both from the business side and from the customer needs where are still the opportunities that we can enter and sell the product. (Respondent RMS)

Initially Solvay established a relationship with Georgia Tech (COPE – Centre for Organic Photonics and Electronics USA) and with EPFL (École Polytechnique Fédérale de Lausanne) in Switzerland in 2006 to build their initial understanding in Organic Light Emitting Diode (OLED). In 2008, the relationship with COPE was further strengthened and expanded into the Solvay Global Discovery Program (SGD) for Organic Field Effect Transistor (OFET). SGD is a unique form of university-industry collaboration as compared to those identified in the literature such as collaborative research partnerships, research services (contractual and consulting), or licensing (Perkmann and Walsh, 2007). In SGD, Solvay not only pursued inter-organisational collaborative R&D with COPE but also created symbiosis and leveraged from the existing network of Georgia Tech academic partners. That is, instead of forming bilateral agreements with different university partners across the regions Solvay left the selection of university partners and the design of collaboration activities to COPE. COPE had existing academic collaborations with the University of Washington and Princeton University in the USA, Imperial College, London in the UK (through AtlantIC Alliance Program)[65] and the Chinese Academy of Science in Beijing. The existing network of COPE's academic collaborators then became part of the Solvay Global Discovery Program.

Figure 7.3 below presents in more detail the researchers and scientists that have been involved in the SGD showing the relationship and value associated with collaborating with reputed scientists.

> In academia we tend to have a global network of colleagues and collaborators […] so why not work with a university such as Georgia Tech that has a global network, and build on that existing network to create a research programme where you have one goal, but you have multiple approaches and these approaches are being carried out by multiple teams across these different continents with some level of co-ordination and transparency and exchanging notes and information – so that you really work together as a team and you build intellectual property rather than having teams that compete with one another and that are disseminated across the globe. (Respondent BKC)

[65] Georgia Tech Provost Jean-Lou Chameau, Imperial College, London (ICL) Rector Sir Richard Sykes and Oak Ridge National Laboratory (ORNL) Director Jeff Wadsworth met in London and signed a memorandum of understanding (MOU) formally creating the AtlantIC Alliance for BioPower, BioFuels and Biomaterials in 2004.

Figure 7-3 Solvay Global Discovery Program

Source: Author

Another differentiating factor of the SGD programme is that though it represented a form of industry-sponsored research, funded by Solvay, it also required reciprocal commitments in terms of lab and equipment from COPE as Solvay initially did not have the lab to evaluate the results of university research. There was a time lag of three years from engaging in academic networks to exploiting the results and creating an owned infrastructure in the form of labs at Solvay.

Academic collaborations between research scientists drive knowledge creation and facilitate idea generation thus enhancing scientific productivity in nascent science-driven industries (Lavie and Drori, 2012). Therefore, existing academic collaborations between the academic partners were used as a driver for knowledge creation and a contributor to knowledge application in the SGD programme. This model is inherently different from the linear model where scientific research in university creates spillovers that facilitate commercialisation by industry. In practice, the knowledge exploitation by industry impacted further knowledge creation and there was an iterative process of knowledge exchange between university and industry.

> […] with these new technologies, involve a lot of different challenges and aspects, it's kind of a feedback loop. It's not that old, linear model where you say, "OK, you know, we've invested in research; we have a couple of broad patterns; now it's time to move these things down to development and we're going to take one material or two […] I think that model is certainly not the best model for printed electronics. I think there is no winning material; there is a constant need for better materials; and so that old, linear model has to be replaced by an integrated, kind of a circular model where you have a feedback loop where at all these points along the value chain you sometimes go back to some basic science. (Respondent BKC)

Apart from tapping into the academic networks, Solvay along with COPE organised the Solvay-COPE Symposium thus leveraging the potential of such interactions outside the research collaboration framework (Hermans and Castiaux, 2007). The symposium not only attracted reputed and distinguished scholars in the field of Organic Electronics but was also well attended by industry participants. Around 150 participants attended the 7th COPE symposium held in 2013. Academic collaborations with renowned scientists across the globe and the initiation of these networking events built momentum, signalled Solvay's credibility and reputation in the field of Organic Electronics to the external world and brought Solvay up to par with other established players such as Merck and BASF.

Managerial cognition tends to be an important driver for development of capabilities (Eggers and Kaplan, 2009). The selection of Georgia Tech was based on Leopold Demiddeleer's vision and existing personal relationship. Cope's strength lay in the fact that it could offer expertise in multidisciplinary areas that tend to be prerequisite for printed electronics, from the synthesis of new materials all the way to device work and device integration, thus offering the heterogeneous competencies required for OPE under one roof. In addition to having an international academic network, COPE had also developed various mechanisms to facilitate exchanges among industry and universities through their industrial affiliate programme that attracted industrial partners along the value chain, from material suppliers to equipment providers and integrators.

This university-industry consortium has been a win-win situation for both academia and industry. It facilitated Solvay in getting the initial understanding of the field, generated useful IP that could be further exploited, provided intellectual capital and developed the required social capital. For Georgia Tech, the collaboration resulted in production of a lot of new materials that could be beneficial for moving to the next generation of low-cost materials, and generated many patents and publications.

> …there are some valuable approaches but I am not yet sure that we have a conclusion when they come to the market. There are interesting things, you have to figure which one but at the end for sure there are 80% of things which you will not use. (Respondent RMS)

> Probably when you see what we did within the field of organic electronics, at the beginning when you do nothing it is good you get to know people and you experience a lot, so you will do lot of these things outside and once you are yourself expert in the knowledge, you will need less and less these inputs. Still it is valuable especially to explore new things and to have new ideas coming in but in the beginning it will be different because you don't know anything so it is very valuable input, you will also look for instance to hire people because you need good people. Then you find talented young people that you can put in your labs, a lot of knowledge you don't have so it is valuable over one two or three years and then it is less value coming from that because once you have acquired, you will put less money in the university than at the beginning. (Respondent LDS)

However, to what extent Solvay would be able to exploit the results for future product development is difficult to comprehend ex ante. As of 2011 Solvay has invested over $10 million in research at Georgia Tech.

7.5.1.1.2 Partnership with Applied Research Institutes

Working in the field of OLED and OFET also requires competencies in device physics and so for the material companies understanding of the physics and its interaction with chemistry is equally important.

OPE is still in its early ferment stages and dominant designs are yet to emerge for diverse applications. There are several approaches that are pursued in parallel. For material providers, mostly large organizations and located upstream, collaborating with research and technology organizations enables them to acquire device design competencies, printing know-how and in certain cases independent evaluation of results. To move from research to development and benefit from the research generated with universities, Solvay developed partnerships with intermediaries like Holst Centre (an Open Innovation Centre in the Netherlands) for OLED and OFET and with IMEC for OPV (Holst Centre and the role of intermediaries for emerging and breakthrough technologies will be discussed further in Chapter 8).

Loose coupling between basic and applied research is recognised to be important for affiliating commercialisation. According to Hill and Rothaermel (2003), "basic R&D spending will not lead to adaptability in the face of technological discontinuity unless the basic research function of the firm is coupled with applied research and product development efforts".

> The difficulty in this area is that materials itself does not mean too much so you have to place it in the device context. The performances are related to device […] if we want to do real prototyping then we work with external partnership like for OLED in Holst centre or for OTFT. (Respondent RMS)

> […] we are participating in the Holst Centre. This is more about processing aspects where clearly we have lack of knowledge because it is very specific for these kinds of things and how to do printing; you have to learn how to formulate inks and printing. We have people for instance working in processes. It is a question of equipment also because equipment is expensive, you don't have everything for instance printing in your own labs […] So these are things where we typically send people outside. (Respondent RMS)

7.5.1.1.3 External Venturing – Corporate Venture Capital

CVC was used as a real option tool within Solvay to guide the investment decision under conditions of uncertainty. The use of CVC as an alternate mechanism for acquisition and identification of industry trends, promising technologies and growth perspective of entrepreneurial ventures has been shared by practitioners and academics (Tong and Li, 2011). These views were also highlighted during the interviews with Respondent JLS of the corporate venturing team within Solvay:

> As a venturing team we see more than what we see in-house as R&D and investments. We use different sources of information so it can be specialised forums, it can be reports from analysts like Lux Research, IDTechEx, websites where you can have detailed information about new areas for Solvay like printed electronics, batteries, nanomaterials, green chemistry so our scope is quite large as a venturing perspective.

> We are like the antenna for Solvay in terms of technologies, business models and new opportunities to sustain growth of Solvay. This is the mission to intensify business collaborations with start-ups to create strategic value for the group and its businesses.

> […] In the past we saw there was a missing link between the work done at universities and the new business. The start-ups, their mission is to take an idea – a

> new technology – and convert that into new business. This is something that can be done internally in Solvay with our R&D resources, partnerships with universities, with proprietary IP at Solvay but we need this kind of entrepreneurial profile to grow a new business. It was easier, faster to interact with start-ups via venturing kind of collaboration and investing in specialised funds.

Solvay adopted an active venture capital model in 2004 to support future business activities and at present it has its presence in all geographical regions. Up to 2014 it has made over $100 million and made six direct investments out of which two have been in the area of OPE – Plextronics and Polyera. However, what differentiates Solvay from other chemical companies like Dow Chemicals who have been investing in the material space for more than 10 years or BASF that started its CVC activities in 2001, is that Solvay's venturing activity is not a legal entity with its own budget. This structure, while beneficial to maintaining the strategic focus without being dictated to by short-term financial goals, results in decreased autonomy, a reactive rather than proactive approach and prolonged decision making.

The growing scholarly literature provides different typologies such as strategic/financial, exploration/exploitation, internal/subsidiary or integrated/arm's length (Souitaris and Zerbinati, 2014). Corporate Venturing Capital activities within Solvay are driven by both strategic and financial objectives as stated below and followed the integrated investment logic. According to Maula (2001), strategic objectives can be classified as "learning, option building and leveraging."

- Deliver new growth territories and breakthrough innovations to the group and its businesses
- Deliver competitive intelligence on breakthrough technologies, markets and business models for the group and its businesses
- Generate returns on invested capital

This systematic, top-down focus that the corporate venture capital mechanisms received within Solvay established the credibility of Solvay for entrepreneurial companies as well as independent venture capitalists. Corporate investors are sometimes perceived as opportunistic and high-risk appropriation partners owing to the cyclic nature of their investment. Maintaining continuity and stability for CVC is also associated with increasing returns through later acquisition of start-ups (Benson and Ziedonis, 2009).

According to Basu et al. (2011), one of the factors that induce companies to form CVC ties is the industry dynamism. Dynamic environments are characterised by rapid technological changes and in these conditions the CVC activities provide the required flexibility to rapidly explore emerging trends without being locked in. Solvay opted for both direct investments in entrepreneurial ventures as well as syndicating and investing indirectly through funds. For instance in 2010 Solvay invested KRW20 billion (€13 million) in the Korea Advanced Materials Fund along with Korea Venture Investment Corp (KVIC) and AJU IB Investment, each contributing KRW10 billion (€6.5 million) to the Fund. To facilitate learning and leverage from the corporate venture activities they initially invested in independent venture capital funds to learn about the venture capital activities, then moved to co-investment and finally to direct investment. Independent venture capital firms (IVC) are more exposed to emerging technologies and start-ups and thus provide established companies with diverse monitoring information about the value of the company and the potential of technology to match the established company's platforms (Maula, 2007; Benson and Ziedonis, 2009). Therefore, the initial strategy of establishing relationships with independent funds results in reduced search, monitoring and evolution cost and is also beneficial for the corporation to establish its reputation and credibility, as confirmed by this respondent:

> The idea of investing in venture funds was to get familiar with venture capital approach and how you invest in start-up and how you manage a relationship in a start-up. (Respondent JLS)

> If you do direct investment then you need to have the right people to negotiate, to structure the deal, to do the legal due diligence, follow the company. You have to help the company to grow. It is very difficult to find the right profile. When you invest in a company you can have a board representation, if you invest from Solvay you need somebody from Solvay to take a seating on board of that company. Are you going to have technical people on the board? Or a business guy on that board this will influence the evolution of that company. […] Venture capital professionals do it better than industrial people. There are always exceptions. They have more flexibility, they can work faster. (Respondent JLS)

Learning mechanisms from venture activities within Solvay vary from dedicated deal flow analysis to secondment, internship and securing a board seat. Securing a board seat along with due diligence that is performed prior to capital investments is argued by both practitioners and academics to be one of the channels that facilitate learning in organisations about technology potential and market attractiveness and provides a window to identify novel technology (Dushnitsky and Lenox, 2005). Furthermore, most of the start-ups are small and privately owned and therefore using CVC and acquiring a board seat within the new ventures serves as a "coping mechanism" and a way to "garner informational advantages in these relatively non-transparent and uncertain take over environments" (Benson and Ziedonis, 2009: 330).

CVC activities enable identification, valuing and accessing of external sources of knowledge but in order to benefit from the knowledge acquired it needs to be channelled to the relevant division or personnel within the organisation and this requires setting up of internal networks in addition to the external network (Wadhwa and Kotha, 2006). The venturing team acts a gatekeeper and efficiency of knowledge transfer depends on their technical and market knowledge as well as their social capital within and outside the organisation (Ernst et al., 2005).

> […] you need to have a good network of people inside Solvay and outside Solvay. If you identify a company that might be interesting for Solvay we have to speak to people in the future businesses […] or talking to the business units, the established businesses of Solvay because you have seen a company that has a technology that can fit to your activities, that can improve your processes, or a new product that is complementary to the products that our business units are offering. (Respondent JLS)

> I work closely with people in nanomaterial team. If I see graphene company, graphene is a material which is very hyped now; which is the good process to produce graphene, which is the good quality, how we assess this graphene, it is something that I can't answer to those question I can work with them and present the companies to technical people there and they will ask for samples, they will assess the quality of those samples. (Respondent JLS)

Indirect investment in specialised funds, insights from deal flows and due diligence have also led to identification of interesting new ventures for further investment or future acquisition, a few prominent examples being Plextronics (Organic Printed Electronics) where the initial stake of 15% has increased to 40% due to the increased strategic alignment with Solvay, Amminex, ACAL and Polyera (n-type semiconductor). In addition, Rhodia, recently acquired by Solvay, also started its venturing activities in 2010 which has led to investment in OPV (Organic Photovoltaic) start-up Eight19.

> The funds were the legal investor the one who could decide what would be the evaluation of the company, conditions of the deal and Solvay invests as an industrial strategic partner into that company. It is easier for us because we have

> access to lot of information. The due diligence is done by fund in terms of market, in terms of legal auditing of the company; you mitigate the risk that you would have if you decide to invest by yourself in a start-up. (Respondent JLS)

Solvay initially screened the potential of Plextronics (founded in 2002 as a spinout from Carnegie Mellon University) research products via its venture capital activities and over the years increased its investment in Plextronics. Acquiring a board seat within the start-up enabled Solvay to critically evaluate the strategic evolution of Plextronics and also resulted in reducing the time required for doing the due diligence when acquiring the target company via traditional means, as elaborated by this respondent: *"The venturing helped me a lot there, because if you take the same mechanism for making new venture investments, it will never work. So, yes, we had a very special way to go to decisions, so, short-cuts"* (Respondent LDS). The findings resonate and contribute to Benson and Ziedonis's (2009) argument that CVC investment increases firms' performance when acquiring technological start-ups.

> […] This is a way to really follow the evolution of the company, to discuss strategy. And when you have the board meeting you can certainly give some input and criticise positively or negatively about the choices being made by the company. And that's one way to clearly interact. (Respondent PBS)

A joint development agreement was also devised with Plextronics within the field of OLED to develop complementarities in materials whereby the hole injection layer (HIL) was supplied by Plextronics and for the hole transport layer (HTL) there was a joint development agreement between Plextronics and Solvay. Solvay's strategy has been to design and offer a complete value proposition for the end customer within the field of OLED lighting.

> What something new is not a single product but sets of products that you can sell as a proposition of technical performance that customer needs, this technical performance now can be in different areas – alternative energy generation, energy storage, organic electronics. In all these technologies that will bring answers to big questions we have. You see that the key of all this is the way you bundle the materials together, to give outstanding properties. If you sell all the pieces, it is like human body, if I sell you in pieces it is not worth a lot. I will end up with 40 litres of water, a small bottle of minerals, small organic materials – What's that? You tell me that's human being. Everything stays in the interaction. (Respondent LDS)

These strong interactions facilitated developing "common ground", informal and tacit coordination and synergies between Plextronics and Solvay. Common grounds "arise because of socialization, shared location, prior interactions and artifacts" (Srikanth and Puranam, 2009). According to Puranam et al. (2009), common ground facilitates post-merger integration. These objectives were stated in an interview as well:

> We do both we never invest without a joint development agreement and my bet is that if you have a joint development agreement with somebody where you have stake in, you look at it more carefully than if you just make it arm's length and more carefully than if you are 20-25 around the table in EU in the global project. You start to create personal relationship in between people also and if one day you want to acquire this activity that's very important; that people feel they could be part of this activity also and not just exchanging data. (Respondent LDS)

7.5.1.2 Intra-Organisational Routines for Assimilation

According to Lim (2009), there are three different types of absorptive capacities (AC), depending on the knowledge that needs to be absorbed. These are disciplinary, domain specific and encoded. Disciplinary is concerned with developing general scientific knowledge and relying on exploratory internal R&D; domain specific deals with finding solutions to specific problems, influencing R&D at consortia and universities, establishing strategic alliances and hiring scientists; while encoded absorptive capacity deals with knowledge embedded in tools and developing relationships with suppliers. Disciplinary AC is more relevant at early stages of technology development compared to domain specific AC that is useful at the intermediate stage, while encoded AC is important at later stages when technology is mature and embedded in tools and processes. He argues that the firm's external connectedness is as important as its internal R&D. For Solvay, being a late entrant in the field, the initial task was to develop the disciplinary AC and establish ties with universities. The next challenge was to develop the domain specific AC, focusing on a few promising approaches and facilitating the scaling up of the knowledge developed by external partners, which they did by setting up a lab in Brussels.

> Typically, what we will do is that we will check how that fits to the strategy […] then also we have to see at the start what will be […]. If you do something at less than a gram or up to gram scale in the university than you have to check all the aspect related to how to synthesise the materials, the aspects related to not only the cost, environmental aspects. In many case you have to look at detailed synthesis […] you may have problems linked to minor amounts, traces of impurities so there are many problems coming which in university are not at all treated. So the most difficult thing starts once you say you have to develop, than you have to screen certain number of important things to decide whether or not you want to go ahead. (Respondent RMS)

The lab in Brussels was comprised of two big groups, one on material synthesis where Solvay had competencies, and therefore the core team was selected internally. But for commercialisation and improving organic materials, device understanding is mandatory. The team building in this area was complicated as Solvay did not have an OLED device physicist or transistor device physicists and lacked printing competencies.

The practices adopted by Solvay in this regard were the recruitment of PhDs and post-doctoral researchers from the universities that had the relevant skills within the field and were experts in the technical areas like device development, printing, material synthesis, device testing and OFET.

> You have to build a strong team internally that understand what you are doing, you need to recruit new people […] that are trained in this field […] but if you take them and train them sufficiently early they can manage the academic portfolio of research, they can also be actors in the joint development agreements with the small companies in which you have invested and gradually you create your vision. At the start it is bit fuzzy having different set of materials, but what sets of materials for which application? At the start you cannot answer this question but you must be able to answer it quite fast, […] these guys will help you do that. (Respondent LDS)

> If the post-docs synthesise maybe one 100mg in five or ten steps for synthesis, we have to develop this in Brussels to make this industrial. Because it is impossible from industrial point of view to make money with ten-synthesis step and with 100mg and therefore we scale up the product here in Brussels and we test the product in the ink and device testing lab. (Respondent GLS)

In addition to hiring new employees that facilitated variation and assimilation, Solvay also organised training and arranged workshops conducted by renowned professors from IMEC, other universities and labs.

7.5.1.3 Inter-organisational Routines

Inter-organisational routines, also referred to as interface routines, govern the interaction between organisation and external partners. "Inter-organizational routines are organizational routines where participants are members of different formal organizations" (Pentland, 2004). Inter-organisational routines that were adopted by Solvay included embedding scientists at the university or research centre and adopting coordinating mechanisms that included consortium agreements, meetings and exchanging reports.

7.5.1.3.1 Modes of Coordination

Coordination is defined as "alignment of actions among interdependent partners" (Srikanth, 2007). Priorities tend to differ and create challenges for coordination between academic partners and firms, with the academic world more interested in publications while for industry the priorities are shorter time periods, new ideas and approaches that could meet customer requirements.

The challenges with the Solvay Global Discovery Program were manifold, as identified from discussions: there were those that existed between academia and university, competition among the collaborating academic partners and finally those that arose due to different institutional contexts and national innovation systems, for instance the universities in Europe and USA differ significantly from Chinese counterparts. Sometimes these academic partners worked on parallel but similar approaches outside the consortium and published their results independently. Therefore, an important aspect of coordination when working with a consortium of academic partners was to have alignment and agreement regarding the priorities that need to be achieved in a technical programme. However, the priorities were continuously altered and adjusted over a period of time as the project progressed so there was a feedforward process in place. According to Jones and Macpherson (2006, p.168), "intertwining" with external partners enables institutionalising knowledge acquired from partners. Intertwining refers to "active engagement with external partners" and "indicates that learning mechanisms are at the interstices between organizations and not just within organizational boundaries."

> To begin with you have to manage agreed technical programme of the contract, then within that you have to follow up the progress and also we try to discuss as far as possible with universities the priorities we see, so that as far as we can manage that they work within our priorities. We have reporting, we have meetings and then we have discussion with our partners to get to a common agreement with our partners. (Respondent RMS)

Different modes of coordination were adopted to identify the *know-what, know-where, know-how and know–who* of knowledge while working with external partners such as:

- **Consortium agreement** also referred to as "hard" inter-firm transfer mechanisms by Mason and Leek (2008) provided the general framework and enabled codification of the distribution of work among team members, defining of IP terms and determining knowledge flows. The aim of the agreement was to build a shared vision among partners.

> There has been [a] common programme written to the consortium contract as a technical annex where all the partners give their contribution and once they propose you have to put together so that is fixed. There are no things that are done twice by two different people; that is a long discussion at the beginning. It has to fit within a general theme and general targets. (Respondent RMS)

The main complexity in designing the consortium agreement was to have a unique design around IP. In the case of SGD, Solvay had the option to buy back exclusivity of any particular IP but exclusivity only applied to the field of application, providing flexibility to academia in using that IP in other fields. These inter-organisational mechanisms reflect the continuous process of negotiation and flexibility between academia and industry.

- **Review meeting and reports** enabled "soft" social inter-firm transfer mechanisms reflecting on milestones reached. They also provided flexibility for continuous iterations in work in progress via mutual discussion and agreement.

  > …what we had organised that we had at the end of six months meeting of the consortium where everybody present his results and the people have the possibility of talk together and there is a common discussion so that should have initiated new ideas and that there should have been something peripheral but it gets quite important and we also had reporting, people have to write reports together which have been available on some database to all consortium members. (Respondent RMS)

- **Bilateral meeting** – at the later stage, the consortium meeting was followed by bilateral discussion with individual members in order to have detailed discussion with the post-docs working on the project. The social interactions helped in internalisation and also identified the areas where the two parties could work together apart from working within the consortium.

In addition to the development of the hard and soft knowledge transfer mechanisms, Solvay also brought in specialised people to monitor, coordinate and evaluate the inter-firm knowledge exchanges and to improve transparency among the consortium members.

7.5.1.3.2 Tacit Coordination Mechanism: Embedding Scientists

In order to facilitate the assimilation and integration of knowledge developed by external university partners, an approach that was advocated by Leopold Demiddeleer was to send insiders to gain knowledge. Therefore, a scientist was embedded in Georgia Tech to work in the lab of Bernard Kippelen on OFET. OFET still has scientific challenges compared to OLED where industry has been able to progress more as compared to academia. A similar approach was adopted for OPV where a scientist was embedded at Imperial College and another one was placed at IMEC. Thus embedding scientists in universities and research labs resulted in providing these young minds leeway to experiment and develop their knowledge, gain tacit understanding of processes that were being developed at universities, establish relational networks, and identify equipment that could be appropriate for optimising the processes and setting up a lab internally.

> At Solvay we didn't want to have a photovoltaic laboratory. So I had the benefit of using the laboratory at IMEC which is a very well-equipped laboratory for solar cells. And that was a bilateral project for one and a half years. And we had the aim to reach – at that time it was 7% photovoltaic solar cells. (Respondent RRS)

> We wanted to be as close as we could from the source, from where the innovation is going on, so we could soak into it and we could extract the maximum knowledge in the minimum of time, and being as proactive as possible. (Respondent MMS)

The interns not only worked on bilateral projects between Solvay and academic partners but were also involved in supervising students in university and working on other collaborating projects with the host institution. For instance, a resident at Imperial College actively participated in writing grant proposals to work on collaborative projects announced by the Technology Strategy Board (TSB) or the Engineering and Physical Research Council (EPSRC).

> If you have university like Georgia Tech there are many interesting people not only those that are directly involved in our work but you can have many contacts. There are other presentations in other areas so that is something that is quite valuable to increase the horizon of people. (Respondent RMS)

In addition to that, every three months a team of four scientists was also sent to work in the labs at Georgia Tech to analyse the results and select the best approach to move forward with the research programme. The move from research to development is based on iterations and feedback loop especially in the case of technology that is still in its ferment stage.

> It's not that you outsourced an R&D programme, you go to university, you sign the R&D agreement and then you say, "OK, I will come back in two years and you provide me with the report." (Respondent PBS)

> We have very, very regular meetings, face-to-face meetings where we involve the Solvay scientists together with the team working in the university. So as the project is developed in the university, the Solvay scientists are involved and understand and can even contribute to, you know, slightly shifting the direction of the programme. I believe this is the only way. (Respondent PBS)

However, the interactions between embedded scientist and university were not without firewalls and challenges, as elaborated by one embedded scientist: "*we are Chinese wall-fencing our brains and our activities"* (Respondent MMS). In order to facilitate the exchange of tacit knowledge and enhance learning the boundaries related to the work were discussed at the beginning of the project and codified in the form of contracts and agreements.

> They work within our programmes and we don't manage directly what they are doing. They are more or less working within the programme and it is something that is decided on a common agreement but it is the professor responsibility of what will be from day to day his contribution. (Respondent RMS)

> But there have been very intensive discussions when we started any project, to define… and that's usually what takes the longest time, is – it's not to define a scientific work programme, it's to define how the IP will be exploited and how the IP will be set. (Respondent MMS)

The above inter-organisational practices also served as a means to overcome the "space" and geographical distance among the consortium members that tend to be barriers in knowledge transfer (Mason and Leek, 2008). Embedding scientists at the external partner enabled assimilation of external knowledge at the individual level. However, institutionalisation at the organisational level requires developing routines for enabling a feedforward learning process so that the knowledge gained at the individual level can be integrated with the organisational level through internal knowledge sharing mechanisms. This was mainly achieved through frequent calls, real time discussions through Solvay Google (an internet communication tool) and compiling information and reports in a knowledge database.

7.6 Discussion and Conclusions

The chapter has discussed the reconfiguration mechanisms developed by a large incumbent material firm, Solvay, to respond in a timely manner to the challenges offered by breakthrough technology. Materials have a dominant role within Organic Printed Electronics as is evident from the large number of active material firms that include large and established chemical firms, notably Merck, BASF, Solvay, Dow Chemicals and substrate providers such as DuPont Teijin. In addition, a large number of dominant entrepreneurial firms have also been active such as Universal Display Corporation (USA), Polyera (USA), Plextronics (USA), Novaled (Germany), Cambridge Display Technology and SmartKem (UK).

Schumpeter (1934) associates early success for radical innovation with de novo entrepreneurial firms that eventually displace incumbents. This process of creative destruction has been discussed in great detail within the scholarly literature (Foster and Kaplan, 2001). Several explanations – economic, organisational and strategical – have been highlighted to explain the decline of incumbents. Another dominant stream of literature focuses on incumbent advantage over entrepreneurial firms, building on Schumpeter's (1950) work and argues that there exists heterogeneity in incumbent responses and performances to radical innovation (Ansari and Krop, 2012; Bergek et al., 2013). According to Hill and Rothaermel (2003, p.257), "when confronted by a significant market dislocation, triggered by radical technological innovation, some incumbent organizations can and do adapt, survive and regain historical performance levels". However, most of the studies discuss the incumbents' response retrospectively once the dominant design has emerged rather than during the emerging phase (Jiang et al., 2010). Furthermore, the differential responses of the incumbents are only investigated focusing on single mechanisms such as complementary assets, managerial cognition, institutional environment or structural orientation (van Moorsel, et al., 2012). The presented case study addresses this gap.

OPE is an enabling and general-purpose technology with the potential for various applications. Despite the decades of research there are few commercial successes such as that of OLED in smart phones. In this long gestation period, we find evidence of the presence of a large number of incumbent organisations especially the upstream material companies. The main contribution of the case is in investigating how incumbents proactively develop reconfiguration capabilities in the emerging industry. Reconfiguration can occur through a process of substitution, evolution or transformation. Transformation in comparison to substitution and evolution is an intermediate response to the technological change. The case study provides a rich evidence of adoption of transforming routines by an incumbent organisation in the emerging phase. In the context of breakthrough technologies, whereby the technological change is rapid and uncertain, substitution may result in early lock-out and unsuitable response as the technology is still developing and deleting old routines or acquiring new ones may incur substantial irreversible investments while adopting the evolution mechanisms may results in delays and untimely responses (Lavie, 2006).

The case study provides an evidence of a holistic approach adopted by focal incumbent firm in responding to radical change during the early stages of industry emergence thus suggesting that survival and performance of incumbent firms once the dominant design emerges depends on complementarities among intra-organisational and inter-organisational routines developed during the inventing and early phase. Investing in the early phase of the industry emergence facilitate developing absorptive capacity and ensure increasing returns from knowledge accumulation in the new emerging field thus preventing lock-outs. According to Kaplan and Henderson (2005, p.517), "The central problem, we suggest, is not that of cognition versus incentives, leadership versus structure, inertia versus conscious action, and so on, but rather of how to develop a richer understanding of the ways in which these various elements interact—endogenously and dynamically—to shape the choices and behavior of the modern firm in the face of significant change."

Solvay adopted an ambidextrous approach and opted for structural separation to facilitate exploration and exploitation simultaneously through initiation of New Business Development (Duncan, 1976). Organisational ambidexterity enables firms to manage exploitation through incremental innovation and exploration nurturing breakthrough innovation (March, 1991; Tushman and O' Reilly, 1996; O'Reilly and Tushman, 2007). Dual structures enabled balancing trade-offs between paradoxical objectives of alignment and adaptation (Rothaermel and Alexandre, 2009) and provided necessary buffering from existing efficiency oriented cultural tradition and incentive systems, thus facilitating experimentation in new emerging domains (Benner and Tushman, 2015). While structural separation is necessary it is not sufficient to deal with other related cognitive and strategic paradoxes that are related to coordination across boundaries. Embeddedness of incumbents within their value network results in localised search in related domains that also hamper incumbents' capability of sensing and identifying promising domains (Hill and Rothaermel, 2003).

Furthermore, hiring of new employees and inter-firm mobility, though effective in entrepreneurial ventures, may not result in change in higher order routines within an established organisation (Wezel et al., 2006).

Three mechanisms were adopted to identify and access the external knowledge and included the development of university consortia, creating a loose coupling between basic research at university and applied research through collaboration with renowned applied research institutes, and finally use of the real option approach for investing using corporate venture capital (CVC). Furthermore, employing transformation mechanisms needs assimilation of the acquired external knowledge and its integration with existing knowledge. Intra-organisational routines were developed to assimilate the new information by employing PhDs and post-docs with relevant competencies so that the research from the universities could be commercialised and modified based on customer feedback. In addition, inter-organisational routines were developed to ensure coordination with external partners. Since the knowledge within the emerging domain is mostly tacit the emphasis was on embedding scientists within the universities and public research institutes. This mechanism enabled increased engagement with the scientific community and also endowed the individuals with increased flexibility to alter technological direction and adopt the most promising ones.

University-industry collaborations have been discussed to a larger extent in the case of life sciences however their focus has been limited to areas such as nanotechnology, electronics or advanced materials (Baba et al., 2009). Furthermore, most of the studies deal with the transfer of untargeted knowledge that is through publications, patents and seminars using quantitative measures (Hermans and Castiaux, 2007). According to Fontana et al. (2006), the propensity to collaborate with universities and research institutes differs with the sectors, tends to be higher for the chemical sector and aims to acquire or update knowledge. Furthermore, though the extant research highlights the propensity of larger firms to engage in university-industry collaboration and partnerships, Perkmann and Walsh (2007) pointed out that a research gap exists in exploring approaches adopted by firms to engage in these collaborative arrangements and interfaces employed to exploit the research results. The study contends that with OPE being a radical technology, both the large and small firms collaborate with universities, however the propensity to collaborate to some extent also depends on the position within the developing supply chain and business model. Being upstream and farther from product innovations requires developing an IP portfolio initially. The dominant position as measured by the number of useful patents then acts as a signalling mechanism to attract the collaborators further downstream.

Solvay's collaboration with Georgia Tech's Center for Organic Photonics and Electronics (COPE) proved instrumental not only in experimentation in many novel areas and in knowledge creation but it also enhanced the focal firm's capacity to develop required processes for further exploitation of acquired knowledge (Bishop et al., 2011). Thus it deviates from the traditional linear model where the university acts as a supplier for untargeted basic sciences that is later exploited by industry. It tends to be more interactive and iterative, implying a constant feedback loop between the research generated by academic collaborators and applied by the industry.

Furthermore, organisations may not be able to benefit from mere investment in universities until and unless they invest internally in R&D (Cohen and Levinthal, 1990). According to Cockburn and Henderson (1998), connectedness and active collaboration with public research institutes improves research productivity. Practices such as hiring of scientists, placement of residents, regular visits, participation in collaborative projects, and exchange of written reports ensured alignment of shared visions and expectations between the university and Solvay thereby ensuring continuous learning through both tacit and explicit knowledge sharing mechanisms.

Another dominant factor that has been given in the literature for the incumbent's failure is related to economic incentives and underinvestment in emerging domains. Due to the uncertainty and long gestation period associated with breakthrough technologies, Solvay used the corporate venturing mechanism to track the technology development and identify promising entrepreneurial firms for later acquisitions. Breakthrough technologies are characterised by high risks, uncertainty and long gestation periods. In these circumstances, the use of CVC as a real option model allows flexibility, deferring the irreversible commitments related to acquisitions (Basu et al., 2011; Tong and Li, 2011). A technologically uncertain and dynamic environment hinders extensive resource commitment thus attenuating incentives for acquisitions and favouring lower level commitment such as CVC, thereby decreasing risks but providing growth options to investors (Basu and Wadhwa, 2013; Titus et al., 2014). It further ensures that investors do not prematurely shut down investments in the radical innovation owing to their long time maturity thus resulting in lock-out (Hill and Rothaermel, 2003).

The use of CVC has been advocated as a strong instrument for accessing relevant external knowledge from entrepreneurial firms and impacts innovation output for large established firms (Dushnitsky and Lenox, 2005). CVC enables overcoming the existing cognitive schemata of established firms and plays a special role in directing top management attention to technological discontinuities (Maula et al., 2013). Growing literature suggests heterogeneity in CVC mechanisms adopted by organisations. Solvay's motivation for setting up of CVC activities was mainly driven by strategic benefits rather than financial. They followed an integrated logic rather than arm's-length that required continuous and focused feedback to the parent during stages of deal screening, evaluation, due diligence, deal structuring and approval (Souitaris and Zerbinati, 2014). Furthermore, syndication with other independent VCs provided greater exposure to the large number of emerging and relevant deals, allowed them to develop diversified portfolios, instigated entrepreneurial orientations and facilitated better decision making.

The growing literature on CVC and its impact on innovation has been criticised for its static approach and less emphasis on its evolution over the technology life cycle (Vrande and Vanhaverbeke, 2013). The case provides evidence of staged investments in the targeted ventures by Solvay (Hill et al., 2009) and the evolution of CVC finally into strategic alliances and later into acquisitions. Solvay opted for a real option model and, prior to making increased commitments in the form of acquisition in new ventures, monitored their performances, maintained board seats and opted for strategic alliances. The early interaction with new ventures results in reducing information asymmetry related to both partner and technology that is usually higher in a new domain and for breakthrough technologies. The findings therefore contribute to the processual nature of external venturing, rather considering them distinct activities as proposed by Maula (2000).

Solvay was able to invest in two promising ventures – Plextronics and Polyera – as an outcome of their capital venturing activities. Post investment they also maintained a board seat in these ventures and were thus able to monitor and even direct the evolutionary trajectory of these start-ups. The relations with the entrepreneurial firms were further strengthened by working on complementary materials thus adding value to Solvay's offering of a portfolio of product and increased knowledge creation (Wadhwa and Kotha, 2006).

This in-depth case study's contribution is not only that it identifies intra-organisational routines and elaborates on a reconfiguring mechanism but also that it discusses the inter-organisational routines that extend this line of research beyond the boundaries of the firm (Mason and Leek, 2008). Inter-organisational routines enable coordination among divergent organisations. They sometimes take the form of formal contractual mechanisms and, at other times, are more tacit. Developing these routines enabled Solvay and COPE to manage expectations, build trust and increase reciprocity.

Intellectual human capital and its impact on contributing to heterogeneity in organisations' innovative performance have been stressed in the growing literature on microfoundation of capabilities (Felin et al., 2012; Rothaermel and Hess, 2007). Recruitment of new employees to attain capabilities has been discussed in the pharmaceutical context for biotechnology (Lacetera et al., 2004). Bringing in new employees enables the firm to develop new routines and results in recombination with existing practices and increased receptivity to change existing routines (Kaplan, 2015). These findings extend the debate on routines as truces and the role of both cognition and incentives in bringing about organisational change (Kaplan and Henderson, 2005). The focal firm had a long history of focusing on the efficiency dimension and established incentive system. In the context of transformation, bringing in new employees resulted in creating new cognitive structure but also implicitly implied that experimentation can be rewarding. Furthermore the existing social network of new employees who were mostly PhDs or postdocs and early stage researchers resulted in strengthening links with public research organisations and developed the culture of exploration within Solvay. Embedding scientists within the university and applied research institutes was adopted as an effective mechanism for assimilation and integration of new tacit knowledge and thus facilitated building capabilities in the new domain.

These results thus set the stage for further exploration in the underresearched area of developing routines in dynamic and uncertain environments as opposed to the long established tradition of studying them in a stable environment.

Chapter 8: Intermediaries and their Roles in Industry Emergence

8.1 Introduction

From the discussion of the dynamics within OPE in Chapters 4 and 5, the dominant role of "hybrid forum" intermediaries emerged as an enabler for innovation within the emerging phase of industry and important locus where inter-organisational routines are developed. The term "intermediaries" as discussed in Chapter 2 refers to "a range of organizations including brokers, third parties and agencies that are involved in supporting the innovation process" (Howells, 2006, p.715). However, as argued by Meyers and Kearnes (2013), intermediaries are not only passive matchmaking agents or brokers that are merely involved in knowledge transfer, but their practices tend to be more active and exploratory such as co-development of innovation, network facilitation and governance.

The objective of this chapter is twofold: to describe the two prominent intermediaries in the context of OPE – research and technology organisations (RTOs) and the industry association or meta-organisation – and to explore the roles played by them in the emergence of new industries. Whereas the research and technology organisations facilitate bridging the "valley of death" and contribute to learning, exploration, de-risking and stabilisation of processes, institutional actors such as trade associations are instrumental for evangelising this early phase of industry and contributing to cognitive as well as sociopolitical legitimacy. Their main activities, comprising developing infrastructural knowledge, articulating expectations and visions, building social networks and shaping inter-organisational exchanges, contribute to developing an environment conducive to building trust among organisations and therefore support the functioning of the OPE ecosystem.

8.2 Research and Technology Organisations (RTOs)

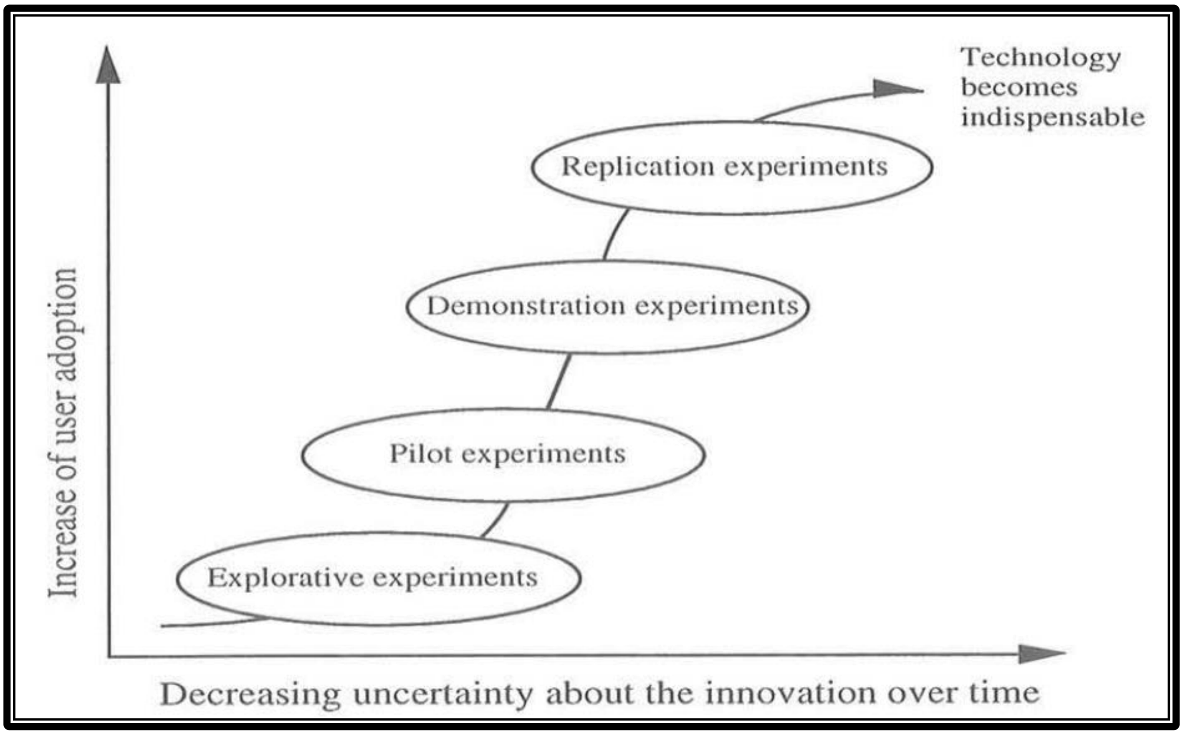
Intermediate research organisations, referred to here as RTOs[66], act as providers of knowledge and bridge the gap between university research and commercialisation (Mina et al., 2009).

Organic and Printed Electronics is an emerging technology developing within the niche or protective space. A niche is "a habitat supplying the factors necessary for the existence of a new technology" (Hoogma, 2000). In this context, prototypes and close-to-market demonstrators are instrumental for improving the materials and production processes as well as increasing the visibility of the maturity of the technology to create demand pull and attract end users. Intermediaries enable the creation of a learning environment through a range of experiments that may be classified as exploratory, demonstrations, pilot and replication or dissemination (Hetland, 1996) (see Figure 8.1). Exploratory experiments are useful at early stages of technological developments characterised by a large number of uncertainties. They help researchers to identify the problems and suggest possible directions. Pilot experiments increase public and industrial awareness and test applicability of innovations in similar conditions to those of exploratory experiments. Demonstration experiments are designed to show the adopters how they can benefit from innovation. Replication or dissemination experiments aim at disseminating testing methods, techniques or models through replication.

Experiments with new technologies help to create constituency around the technology and exert political pressure resulting in more grants and dedicated effort towards collaborative work (Hoogma, 2000).

[66] Research and technology organisations (RTOs) have also been referred to in the text as research institutes or applied research institutes.

Figure 8-1 Range of Experiments



Source: Hetland, 1996

There are around 17 clusters that are active within the space of OPE in Europe. These clusters are mostly centred around research and technological institutes or Centres of Excellence that offer collaborative R&D, pilot lines, and prototyping facilities. Among the most innovative and recognised are the Fraunhofer IPMS (Germany), CPI Plastic Electronics Centre UK (formerly PETEC), TNO (Netherlands), IMEC (Belgium), Holst (Netherlands), VTT (Finland), Acreo (Sweden), CSEM (Switzerland) and CEA (France). These applied institutes are identified as important players within the OPE ecosystem and some, like Holst Centre, also assume the role of hub player or orchestrator for the ecosystem's development. According to Georges Kotrotsios, Vice President Marketing and Business Development at CSEM:

> No single research institute is capable of covering the whole range of technologies, infrastructures or competences required. Therefore the research centres in Europe have to put their strengths together, by sharing existing infrastructure and facilities, and cooperating in defined key areas of research, in order to create significant added value. (Curry, 2013, p.43)

The next section will provide a description of four research and technology organisations, namely Holst Centre, CPI Plastic Electronics Centre (UK), Fraunhofer IPMS (Germany) and VTT (Finland) that have been identified as the most important hubs or nodes for technology development during the fieldwork.

8.2.1 Holst Centre in Netherlands

The Holst Centre, located at the High Tech Campus in Eindhoven, also referred to as "The brainiest square kilometre in the Netherlands" by Rick Harwig, former Chief Technology Officer of Philips, is one of the thriving hubs for Organic and Printed Electronics. It started its activities in 2005 as a result of the Philips Research Open Innovation initiative and was set up by TNO and IMEC. Their business model is based on government funding (45%), participation and entrance fee from industrial participants (45%) and 10% EU project funding. The Centre has now grown from 15 people to 170 in 2011 and includes 70 resident researchers from university and industry. They are organised in what they call "shared research programmes", with 15 shared programmes at present that include 11 technology programmes and 4 technology integration programmes. The focus of the technology integration programme at present is body area networks, printed organic lighting and signage, flexible OLED and displays, and organic photovoltaics (OPV). Within OPV, a notable initiative is that of ***Solliance***, which is a research collaboration between IMEC, TNO, The Technical University of Eindhoven, ECN and Holst. The programme has been able to attract players from the entire value chain due to the presence of end users such as Philips, DisaSolar and ThyssenKrupp.

Organisations participating within the Holst Centre include both large multinational corporations and SMEs. They can either join the shared programme for a fee, or they can be involved in bilateral programmes. Research programmes are designed based on discussion and dialogue with industrial partners. These research programmes are then translated into a work module referred to as the "technical annexe", and the "roadmaps" that act as a governance mechanism for monitoring the project progress, its milestones, achievements and challenges. These roadmaps bind participants together, aligning their objectives and creating shared vision for technology development.

> We try to find a commonality and also it has to fit with the roadmap we're doing. And based on that input we have all these discussion with companies we make a roadmap and the work plan. (Respondent VTMH)

> It is clear when looking at all the partnerships that Holst operates, that a group of companies with seemingly different interests in various technologies can work together for the benefit of development. Holst acts as the Centre, pulling the relevant institutions and developers together on a particular task. (Curry, 2013, p.59)

Many interviewees and respondents shared these views as well, as is evident from the quote below:

> We feel at the moment there is more value than loss to participate to that. […] Because it is still the early stage of industrialisation so I think the goal is really to grow the pie not fighting for the slices of a small pie. (Respondent VTS)

Holst Centre also works closely with some of the leading universities and research institutes. The involvement extends from designing of the PhD programmes such as that with Eindhoven, Delft and Twente to funding of the theses and participation in framework programmes.

> We work with several universities, […], we have quite a lot of Ph.D. programmes funded, and most of them also work here on site. […] it is about 40 Ph.D. students we fund […]. And we try to work with those university groups which we think are state of the art; they can really contribute to something. (Respondent VTMH)

In areas of complex technologies such as OPE, the motivation for the companies to join the Holst Centre varies from reducing risk and uncertainty, to getting access to state-of-the-art knowledge and leveraging from the synergistic effect of other residents. This was evident from the interview with a respondent at Holst and also during discussions at Solvay.

> Partners come really because they can have access to really interesting technologies. What is surprising is that most of them also come because of the ecosystem. They like to be in an ecosystem with 35 other companies. Not just to learn from each other, but also to understand each other better, to understand what the role of these companies is in the supply chain of the future and to collaborate with them. Of course also the obvious reasons for shared innovations – shared risk and cost, because it's expensive. (Respondent VTMH)

> So our proposition… is, Company keep most of your budget in your exclusive R&D but focus on what you want to be good at. And the rest put that in a shared R&D programme, so you still get the technology you need to tackle your market, by doing that you share the cost of R&D and the risk of R&D. And if you do this right you can get access to an R&D effort of 10 times of what you initially put in. (Respondent VTMH)

> […] we are participating in the Holst Centre. This is more about processing aspects where clearly we have lack of knowledge because it is very specific for these kinds of things and how to do printing; you have to learn how to formulate inks and printing. We have people for instance working in processes. It is a question of equipment also because equipment is expensive, you don't have everything for instance printing in your own labs […]. (Respondent RMS)

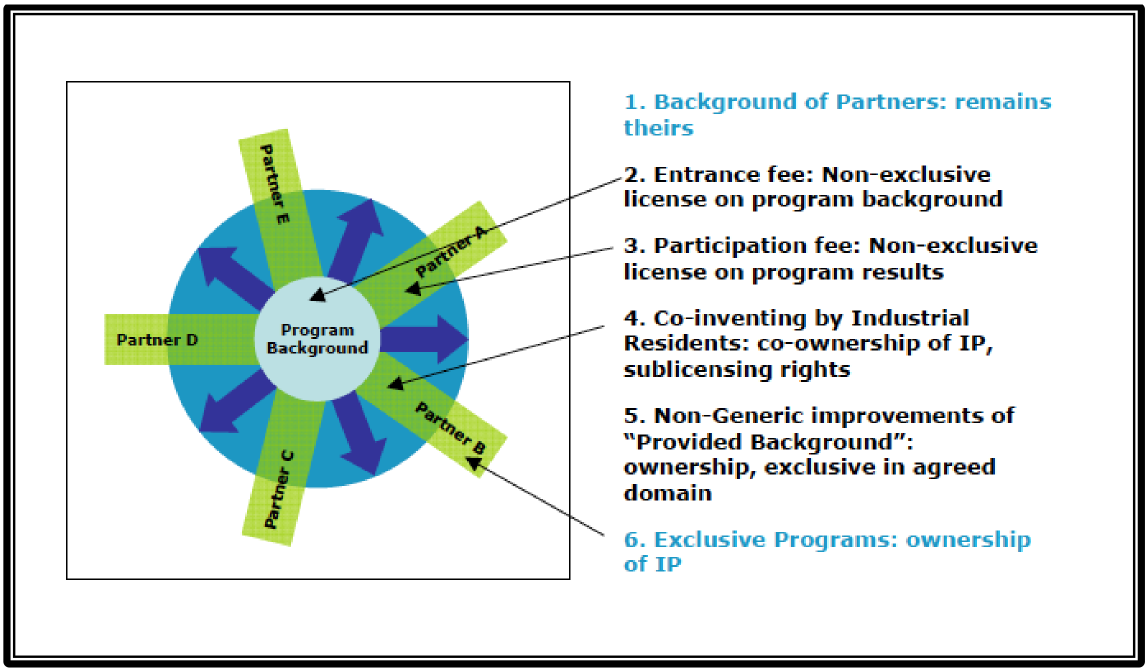
Most of the participants of the shared research programmes are resident at the Holst Centre and work with internal team members. This arrangement not only facilitates hands-on training and knowledge transfer but also provides opportunities to influence the directions within shared programmes as elaborated by a programme manager at the Holst Centre. These efforts result in creating alignment and shared vision among participants. In breakthrough technologies and emerging industries such as that of OPE where there are multiple technologies and approaches, these shared programmes facilitate convergence.

> […] When you have a resident here on site, this resident is participating in the research, participating in the weekly meetings. […] They also have an influence on the research on a weekly basis; also the transfer of know-how to a partner is very important. We don't believe in transfer of know-how by writing a report and sending it to a company […] These people also get trained in the technology when they are working here […] And so it's not a permanent position, you spend a few month or a few years and then you take the knowledge and implement in your own organisation. (Respondent VTMH)

Another important feature of Holst Centre that has been able to attract collaboration and achieve coordination even among the competitors within the programme is its IP structure and non-exclusive license (see Figure 8.2). With their IP model the organisation retains exclusivity for its background IP. However, foreground IP that is generated within the shared programme has joint ownership. This IP model of value creation for emerging technologies with distributed knowledge has been applied by IMEC for nanoelectronics technology and is successfully leveraged within the OPE context by Holst.

> We have for example six partners in the barrier programme, all six of them have a non-exclusive license and royalty fee on all the IP and know-how generated in that programme. If you have an initial resident working then what can happen is that, it's still not exclusive, but you can get ownership of IP. So if the initial resident was involved in the IP creation then a company can get co-ownership with Holst together. (Respondent VTMH)

Figure 8-2 Holst Centre IP Model

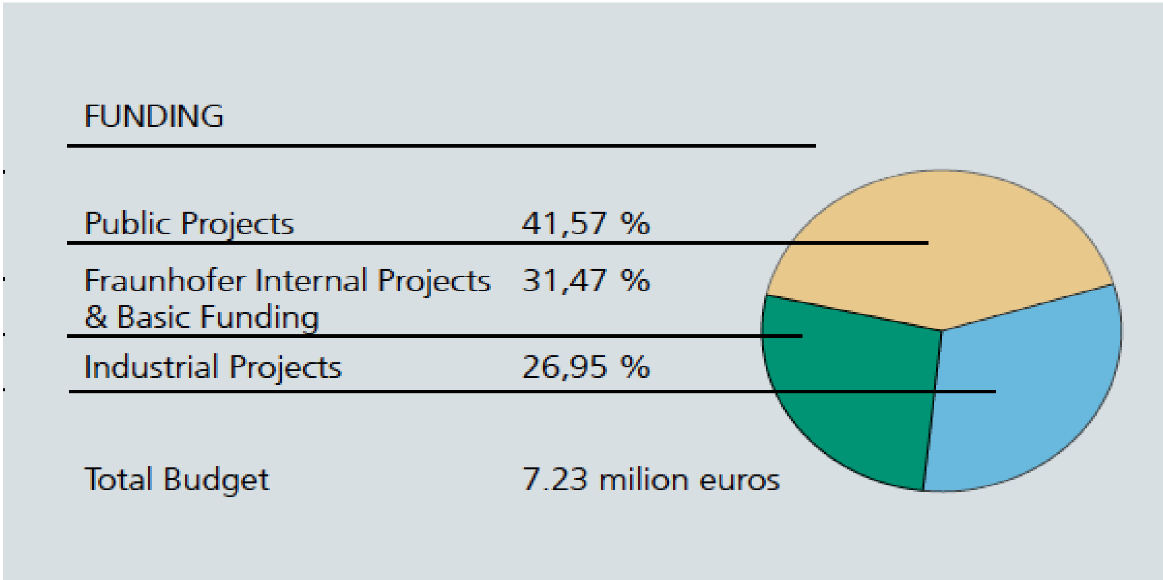


Source: Holst Centre

8.2.2 COMEDD—Centre for Organic Materials and Electronic Devices in Dresden

Work on OLED within the Fraunhofer IPMS (formerly IMS) started in 1999 and in 2002 the world's first OLED deposition line was established. At that time the activities were mainly focused around displays and the aim was to bridge the gap between research at universities and the needs of industry. However, it was soon discovered that most of the competencies for displays are located in Asia, whereas Europe, and in particular Germany, can gain a stronghold when it comes to lighting due to the presence of an established value chain. This resulted in a change in focus and in 2008 COMEDD was established by the Fraunhofer IPMS with a €25 million investment from the Federal Government of Germany, the State of Saxony and the European Union. The initial focus of the institute, owing to the thriving organic electronics community within Saxony, was on small molecule OLED and scaling up production processes for OLED lighting, OLED micro displays and OPV. These initiatives were mainly taken so that Europe would maintain its leadership position within organic electronics. COMEDD has been a participant in many successful consortium projects such as R2Flex and So-Light. R2Flex was a BMBF-funded project with a total sum of about €11 million that was initiated to develop the roll-to-roll process for manufacturing of OLED lights. It was a follow-on project after OLLEX (2007-2009) and included the same consortium members.

Figure 8-3 COMEDD Revenue Streams 2013



Source: COMEDD Annual Report, 2013[67]

According to Karl Leo, director of IPMS and COMEDD, "An industry for organic illumination will only be created when we in Europe not only provide development and design, but if we also manufacture."[68]

COMEDD is an independent research institute with its revenue model based on Fraunhofer's contract research, consulting services and participation in collaborative research projects (shown in Figure 8.3). In addition to that it has maintained a close relationship with Technical University of Dresden and offers training whereby students can enhance their knowledge through trials on smaller equipment.

[67] http://www.comedd.fraunhofer.de/content/dam/comedd/common/annual-reports/Jahresbericht%202013_web.pdf
[68]http://www.ledsmagazine.com/articles/2008/11/fraunhofer-opens-center-for-organic-materials-and-electronic-devices-in-dresden.html

> We are performing services for the customer, it is not the case that the customer come here and make their own work using our equipment, we operate the equipment, although the customer can join the experience. (Respondent CM)

COMEDD also played a role in establishing cognitive and sociopolitical legitimacy by conducting seminars, workshops and offering their "Tabola" OLED lighting modules for customer evaluation and attracting the attention of luminaries.

8.2.3 The CPI (Centre for Process Innovation) Printable Electronics Centre (formerly PETEC)

The CPI Printable Electronics Centre (formerly PETEC), located in Sedgefield in the north-east of England, was set up in 2009 by CPI to bridge the "valley of death" between university invention and industrial scale-up and commercialisation. The project was funded by One NorthEast (£6.3 million), The Northern Way and the Regional Development Fund (£3.8 million).

CPI was set up in 2004 to support the thriving process industry in the north-east region. The opportunity for setting up a prototyping facility was realised owing to the earlier FLEXYNET initiatives that included participants from the newly emerging players and divergent organisations such as DuPont Teijin, Plastic Logic, Polymer Vision and Cambridge Display Technology. "*And that was very, very helpful to us because it brought a community together of the academics and the industrialists at the time.*" (Respondent TTP).

> We would not have invested in this area if we didn't get serious industry backing it. So the first investment proposal I made was for a coater of film, and there was a co-investor who put in an equal sum of money into that, that asset, and that was DuPont Teijin Film. So they were investing in that to support companies like Plastic Logic, Polymer Vision, who had a roadmap to make plastic displays. (Respondent TTP)

The Centre for Process Innovation was set up as a design, prototyping and development centre to facilitate the fledgling UK industries that had many SMEs and start-ups involved in OPE in testing their ideas on installed equipment, de-risking prior to capital investment, and scaling up their processes. The CPI lends support to industry via a range of mechanisms, from hiring of the facility (also referred to as the 'shed option') and consultancy, to joint development agreements and sharing of IP. According to Tom Taylor, CPI's printed electronics director, "We are not a research institute; we provide the equipment and toolsets, with knowledge and expertise, for scaling up plastic electronics” (Ver-Bruggen, 2013, p. 26)

> And CPI help companies […] to de-risk the investment—because they can come in, they can get access to that kit at market rates for a limited number of days, or long enough to prove whatever concepts they have or to test their ideas and see whether they’re suitable for scale up or manufacture. (Respondent JHP)

A notable effort recently made by CPI has been to involve the printing industry within the UK through workshops on installing a standard Nilpeter roll-to-roll press to print conductive inks to demonstrate how the existing equipment can add functionality to the point of sale or smart packaging, thus acting as an interface between science and industry.

> And the idea was to show to the printing industry that, "Oh, I've got one of those, I could do that" and to show to… let's call it the science part of it, the science industry, "Oh, right, so a lot of people have got those already, have they? All right, OK, so we don't need to do that." "No, you don't need to do that". (Respondent MHO)

8.2.4 VTT Technical Research Centre in Finland

Valtion Teknillinen Tutkimuskeskus (VTT), a non-profit government-owned research centre, is amongst the key players within OPE owing to its investment in the manufacturing infrastructure for diffusion and adoption of printed intelligence. Printed intelligence “are components and systems which extend the functions of printed matter beyond traditional visually interpreted text and graphics, and perform actions as a part of functional products or wider information systems”.

Work on printed intelligence within VTT begin in 1990 within Professor Harri Kopola’s group. In 2009, VTT, the University of Oulu, Oulu University of Applied Sciences and Oulu Innovation Oy founded an innovation centre for printed electronics named “PrintoCent” in the Oulu region. According to IIkka Kaisto, the PrintoCent director:

> In the Oulu region, the electronics manufacturing was moving to Asia… Since 2005 about 5,000 people have come out from the Nokia cluster, and they have been looking for new opportunities. From Oulu’s regional point of view, as VTT had a strong push from 2006 (50 persons) to 2009 (100 persons) for Printed Intelligence, and Oulu-based universities were willing to cooperate, it was an

> opportunity to invest to this new printed roll-to-roll manufacturing technology and thus to speed up the commercialization and industrialization.[69]

The consortium aimed at providing member companies novel business ideas and at moving the technologies from lab to fab to markets. At present there are 30+ members that include start-ups Enfucell, SMEs such as Benq, Coatema and Ynvisible and large companies such as Merck and BASF. The annual R&D project spending by the founding PrintoCent members was €15 million for 2009-2012 and by 2013 it had more than 200 experts employed; 15 start-ups have been established since 2010.

Form the above discussion, it is clear that the research centres demonstrate variety in composition and their approaches towards OPE technology, with each having complementary expertise. While COMEDD has competencies in small molecules owing to the networks around Dresden and is mainly focused on providing contract research, CPI National Centre for Printable Electronics is working towards scaling up and commercialisation. Among these centres the most dominant hub is Holst – an Open innovation Centre that has been able to attract a large number of multinational corporations, notably the upstream material companies active within the OPE space.

These research centres are mainly aimed at de-risking investment, sharing resources, reducing risk and creating a shared space. They also facilitate innovation at regional levels by fostering clusters. Collaborations are key to emerging technologies, therefore, working closely with the emerging supply chain partners; these research institutes aim towards convergence of approaches and stabilisation whilst creating the necessary demand pull. The next section will elaborate on the roles of the RTO.

8.2.5 Role Played by Research and Technology Organisations

Distributed sources of knowledge and, increasingly, the importance of external sources of knowledge have highlighted the importance of research and technology organisations (RTOs) for contributing to SMEs' innovativeness (Albors-Garrigós et al., 2013). Aström, Eriksson and Arnold (2008) identified a number of roles for RTOs

[69] http://www.printedelectronicsnow.com/contents/view_online-exclusives/2013-12-18/printocent-consortium-seeks-to-develop-commer/#sthash.5CAmWcPt.dpuf

in the National Innovation System (NIS) such as mediators, importers, creators and suppliers of knowledge; furthermore, they also act as provider of infrastructure and impartial testing and certification.

Emerging technologies such as OPE are characterised by uncertainties and embryonic phase of development; the technology for most of the applications is still in its fluid phase and therefore requires a number of iterations within the process development. The main innovation challenges associated with OPE are scalability and manufacturing. Initially, the vision of OPE was of low-cost technology owing to the advantages associated with solution-based processing, additive manufacturing techniques and roll-to-roll printing. However, technological challenges associated with OPE add up further in a high yield manufacturing environment.

Owing to the increased uncertainty, rapid changes and absence of dominant designs, research and technological organisations facilitate not only start-ups and small companies but also large firms to progress with their technology and process development without investing initially in capital equipment, thus reducing the time to market, decreasing cost and *de-risking capital* investment. “Scaling up of a new technology is so hard to do, because it is where companies start burning through cash on capital investment in expensive production tools and equipment, as they seek to get their processes in place. This can often take many years, without the guarantee of a market to recoup the investment and become profitable.” (Ver-Bruggen, 2013, p.27). These research centres are equipped with state-of-the-art equipment and work in close collaboration along the whole of the emerging supply chain – equipment providers, designers, printers and material providers. According to Murtha et al. (2001, p.12), “…critical bodies of new knowledge accumulate in shared rather than proprietary domains of activity, such as interactions with equipment and material makers whose customer base includes multiple competitors in the same industry.” In certain cases they also take the role of integrators for product development to demonstrate the potential of the technology and facilitate its adoption with the end user.

Organic and Printed Electronics is still in its early ferment stage and dominant designs are yet to emerge for diverse applications. There are several approaches that are pursued in parallel. For material providers, mostly large organisations and located upstream, collaborating with research and technology organisations enables them to acquire device design competencies and printing know-how. For example, for Solvay, partnership with the research institutes such as Holst Centre and IMEC provides technology and market foresight and is therefore a means to explore the opportunities or threats associated with other alternative and emerging material possibilities. These foresights facilitate early identification of trends and opportunities and prevent "lock-in" in low promising pathways, a pitfall firms can easy fall into.

These RTOs in certain cases also provide independent evaluation of results, for instance characterisation of material performance, that enables large organisations to legitimise their claim and sell their products to the end customers.

> Holst centre is really an independent way of having an assessment of the properties of either company like Polyera in which we could invest but also they are investigating printed oxides. For us it is a way to know if printed oxides are threats or not to our development in organic semiconductors because it can be seen either as a threat or an opportunity […]. […] You have to know it, because don't spend your money if organic semiconductor is dead end, you better know it soon to stop it; or you could also see it is not such a threat because there are advantages but there are also defect; or you can also see that there will be a market for organic semiconductors but there will also be a market for printed oxide, so what do we do? We feel that our market is enough with semiconductor, or it means you also have to make research and find a way to collaborate with some printable oxide material companies. It is a very good way to have global view of the materials and also what are the important topics from industrial point of view. We are not electronic specialist. (Respondent VTS)

Another important interaction that has been witnessed in the domain of OPE is that between RTOs and equipment providers. Equipment providers work closely with RTOs and usually place their equipment in order to understand fully the technology requirement. The equipment complexity varies from lab scale to prototyping and pilot scale equipment. In uncertain technologies, paradoxically, on one hand the equipment needs to be general purpose and flexible in the early stages as the specification and requirements are evolving and vary with the end application; however, as the technology progresses and moves towards a production window, *"...you have to close those flexibilities down and go for production throughput"* (Respondent MSF). Placing the equipment in shared research facilities results in further customisation based on processes and material requirements. The iterations and feedback loop that are thus achieved among material providers, technology developers and product integrators through the use of common equipment enable learning and identifying the requirements for the next generation of technology and moving beyond the state of the art.

> Very early we went to the university players, professors, institutes, R&D leaders worldwide and there we tried to place equipment. Based on this network, we are then easily and directly able to move to industrial players and we get a good understanding of technology. (Respondent TKC)

The next section will discuss another important intermediary – an industry association, a meta-organisation (Ahrne and Brunsson, 2005) that is working towards managing expectations for the field, building future vision and credibility, defining infrastructure and creating demand articulation.

8.3 Organic and Printed Electronics Association (OE-A)

Nascent technologies, as argued by Rao (2002, p.308), resemble a "social movement" and require developing constitutive legitimacy and mobilising actors and support. Formation of an industry association is one possible path for achieving the taken-for-granted status. These aspirations have been the driving force for the emergence of OE-A as is evident from the quote below by one of the association's champions:

> In the best case what you do is you provide the platform that people use to have a constructive dialogue that leads to better direction of financial intellectual resources.
>
> The initial thing… an initial driving factor for me was… it's a question of how to get to a critical mass without having a single big organisation there. So that was one of the driving factors. (Respondent WMP)

8.3.1 Evolution of OE-A from Small Group of People to International Association

The Organic and Printed Electronics Association (OE-A) was established in 2004 as a working group under VDMA's (German Engineering Federation) "Innovative Business" division. VDMA is the largest trade association within Europe, representing 3,000 companies within the engineering industry, and includes related associations such as Productronics (Production Equipment for Microelectronics), German Flat Panel Display Forum (DFF), and Micro Technology. OE-A is a non-profit organisation and for resources depends on membership fees. The association's direction – that is, tasks, strategies and activities – is determined by its Board of Directors. Industries as well as institutes represent the Board that is elected by general assembly every two years. Being in a board member position within OE-A is a source of legitimacy to the members and their related technology. It also facilitates shaping the vision of the technology. Figure 8.4 shows the board members for the period 2011-2013. It is evident that the board members represent different regions as well as important competencies needed for a potential value chain.

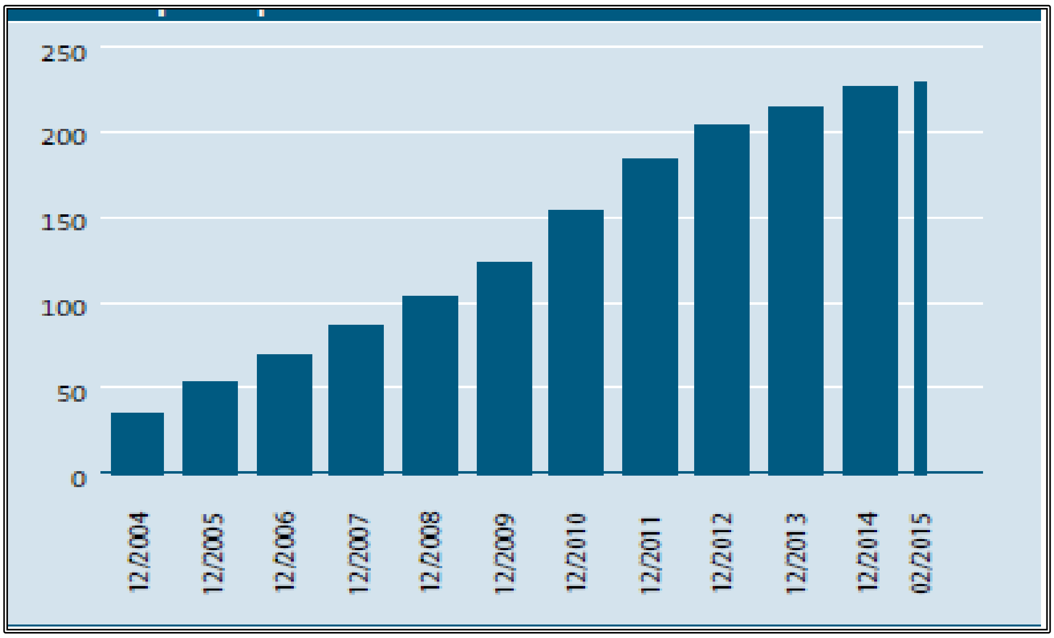
> […] We have lot of discussions with board members which are our customers and also sometimes are our competitors or have interest in technologies. And I'm also running a working group at the OEA which is called upscaling production. So there are a big number of members of the OEA which are working in this working group. So first of all its communication, networking but it's also getting more influence as small company in Brussels and in maybe changing ways of operating FP7 projects for small companies […]. So it's a big number of opportunities you have working in the organisation. (Respondent TK)

Figure 8-4 Board Members of OE-A for period 2011-2013

Source: OE-A, 2013

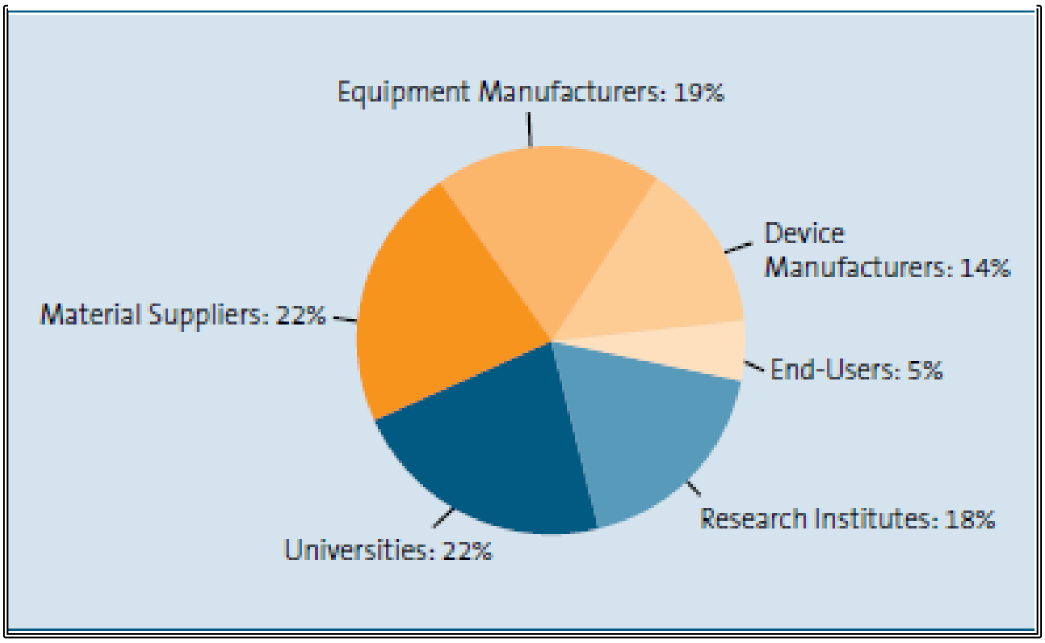
OE-A currently has 200 members; the main objective of the association is to legitimise the new emerging space, mobilise actors, create a shared space through field-configuring events, develop the roadmaps for printed organic electronics, identify the “red brick walls” or challenges (a term corresponding to the International Technology Roadmap for Semiconductors (ITRS)) in the technology’s development and provide an international forum for cooperation between diverse players along the emerging value chain of printed organic electronics. Figure 8.5 illustrates the growing participation of members within OE-A over the period of 2004-2015 while Figure 8.6 shows the relative competencies of its members.

Figure 8-5 Membership Growth of Organic and Printed Electronics Association



Source: OE-A, 2015

Figure 8-6 Competencies of Members



Source: OE-A, 2015

The establishment of OE-A is an emergent process whereby a few individuals – notably, Wolfgang Mildner from PolyIC and Professor Reinhard Baumann who at that time was associated with Manroland (now affiliated with Technical University of Chemnitz) – played an instrumental role in identifying the need for a common platform or shared space for the discussion of the newly emerging technology. These individuals can rightly be called institutional entrepreneurs and are defined as "organized actors who envision new institutions as a means of advancing interests they value highly yet that are suppressed by extant logics" (Greenwood and Suddaby, 2006, p.29). Van de Ven and Garud (1993), while studying the emergence and commercialisation of cochlear implants, discussed the beginning of an innovative process as a few independent entrepreneurs who undertake cooperative and competitive activities that eventually result in convergence and intersection of paths. "As the number of actors gains a critical mass, a complex network of relationships begin to emerge that becomes recognized as a new industrial sector and that takes the form of hierarchical loosely coupled system" (Van de Ven and Garud, 1993, p.9). Over a period of 10 years OE-A has been able to grow incrementally from a small group of people who believe in the disruptive potential of the technology to achieving the status of sole international representation for the OPE community. The presence of other related associations such as the Flat Panel Display Association (DFF) within the division of VDMA provided a further impetus for cooperation and initial structure.

The quotes below demonstrate the rich description of the emergence of association in Germany and its initial objectives.

> It’s always a small group, a core group of people that starts such a new thing. And we had a meeting where we invited about 10 people from industry and also some Fraunhofer, who were most active there, and discussed with them raising such a network… or installing such a network.
>
> And then we decided to have a conference first. So in 2004, we did a one-day conference—in German at that time, only—to check how the interest… and it was, I think, almost 200 people. It was the largest organic or printed electronics conference worldwide that year.
>
> And we organised this as a conference and we had a discussion there with the community, as a forum discussion, checking whether they were interested to join such a network. And we had about 30 people stay. And six weeks later we started OE-A formally, with an inaugural… things… and electing a board and having 35 members, member institutions, from the beginning. (Respondent KH)

OE-A organises a yearly conference named LOPEC (Large-Area, Organic and Printed Electronics Convention), conducts work group meetings in Europe, Asia and USA for its members that provide an opportunity to enrol new members, discusses roadmaps, visits member sites, works on standards and other road blockers like encapsulation and also identifies future academic requirements. OE-A also participates and collaborates with other regional associations active within the Organic and Printed Electronics arena such as KOPEA (Korean Printed Electronics Association) and JAPERA (Japan Advanced Printed Electronics Technology Research Association). In addition to that it presents or sets up booths at other cross-industry events such as DRUPA (for print and cross-media solutions), K 2013 (conference for plastic and rubber industry where a special pavilion, PEPSO (Printed Electronics Products and Solutions), was set up to discuss the theme “Printed Electronics—Chances for Plastic Industry”) and the Printable Electronics trade fair 2014 and 2015 held in Tokyo, Japan.

The next sections will elaborate on the role of OE-A and discuss its main activities: field-configuring events, working group meetings, roadmapping and demonstrator competition.

8.3.2 Activities of OE-A

8.3.2.1 Field-Configuring Event—Large-Area, Organic and Printed Electronics Convention (LOPEC)

Lampel (2001) discussed the importance of technological dramas in the case of new technologies that suffer from a wait-and-see attitude due to the constituencies' critical evaluation routines. In an uncertain situation, commitment routines that focus on "achievements and future potential of new technology" produce changes in collective behaviour and contribute to more positive interpretation of the technology. The task of the technological community, therefore, is to ensure active participation of important stakeholders by creating public spaces for enactment of dramaturgical events that ultimately results in creating awareness and attraction, thus contributing to certainty of technology. OE-A has been instrumental in orchestrating dramatic performances through its field-configuring events (FCE) such as LOPEC and creating a desired market pull.

LOPEC is held every year in Germany and is an event of international significance that also can be considered as the voice of industry. What set LOPEC apart from other similar events organised within OPE by market consultants such as IDTechEx and IntertechPira is the presence of decision makers rather than only organisation representatives. In 2014, the convention was able to attract around 2000 participants, not only those active within Organic and Printed Electronics but also from other sectors where applications of OPE can be a differentiating factor. According to Lampel and Meyer (2008), evolution of fields occurs at two levels, organisational as well as individual. FCE provide the shared space to individuals to represent themselves as well as their organisations. Technological innovators realise that the shaping and emergence of a new technology like OPE would necessitate invoking human imagination and social shaping.

LOPEC not only provides networking opportunities but is designed to demonstrate the potential of the technology, creating shared vocabulary and establishing a sense of community. The conference is organised alongside a trade show and is divided into plenary sessions discussing the strategy of iconic companies, with business, scientific and technical sessions, and is followed by dinner. It also provides an opportunity to learn about materials, devices, processes and applications via short courses delivered by experts from the respective categories. Additionally, LOPEC illustrates what is possible presently and portrays a vivid picture of what the future holds through its "live demo lines" and Demonstration Street. This results in generating a lot of excitement and hype, creating momentum and finally getting commitment from heterogeneous constituencies.

Field-configuring events provide discursive spaces and are considered as catalysts for institutional change and creating collective identity for the technological community (Hardy and Maguire, 2010). LOPEC in this regard can be considered successful for creating desired political attention. This is evident from the EU's commitment of €70 million for the development of Organic and Printed Electronics for 2014-2015. Furthermore, it provides an interactive forum where diverse communities enter into negotiations around what they expect from being a participant in this emerging field. For instance, the user communities such as brand owners identify the problems where OPE can provide a solution, a venture capitalist evaluates the credibility of the promises and ascertains future bets. Thus there are contested discussions and debates around the problems of the field, its virtues and future potential. The conference therefore serves a dual role: while it aims to provide a converging message of growth to the outside community, it also invokes debate around contested claims for various approaches.

Conferences are also avenues for collective sense making and, as the field evolves, help achieve stabilisation. OPE is still in its emergent stage and, as discussed in Chapter 5, the competition does not exist only among the incumbent and new technologies but also within different variants of the developing technology. This is an interesting aspect that can be witnessed in the case of LOPEC where the tradeshow brings competitors together to discuss each other's progress in informal settings and demonstrate the progress of their technology. Thus, as described by Garud (2008), "they are arenas for competition among self-interested contestants" advocating different technologies, equipment and devices. According to Lampel (2001, p.321), "prior to lock-in, events may be influential because they trigger or accelerate the accumulation of choices that push technologies past a certain threshold that represent a "point of no return" for technological evolution."

LOPEC has been able to mobilise resources and influence expectations around technology. Innovators use it as a forum to generate credibility and claim that OPE is a sure bet and clearly a winner when it comes to creating future competitive advantage.

8.3.2.2 Working Group Meetings

OE-A holds quarterly working group meetings in Europe, North America and very recently in Asia. Initially the meetings were mainly organised in Germany but over a period of time, in line with OE-A objectives of achieving internalisation, the meetings were also organised in other parts of Europe and, since 2008, in USA. The working group meetings provide a thriving environment for networking, sharing latest developments and collaborating for new projects. *"A lot of the cooperations and projects and also products and businesses that are there had its origin in an OE-A meeting."* (Respondent KH)

Members work closely during these meetings on topics of mutual interest such as roadmapping, upscaling, education, standardisation, hybrid systems and sustainability that are instrumental for the progress of the technology.

> So here in the meetings you get a better… or good access to the right people and you meet the right people within a company. (Respondent KH)

8.3.2.3 Roadmapping

Developing a roadmap is one of the major activities within the OE-A, and is considered to be the benchmark, as is evident from interviews within the industry. Roadmapping is not only a social process but its activities entail the performative nature. The objective is to develop a common opinion of where the technological activities will be headed, what are the main application areas, what are the key challenges, and also to influence policies and investment decisions. The European Commission also uses the roadmap as one of its tools to identify dedicated areas for funding and intervention and to ascertain future educational training needs.

> […] It was interesting, because one of the earlier editions, in version 3 or 4, it turned out that… what we described in the white paper as the key brick walls […] the European Commission actually took that paper as one of their guides for their following series of calls in the large area electronics field – so they said, "OK, well these are the ones that need to be addressed. Let's say this is where we need to start putting some money. (Respondent DLT)

> Roadmapping offers a new dimension to innovation by bringing together a broad base of participants whose collective knowledge is applied to the question "Where are we headed and how are we going to get there?" Roadmapping is a collaborative planning exercise that helps align and organize knowledge essential to innovation, thus the notion *organized innovation*. (Schaller, 2004, p.49)

> Since the technology is still in its early stage - and is in the transition from lab-scale and prototype activities to production - it is important to develop a common opinion about what kind of products, processes and materials will be available and when, as well as the key issues needing to be addressed. (OE-A white paper, 2009)

> So the driving factor behind a roadmap first of all is not innovation, it's making the development faster. (Respondent WMP)

However, the roadmap has evolved over the years from being too optimistic and full of promises to being more realistic as there are now initial products in the market.

> […] What happened in the beginning was everything was very optimistic, and we said, "Ah, in 2003 we have this […]." But it came out it was too optimistic, so the roadmap appeared that… in the next roadmap, that just the years were changed and everything else was not so much changed. So now we are starting to get a more realistic feature. So what do we really have? And the good thing is we do have now things… we have prototypes, we have products on the market, so you have something where you can review on. (Respondent WC)

For the development of the 2011 roadmap (4th edition), the activities within the OE-A roadmapping working group were divided into eight working teams, five application areas (organic photovoltaics, flexible displays, OLED/EL lighting, electronics and components and integrated smart systems) and three technology areas (functional materials, substrates, patterning materials). The roadmaps are subsequently discussed at working group meetings to get the input of active players on the technology parameters, and moderated by team leaders. Roadmapping is an ongoing activity and is revised and updated every two years. For the fourth edition of the roadmap 250 experts along the whole supply chain participated. The dynamics within the roadmapping activities are very complex, as was evident from the meetings in which the researcher participated and also from the interview with the team leader heading one of the application groups. The players have varying, and sometimes contrasting, agendas and motivations.

> […] Everybody wants to have the final word, but everybody wants to have a table where there is written, "This product will be there in 2013, this product will be there…"
>
> The problem is, for the motivation, everybody wants to know, but most people just want to listen. (Respondent WCP)

The roadmapping is a negotiating process. There is an inherent tension as each participant tries to influence the process, a constant struggle as they try to strike a balance between what they need to disclose and what is important to be included in influencing the roadmap's design and future expectations.

> So there is a balance of interest between "it's important to enter in"… between it's important for my company to be shaping the field in the expectations, but it's important not to reveal too much of what's going on. (Respondent NGC)
>
> A tough situation is the roadmap. There is kernel team which is active and then we try to have players for every active element. And there has been always rotation there because people attended one time and then left for a next time. (Respondent WMP)
>
> In this case the semiconductor industry is basically setting the pace at which you'll have to run… And with organic electronics at the moment it's more of trying to shape… and start creating the credibility. But they say the fluctuation could be large still, we could have whole technologies that fall out, they just don't continue or things that go may be bit faster than predicted, but then maybe slowdown. So it's not the clockwork. I think it's more creating the awareness that if there is no agreement between the experts of a general trend, it's difficult to give guidance. (Respondent NGC)

8.3.2.4 Demonstrator Competition

In addition to the roadmapping activities, another important activity for the emerging technology is to have demonstrators to illustrate the potential and possibilities of the technology and create the necessary pull. This is also a way of educating the masses, increasing experimentation and encouraging collaboration. Rao (2002) referred to the demonstration event as an "evangelizing strategy." The OE-A demonstrator project started in 2005. OE-A and its members developed a toolkit to foster competition and education among university students. The toolkit consists of 20 different components (active and passive) and devices along with specification sheets and availability.

> There was an idea… we had a demonstrator project… there are so many different components, let's collect them… and then we ask students to develop some new

> application here, or ideas for concepts—I mean, not a product development—which has two effects: One thing is to foster education – to get students interested in that topic. And the other thing is to get nice examples, new applications, to show the public how it can look. (Respondent KH)

> …an open toolbox, so if people come, want to use things, it can be integrated. They have to provide a data sheet. And this is also published, so of course a lot of people are, "Can you send me a…? That's exactly what I need to convince my management of such a…" or "…for my people in the lab to play around with the different component." (Respondent KH)

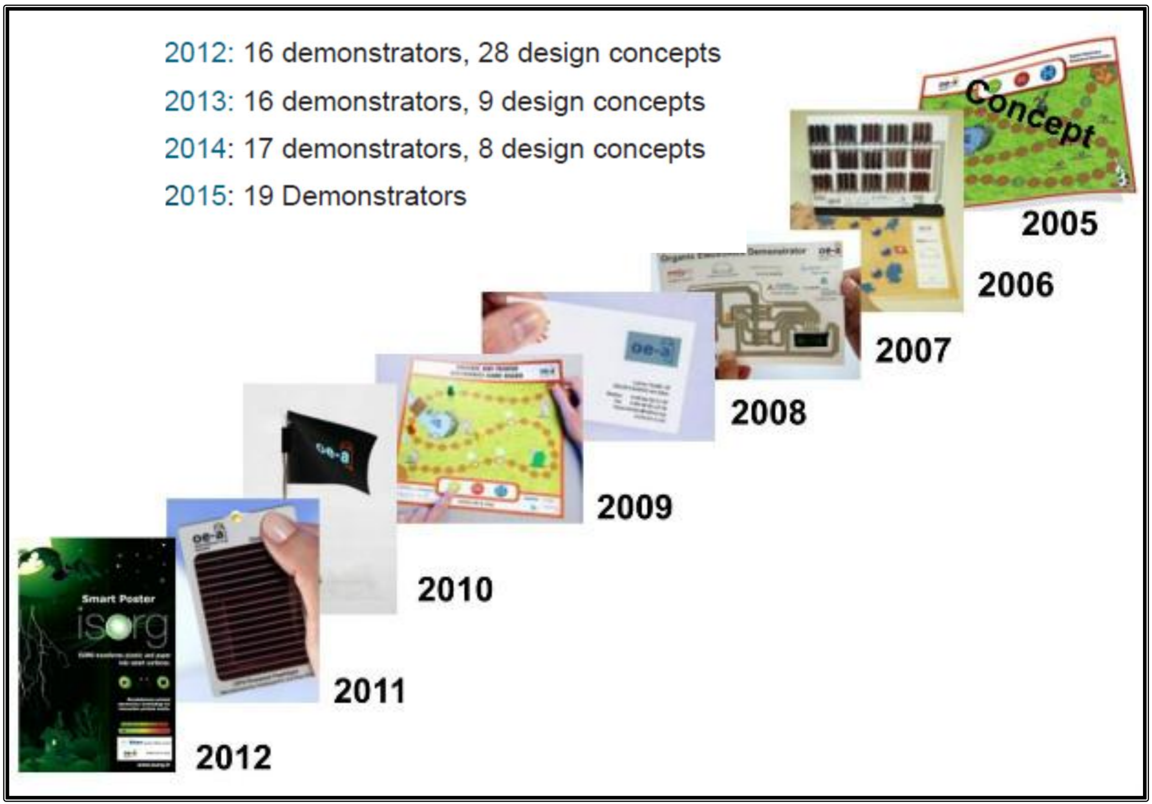
OE-A has also devised a demonstrator competition whereby the members can submit their demonstrators and participate in the following categories (as of 2015):

- Prototypes and New Products
- Freestyle Demonstrator
- Publicly Funded Projects Demonstrator
- Design and Concept Studies (open to designers and universities for design)

> So it's important to establish collaboration. […] there I see OE-A not only providing the platform but also providing a first test field for doing that, for instance with these demonstrator projects. (Respondent WMP)

The ideas for the demonstrators and their feasibility are discussed in the working group meetings that are held in Europe, North America and more recently in Asia. There has been an increased participation in this completion as shown in Figure 8.7. Participants from ten countries handed in 19 demonstrators in 2015. The competition fosters collaboration, generates new ideas and concepts, and also provides a platform for dissemination of the results of public funded projects not only at LOPEC but also at other cross-industry events.

Figure 8-7 Demonstrator Competition



Source: OE-A Member Website

8.3.3 Role of OE-A

OE-A has been instrumental in shaping OPE infrastructure knowledge, articulating expectations and visions, legitimising the potential of the field at the macro level through mobilising resources, enrolling actors and generating critical mass around technology, and institutionalising via development of shared vocabulary and roadmaps. These roles have been identified as instrumental for technological transitions (Van Lente et al., 2003; Kivimaa, 2014).

OE-A has been vital in ***classification*** of the application paths that OPE, as a pervasive technology, can take, and positioning of actors within the arena. For instance the fourth roadmap of OE-A reduced the inherent complexity in the field and integrated and grouped the application areas from nine in the third roadmap to five. According to Pollock and Williams (2010, p.533), "classifications […] shape innovation: they name technologies in a way that anticipates their trajectory of development, the particular shape they will take, the new players who will enter the market and the demand for the technology.” Classification, once successful, becomes enduring and forms infrastructural knowledge.

Creating shared expectations and visions has been one of the major roles performed by OE-A. Expectations are vital for nascent technologies as they mobilise the financial support required for technological development, enrol actors, shape the activities of technology developers and reduce associated uncertainty (Borup et al., 2006; Pollock and Williams, 2010). Hype and disappointment are a trait normally associated with futuristic science and technology and constitute belief that is widely shared. In such instances, expectation-building activities need to be augmented so that they can be constitutive and performative, “in defining roles and in building mutually binding obligations and agendas” (Borup et al., 2006, p.289). Through organising conference and working group meetings, developing roadmaps as well as more recently conducting a business climate survey for OPE, OE-A is able to paint a vivid and promissory outlook of the future. This in turn results in creating positive expectation associated with OPE at different levels—at the more micro or firm level, at the meso-sectoral level and at the macro level of national policy.

Expectations guide action but at the same time are shaped by activities pursued by actors, scientific and technological developments and commercialisation results (Van Merkerk and Robinson, 2006). OE-A not only contributes to developing shared beliefs but its role is also vital as it provides a platform for **agenda settings.** According to Van Merkerk and Robinson (2006, p.412), “ the process of agenda setting is closely related to the dynamics of expectations, where shared priorities of work are articulated for realizing expectations.” OE-A members, while participating in working group meetings, work towards a shared agenda that in turn results in setting priorities, reducing discourses and formation of networks. These networks’ interactions contribute to further shaping of the technology and path emergence in nascent technologies.

An example of agenda setting and formation of network is the dynamics witnessed in the Encapsulation Group that was created in 2010 within OE-A to continue work on the deliverables of the European Framework project “OPERA” (Organic and Printed Electronics Research Alliance) and contribute towards the creation of future standards. The group meets regularly in the OE-A working group meetings and exchanges samples, test results, minutes of meetings and other relevant material on the OE-A member portal. Measuring encapsulation has been a challenge for organic electronics devices such as OLEDs and OPVs. A large number of research groups used different variations of the methods, necessitating a need for better communication across the community and development of standards. The priorities and agenda initiated at the OE-A platform resulted in stimulating participation from varied actors, as around 70 members were present at any one time.

OPE lacks demand pull and that has hampered its diffusion despite developments over the last 20 years, as discussed in the previous chapters. ***Demand articulation*** is vital for the innovation process (Boon et al., 2008) as it makes explicit the preferences and requirements of the stakeholders and their perception of important characteristics for adoption of the technology. This is more important for technologies in their embryonic stages owing to the uncertainties associated with a variety of possible technological options and applications. OE-A through its various activities such as LOPEC has facilitated articulation whereby potential users from industries such as automobile, aerospace or healthcare are invited to discuss their expectations for the technology. These events in turn stimulate discussions among various stakeholders, enable second-order learning within and across heterogeneous organisations and finally convergence around a few options.

OE-A facilitates developing ***social networks*** that tend to be important for strengthening weak ties among members, facilitating diffusion of technology and developing of standards. Member organisations benefit by having access to confidential information and getting first-hand knowledge of the latest developments in the technological domains via boundary spanner individuals (Swan and Newell, 1995). Furthermore, a trade association also plays an important role in shaping inter-organisational relationships and creates an environment that is important in developing trust among its members (Marchington and Vincent, 2004). According to Lane and Bachmann (1997, p.230), trade associations represent "institutional forms of shared knowledge which provides members with orientations for action. Thus they ensure the validity of commonly accepted technical standards and rules of business behavior." Development of shared beliefs, common language and meaning constitutes a mechanism for reducing the uncertainty and complexity associated with inter-organisational relationships. Marchington and Vincent (2004, p.1032) further elaborated on this point:

> Processes and purposes of organizational exchange can only be fully understood by investigating the interplay of interorganizational relations at a number of different levels, taking into account not only any economic rationale for collaboration but also institutional norms and traditions and the day to day behavior of individual boundary spanning agents.

8.4 Discussion and Conclusions

Intermediaries are considered as important in the context of breakthrough technologies and emerging industries, however the studies focusing on their roles in such a dynamic context are few and mainly limited to agriculture and health (Meyer and Kearnes, 2013; Kivimaa, 2014). The seminal contributions such as that by Howells (2006) looked at the role of innovation intermediaries but focused on its impact at firm level (Watkins et al., 2015) rather than viewing it from an ecosystem perspectives. The chapter's objective is to contribute to this underresearched theme and open the black box of intermediaries by identifying their role and practices that are more active and explorative than extant literature suggests (Am, 2013; Meyer and Kearnes, 2013). The discussion of intermediaries (research and technology organisations and industry associations) for OPE provides strong evidence of their critical role of the evolution of breakthrough technology and its transition to an emerging industry. They facilitate articulations of expectation, vision and demand; learning through experiments and iterations; and building of networks. They do not merely act as matchmakers or translators between the worlds of science, policy and market but their roles are performative and "in practice intermediation entails the creation and careful management of a new hybrid world" (Meyer and Kearnes, 2013, p.424).

The chapter contributes to the underresearched theme of RTOs (Barge-Gil et al., 2011; Loikkanen et al., 2011) and their role in the ecosystem of emerging industries. The literature has discussed their role particularly in the context of technology transfer and for facilitation of innovation processes of SMEs but the mechanisms adopted by them for emergence of new industries is undocumented in academic literature. The chapter provides evidence of the complementary role of RTO and universities in technology development as most of the firms have both university and research institutes as their partners. However the importance of interaction with these actors varies owing to the business model of the firm and their position within the supply chain. For instance both TFE and Solvay used a variety of mechanisms for accessing external knowledge; however the selection of partner varied. For TFE, being product oriented they had closed collaboration with research institutes while for Solvay collaborating with universities was of prime importance followed by loose coupling with research institutes.

Research and technology organisations (RTO) contribute not only to SME innovativeness but also provide knowledge diversity and increased specialisation for large organisations, thus contradicting the proposition offered by Barge-Gil et al. (2011). They contended that firms collaborating with universities are large and have internal capabilities while those collaborating with technological institutes have fewer internal capabilities and thus rely heavily on external sources. OPE is both a product and process technology and is characterised by continuous advancements upstream in materials as well as in equipment and manufacturing processes. It requires expertise in chemistry, physics, engineering and manufacturing technologies. Accelerated technology development for OPE demands expertise in a wide range of other cross disciplinary technological areas and therefore the propensity for searching for external knowledge is higher for both large and small firms. RTOs in this fluid phase of technological development are actively involved in developing the supply chain, collaboration along the triple helix with industry, government and universities and co-creation of innovation in areas that are mainly acting as barriers for the fledgling industry.

RTOs facilitate de-risking investment in the emerging phase of industry. For breakthrough technologies, in addition to the technological readiness level, the importance of manufacturing readiness needs to be addressed at the same time. The availability of the processes required for developing components and scaling up manufacturing accelerate the commercialisation of emerging technologies. Here the capability of RTOs is extremely important as they provide state-of-art infrastructure in the form of pilot lines that facilitate experimentation and prototype development that reduces the risks associated with capital investments prior to the dominant design. In addition, RTOs especially provide for the convergence of competing options and are paving the path for commercialisation and scaling up of selected processes. Participation of RTOs in projects both bilateral and at consortium level enables articulation of expectations. Sharing expectations results in alignment and learning among the participants that may lead to further modification of expectations, thus creating a cycle of learning (Hoogma, 2000). Expectations further lead to motivation among actors who, despite the initial technological roadblocks and low market penetration, continue their enrolment in breakthrough technologies owing to the long-term benefits.

The chapter also provides rich evidence of the role of institutions in the emergence of new fields (Kaplan and Tripsas, 2008; Esparaza et al., 2014) and empirically contributes to understanding of the role of industry association thus responding to calls within the academic literature (Pittaway et al., 2004; Barnett, 2013; Prokopovych, 2015; Watkins et al., 2015). According to Greenwood et al. (2002), professional associations are not only arenas for interaction within the community but provide interface for interaction with other communities.

Industry associations such as OE-A actively participate in shaping of technology and industry development and reducing uncertainties related to the unidentified markets and unclear future technological paths. Entrepreneurship literature emphasises opportunity identification that results in mobilisation of resources. However, identification of new opportunities arises only when participating actors imagine themselves and evangelise it to others (Dorado, 2005). Industry associations facilitate sense making of the field and portray the future so that actors can imagine their future and therefore participate in it. These findings make further contribution to the debates on opportunity identification and creation highlighting the role of institutions such as associations.

Thus presence of the association and participation within it results in value creation for its member organisations (Boon et al., 2008; Pitelis, 2009; Reveley and Ville, 2010; Prokopovych, 2015). Stimulating, broadening and enriching at early stages of emerging technology can circumvent Collingridge's dilemma as argued by Van Merkerk (2007). The member firms, both large and small, benefit (both tangibly and intangibly) largely by joining the association to ascertain the direction of technological evolution and also sometimes actively influence the technology's direction through participation in roadmapping activities and working group meetings. For entrepreneurial firms, like TFE, participation in an industry association and being at the board level position increases their bargaining power and enhances their credibility and the viability of their business model. It provides a space for negotiations and discourses, sharing new research findings, to identify technological problems and ascertain promising directions for future work. For large incumbent firms, industry association can be avenues of identifying promising start-ups, evaluating competitive technologies and thus being proactive in identifying what works and what does not.

Actors' positioning influences interaction between them. However, in the case of emerging technologies, actors' positioning and how they relate to each other is uncertain and changing (Merkerk, 2007). In the case of OPE, the findings provide novel evidence of the role of association for developing infrastructural knowledge and classification that enable the relevant actors to ascertain their position vis-a-vis other actors within the future supply chain.

The chapter also contributes to understand the mechanisms adopted by industry associations in establishing cognitive and sociopolitical legitimacy for the entrepreneurs and founders of emerging technologies, especially when the industry is in its formative phase, by mobilising efforts for standards setting, aligning languages among various actors, creating expectations and promoting industry viability to government and financial institutions (Aldrich and Fiol, 1994).

Furthermore, new forms of collaboration and organisational forms such as ecosystem are identified as a success factor in advancement of new fields such as nanotechnology, biotechnology and in this context OPE. Inter-organisational relations and routines are developed and sustained at different levels such as organisational, institutional and individual. The industry association aids in shaping preferences, identifying partners, providing a conducive environment for exchanges at organisational and individual level, supporting building of trust, promoting transparency and facilitating expectation management (Lane and Bachmann, 1997; Marchington and Vincent, 2004). Thus the association enables coordination among the partners.

However, not all membership associations are successful in bringing organisations together and fostering a climate of entrepreneurship as argued by Teckchandani (2014). He emphasised the sociodemographical diversity of the members and their linkages with other associations as contributing factors. In the case of OE-A it is not only diversity of members in terms of the international orientation but also in terms of knowledge and their affiliation with different industries that spurs active engagement among its members and results in flow of diverse knowledge rather than localised knowledge. Furthermore, active participation of OE-A at diverse forums and with other regional associations facilities bridging structural holes for its members.

Thus the chapter elaborates that the emergence, development and evolution of new technologies is contingent upon “interactive and reflexive sites” that may take varied forms, thus moderately contributing to the notion of hybrid forums (Callon et al., 2002).

Chapter 9: Conclusions

Stimulating new industries from breakthrough technologies is instrumental for the welfare and success of nations. However, the transition from breakthrough technologies to new industries is complex and requires techno-socio-economic networks of heterogeneous actors, a favourable investment climate, policy interventions, new business models and, finally, market acceptance. This study set out to explore the underresearched theme of emergence of an industry based on breakthrough technology.

The exploration of the dynamics within the emergence phase of industry, though highly important, is underresearched (Forbes and Kirsch,2011; Probert et al., 2013; Gustafsson et al., 2015). Whether and how Organic and Printed Electronics (OPE) will deliver its potential is yet to be seen. This is not surprising given the early stage of the development, but it also constitutes a rare opportunity to study the emergence of a new industry based on breakthrough technology – or its failure? – as it happens.

The new industries "do not emerge in air" and their underpinnings require understanding of the processes and activities of the combination of firms (entrepreneurial and incumbent) as well as emerging institutional structures (Krafft et al., 2014). The study aimed at researching this new emerging domain as it emerges. It provided a global overview of the industry (Chapter 4 and Chapter 5), discussed the dynamics at the meso level and the role of intermediaries (Chapter 8) in articulating the shared vision of the technology and building legitimacy of the industry, and finally focused on mobilisation of inter-organisational and intra-organisational routines by an entrepreneurial firm as it moves towards commercialisation (Chapter 6) and discussed in detail how a large incumbent upstream material firm developed the tools and mechanisms to overcome the gale of creative destruction and capture opportunity as and when it arises (Chapter 7).

9.1 Review of Key Findings

9.1.1 Organic and Printed Electronics—Key Characteristics and Dynamics

Organic and Printed Electronics is considered to be a key enabling technology, with a high economic potential. It basically refers to electronics beyond the classical approach. OPE is a multidisciplinary field and requires developing and combining competencies across physics, chemistry and engineering. It has the potential to provide synergies and requires expertise from different industries (chemical, mechanical, printing, electrical, packaging and consumer electronics) that are learning to collaborate and talk to each other.

Considered as a paradigm shift from the conventional silicon-based products, OPE employs novel materials (organic and inorganic) and cost efficient production and patterning processes (printing, vacuum). It is both a product and process technology and offers numerous operational benefits such as low-cost, subtractive manufacturing processes, as well as unique functionality and product-related attributes such as flexible form factor, unique design, reduced weight and robustness. A large number of potential applications are envisioned for OPE such as flexible displays, sustainable and energy efficient lighting, smart packaging, smart clothing, flexible solar cells and printed batteries, with the potential to impact numerous vertical markets such as automotive, healthcare, packaging, security and consumer electronics.

The highly revolutionary and disruptive potential associated with OPE has contributed to lofty expectations, open-ended promises, considerable hype and waiting games. A large amount of investments, both public and private, have contributed to the progress of this technology, as is evident from the recent penetration of OLED display in mobile phones and TV, and advancements made by printed memory in the domain of brand authentications, but there are still concerns about its widespread adoption and commercialisation success in other domains for applications such as OLED lighting and OPV. Initial progress within this domain is characterised by a higher degree of technology push rather than demand pull. A long gestation period, along with uncertainty regarding the readiness and usefulness of the technology, have contributed to a slower rate of adoption in potential end markets. The initial ferment stage was fuelled by a large number of new entrants – both de novo as well as de alio firms, dedicated network builders, and institutional entrepreneurs – that resulted in creating initial mass around the technology and enrolling other actors. However, there have been more shakeouts than successes and penetration is limited to selected niches.

Many factors contributed to the initial slow progress, the most dominating ones being the continuous improvement of the incumbent technologies, a fragmented value chain and the absence of system integrators. These concerns resulted in a move away from research and proof of concept / demonstrators to scalable business models and manufacturing. There have been attempts to enable the transition from protective space and to increase the readiness level, as demonstrated by the increasing role of intermediaries and setting up of pilot lines such as the establishment of PrintoCent at VTT in Finland and CPI’s Printable Electronics Centre (previously PETEC) at Sedgefield in the UK. Furthermore, the ongoing activities aimed at standardisation in both public and private standard setting bodies such as IEC and IPC have been able to increase the momentum towards stabilisation of the technology.

9.1.2 Entrepreneurial Firms, Ecosystems and Creation of Organisational Routines

Small entrepreneurial firms are considered to have behavioural advantages as compared to their larger counterparts in the introduction and diffusion of emerging and disruptive technologies. However, they do face considerable commercialisation challenges owing to their small size, limited financial, human and relational resources and the liability of newness. These challenges are further compounded in the formative years of new industry emergence (Aldrich, 1999) and also require recognition and creation of new opportunities and markets, developing new routines and legitimising the new ventures.

The study provides evidence that in the context of emerging industries, knowledge tends to be distributed, complex and specialised and therefore requires developing new modes of organising such as “innovation ecosystem” rather than operating in the classical paradigm of arm’s-length transactions. The ecosystem analogy drawn from biology provides a rich and dynamic picture of complexity associated with loosely connected participants (Iansiti and Levien, 2002). Reducing risks and uncertainty drives the creation of an ecosystem.

The Thin Film Electronics (TFE) case provides the rare opportunity to discuss the dynamics related to the orchestration of an ecosystem by an entrepreneurial firm that made a strategic move from being a mere component provider of printed memory to being an integrator and system provider. A key finding from the case study is that symbiotic, interdependent and reciprocal relationships among the ecosystem partners resulted in co-creating value that has led to competitive advantage and commercialisation. The development of an ecosystem was an iterative and gradual process and required defining the boundary conditions such as those related to enrolment and selection of partners, and stratification (tie heterogeneity, exclusivity and redundancy). TFE selected partners based on both technological complementarities as well as supplementary alignment in resources, thus reducing ecosystem risk. Heterogeneity of ties contributed to tiering in the ecosystem. The case demonstrated the presence of not only strong and weak ties but also latent and potential ties.

For emerging industries, whereby the technology is still embryonic and continuously developing and the markets unclear, the study found certain preconditions that bind actors to the entrepreneurial hub such as (1) the expectation of continuity and larger shadows of the future, (2) building legitimacy at the venture level and (3) shared logic. TFE employed intensive and diverse sense giving activities and was able to get the attention of both the generalised and the specialised press. These practices proved instrumental for making TFE’s vision credible and in establishing legitimacy of the new venture for heterogeneous audiences such as investors, shareholders and ecosystem partners.

One of the more significant findings to emerge from this case is that creation of an ecosystem does not automatically translate into capturing or extracting value from the ecosystem but requires developing processes and mobilising appropriate organisational routines. The case interestingly demonstrates that TFE employed a large repertoire of intra-organisational and inter-organisational routines. Top management, diverse experiences, interactions and imprinting all contributed to the heterogeneity of routines. The study believes that the better configuration of these practiced routines and the complementarities that existed between them were ultimately translated into better innovative performances. Furthermore, the large number of routines that were established at TFE implies fast decision making in a dynamic context.

9.1.3 Incumbents and Reconfiguration of Routines

The emergence of new industries is associated with creative destruction and the decline of incumbents. However, there are outliers, and seminal literature provides evidence that when confronted with breakthrough technologies, some incumbent organisations adapt, survive and even regain their supremacy. The case study of Solvay, an upstream material firm, discusses a novel “in-between” dimension of mechanisms adopted in the period of emergence. The case study provides evidence that Solvay adopted mechanisms for reconfiguration of capabilities aimed at transformation rather than evolution or substitution. This implies that they created some new routines and modified a few existing ones while discarding others. Their approach was more holistic whereby they strived for structural ambidexterity and developed a separate business unit to facilitate innovation. The exemplary elements of their strategy were (1) setting up the Global Discovery Program with COPE and their academic partners, thus highlighting that university-industry collaboration in the context of emerging industries does not follow a linear model but is interactive and iterative with feedback loops; (2) creating tacit coordination mechanisms and embedding young, newly hired scientists in universities and research labs to broaden their horizon, get fresh perspectives and internalise the external work done; (3) systematic use of direct and indirect corporate venture capital mechanisms to ascertain future technological paths and promising start-ups.

9.1.4 Intermediaries and their Roles

The transition of breakthrough technologies to emergence requires mobilising actors and creating critical mass, articulating demands, developing shared visions and establishing cognitive and sociopolitical legitimacy. In the context of OPE, the study demonstrates the dominance and importance of two intermediaries – the research and technology organisation (RTO) and the industry association. The RTO facilitates experimentation, de-risking investments and reducing uncertainties through convergence of competing technological options. The industry association is identified as a key actor within this emerging industry. It not only provides the space for networking and sharing but its role is more active as it shapes the technology, develops infrastructural knowledge and helps other actors ascertain their position within the value chain through diverse activities such as field-configuring events and roadmapping.

9.2 Contribution to Knowledge

9.2.1 Entrepreneurial Ecosystem Design and Orchestration

Emerging industries based on breakthrough technologies are highly knowledge intensive. The thesis provide evidence that ecosystem creation can facilitate commercialisation in the case of breakthrough technologies that are characterised by uncertainty and low initial performance and face challenges from incumbent technologies.

"Ecosystem" has been a buzz word mostly used by practitioners, however recently it has gained traction within strategy and entrepreneurship. Within the entrepreneurial literature there are two dominant streams: one around innovation ecosystem (Autio and Thomas, 2014; Zahra and Nambisan, 2011) and the other focusing on regional ecosystem and its policy implications (Stam, 2014).

While the discussion on innovation ecosystems is growing its main emphasis has been on coordination and competition within an established ecosystem (Adner and Kapoor, 2010) and is populated around success stories of large hub firms such as Walmart, Microsoft and Apple that act as a platform provider and thus provide niche opportunities for new ventures and small companies. However, scant attention has been given to the dynamics of an ecosystem such as its early stages, creation, and evolution (Autio and Thomas, 2012) and still less to those orchestrated by small firms and in a nascent market, with the exception of work done by Santos and Eisenhardt (2009) and Walrave et al. (2013). Furthermore, the entrepreneurship literature has mostly associated entrepreneurial venture success with the personal traits of an individual or personal network rather than around business ecosystem (Overholm, 2015).

Technology ventures have to make strategic choices regarding their business models whereby the entrepreneurs may focus on licensing and selling their technology or alternatively may decide to develop the technology in-house and invest in complementary assets. Technological and market uncertainty, however, contribute to information asymmetries that impact the market for technologies and thus make licensing a less desirable business option (Audretsch et al., 2012).

The thesis contributes to understanding of how an entrepreneurial firm created the ecosystem, highlighting its design elements such as enrolment criteria, stratification exclusivity and redundancy. These design elements in turn impact the value creation within an ecosystem. Value creation within this context is associated not solely with developing the technological capabilities or relying on existing patents but is dependent on establishing logic of co-creation, developing norms of trust, reciprocity and transparency.

9.2.2 Organisational Routines

The distributed and dispersed nature of knowledge within the context of emerging industries implies that the routines are collective phenomena, distributed across space and organisations (Becker, 2004). Routines are difficult to observe and operationalise and that has resulted in few empirical studies within the capabilities domain.

The main theoretical contribution of the study is in proposing a routine-based dimension to the orchestration of early stage ecosystem thus emphasising processes rather than structure and position that enabled the hub firm to steer the ecosystem to its advantage. The study and its findings contribute to the theme of ecosystem orchestration processes by an entrepreneurial firm, as earlier focus has been mainly conceptual, such as that by Dhanaraj and Parkhe (2006), within large organisations and in a stable context (Ritala et al., 2009; Nambisan and Sawhney, 2011; Overholm, 2015).

The study extends the Lewin et al. (2011) routine-based model of absorptive capacity and contributes both conceptually and empirically to the emerging themes of meta-routines and practiced routines that provide a microfoundation for capabilities. It goes beyond the proposed typology of internal and external routines that being at firm level loses its significance in ecologies where knowledge is distributed. Extending routines at both intra-organisational and inter-organisational levels and in uncertain environments adds an interesting dimension to the study of the form these routines take in such contexts, for both large and small firms, and the importance of complementarities in making them performative.

Intra-organisational routines focused at the firm level and employed (internal/external) routines not only for exploration and knowledge acquisitions as mostly emphasised in literature (Friesl, 2012) but also assimilation and transformation of new knowledge that are equally important for emerging industries. Sharing knowledge across organisations is mainly associated with assimilation but while working in ecologies and in the context of emerging technologies, prototype development is the main mechanism of assimilation and provides discursive links between the firm and its ecosystem partners. Furthermore, inter-organisational routines were developed at bilateral or dyad level to enable coordination and at collective level these routines aimed to establish both cognitive as well as sociopolitical legitimacy.

In emerging industries, the "rules of game" are still in flux and are being negotiated by the actors. TFE at the firm level mobilised routines for sense giving thus establishing its credibility and identity. Consequently, at the inter-organisational level TFE manipulated institutional logics by employing various proactive mechanisms that enticed other actors to share and adhere to its vision of "Memory Everywhere" and enabled the creation and momentum of an ecosystem. These inter-organisational routines in turn impacted the expectation formation for the technology in general and ecosystem in particular and thus enabled creation of constituency around OPE that is important for technological niches.

Timing and speed are important considerations in dynamic settings. Routines in this context are simple and also take the form of heuristics and rule of thumb in the absence of convincing evidence. Developing a large number of routines enabled faster learning in such a resource constrained environment by an entrepreneurial firm. Furthermore, for young firms, the top management team's previous experiences facilitate the development of routines. Other sources of routines are "learning by doing" and external networks (Miner et al., 2011). Selective importation of routines from previous experiences of the top management team though being dominant in the case was also combined with existing routines that were embedded in the organisation since the time of Intel. This perspective is interesting as it points towards the continuity of existing routines despite its inactivity and only one top manager having direct previous experience.

9.2.3 Incumbents' Response to Breakthrough Technologies

Compared to small entrepreneurial firms, large incumbent firms already have established routines owing to their rich history. The presence of existing routines, while being the source of stability, also results in increased focus on incremental innovation. Extant literature suggests that incumbents fail to respond to paradigmatic change and invest in breakthrough technologies only once the dominant design emerges. Contrary to this, the study found evidence of investments by incumbent firms in the early stages. Though the pattern was more prevalent among the material firms located upstream, there is the presence of prominent players downstream, as well, such as Philips, Samsung, LG, and Siemens.

Developing capabilities in a new domain, however, impose challenges to the incumbents. The seminal literature is divided into two streams: one suggests that incumbents may fail when faced with technological change while the other argues for adaptation through punctuated equilibrium or dynamic capabilities. In addition various mechanisms are suggested such as structural separation or ambidexterity, managerial cognition, wider search patterns and alliances. The assumption of incumbents' failure has been challenged in the context of biotechnology whereby pharmaceutical incumbent firms adopted mechanisms such as licensing, strategic alliances and acquisitions (Rothaermel and Thursby, 2007). The study provides evidence that the approach adopted by incumbents during the inventing phase of OPE is more holistic as opposed to one-off mechanisms and requires developing routines for transformation prior to the emergence of dominant design rather than substitution or evolution. Ex ante it is difficult to establish the future evolution of the technology so adopting the substitution mechanism that may require acquiring new capability or discarding the existing one following a technological change might result in unsuitable response. On the other hand evolution is an ongoing, path dependent mechanism that in the event of radical change would not result in timely response.

Incumbents have an established operational and higher level routines that have imprinted and serve as organisational truce. In this context, structural separation or importing routines from external or internal sources or forming strategic alliance may not be able to address the combined effect of economic, cognition or organisational impediment to reconfiguration.

9.2.4 Emergence of an Industry as a Context

The empirical findings in the study make a noteworthy contribution to the emergence of new industries by giving a rich account of key processes and events as they unfold at multiple levels.

The emergence of new industries is an important context but has received little attention owing to the theoretical and empirical challenges associated with the domain (Forbes and Kirsch, 2011). Exploration of the phenomenon requires attending to multiple data sources and mapping the range of actors such as producer firms that form an instrumental subsystem, suppliers of critical resource endowments such as universities that contribute to the intellectual capital and venture capitalists that help with the financial resources, and finally public policy officials and industry associations that comprise the institutional infrastructure (Van de Ven and Garud, 1989).

Most of the data associated with this emerging phase is ephemeral. Knowledge in the context of emerging industries is distributed globally and stored in the heads of individuals. Furthermore, the diversity, intensity and fast pace of the activities happening at various levels implies actors expending less effort in creating and maintaining these formal records.

The present study can rightly be viewed as one of the first few attempts to overcome the bias of retrospective data associated with the study of an emerging industry. Most of the studies discuss the post hoc identification of industry (Gustafsson et al., 2015). Forbes and Kirsch (2011) refer to the studies based on established industries as low hanging fruit.

9.2.5 Role of Individuals and Top Management Team

The study empirically contributes to the growing literature on microfoundations and role of individual and top management team in developing routines and capabilities in the context of both entrepreneurial firm and incumbent organisation. Routines, according to Nelson and Winter (1982), involve multiple actors and are at organisational level and therefore remain intact even if individuals leave the organisation. They tend to be sticky and this results in their imperfect imitation.

Intellectual humans along with strategic alliances are considered as sources of innovation in dynamic environments such as biotechnology for incumbent firms (Rothaermel and Hess, 2007). Similarly the researcher working within the strategic management stream emphasised the role of managerial cognition in developing capabilities (Eggers and Kaplan, 2013). The evidence from both the cases suggests the important role of managerial cognition in the creation of routines in both entrepreneurial and incumbent firms.

The role of cognition within entrepreneurship has recently received attention as is evident from the special issue in *Entrepreneurship Theory and Practice* (2007, volume 31(1)). Entrepreneurship literature associates firm performance with the cognition capabilities of an entrepreneur (West, 2007). However, the TFE case provides evidence of the role of both CEO as well as team in the success of an ecosystem's creation and evolution. For instance, in the case of an entrepreneurial firm CEO's past successes with the selection of partners for renewable energies was mindfully adopted in the context of ecosystem creation. However, generation of new ideas, the identification of opportunities based on weak signal, pattern recognition and the selected choice was a result of combination of divergent individual cognition and previous experiences of the top management team.

Tripsas and Gavetti (2000) demonstrated in the case of Polaroid that senior management team cognition had an inertial effect and the arrival of an outsider CEO and top management team had a profound impact on changing existing beliefs. However, in the context of a large incumbent firm, the case study on Solvay provides evidence of the prominent role of one of the top management personnel below the CEO level in constructing, assembling and implementing the routines for transformation, which is contrary to the accepted notion of importance of CEO cognition in the dynamic capabilities literature (Helfat and Peteraf, 2015). Thus it implies that key individual managerial cognition may have an impact on the interpretation of the higher order routines. This aspect however required further research and was beyond the scope of this thesis.

9.2.6 Legitimacy

Legitimacy and its importance for new ventures have been an important emergent theme in scholarly literature. Numerous micro level strategies are suggested that enable new entrants to establish credibility, mobilise resources and gain stakeholders support. These strategies for instance include alliances and affiliation with high status actors, endorsement from third party actors, entrepreneurial storytelling and actor's use of narratives to establish its identity. New industry context poses additional challenges in creating legitimacy (Navis and Glynn, 2010). However, the present study extend this line of research and provides evidence that in the emerging context micro level strategies corresponding to legitimacy are important not only for entrepreneurial ventures but are of relevance also for incumbent organisations. Furthermore, in addition to the organisational level strategies, legitimacy needs to build at both intra-industry and inter-industry levels and for heterogeneous audiences such as OEM and early adopters, investors, alliance partners and government. Thus the legitimation of new industry involves the confluence of strategies of entrepreneurial firms, large organisations and intermediaries such as industry association, industry setting bodies, government and regulatory agencies. Rather than adopting the macro level and top-bottom perspective whereby the industry drive legitimation of individual ventures or micro level perspective, whereby the individual actors are assumed heterogeneous, in practice both perspectives have a discursive relationship that have a combined influence on audience judgements. These results thus contribute in bridging the micro and macro perspective as advocated by Überbacher (2014).

At the organisational level whereas an entrepreneurial firm engaged in sensegiving activities to establish trust and shared vision among its ecosystem partners, the large incumbent organisation articulated compelling visions to win support of internal organisation stakeholder regarding the promise of new technology and also engaged in symbolic activities to establish itself as a committed player and cognisant referent in the new industry.

At the intra-industry inter-industry level, legitimation requires actors to move beyond the individual venture level and run in packs (Aldrich and Fiol, 1994). Therefore the intermediary organisation such as industry association and member organisations play a collective role in creating cognitive and socio-political legitimacy of new industry. The collective action helps in portraying the stability and establishing the reputation of new industry to external audiences thus facilitating desired market-pull.

9.2.7 Convergence and Role of Industry Association in Industry Emergence

According to Meyer and Kearnes (2013, p.426), intermediaries "not only stand 'in-between', but their work, practices, roles, effects and identities also make them 'in-themselves' relevant actors to analyse." The study contributed to an important research gap, discussing the role of the institutions and intermediaries especially that of an industry association "in the making". The extant research has used the umbrella term "intermediary" that points toward the range of actors, institutions and instruments. However, there is still lack of understanding as to the importance of which types of institution or actors are instrumental in the early stages and especially for transition.

Though the research on meta-organisations is growing, not many focus on the role of the industry association, the exception being studies on SEMATECH in the semiconductor industry. According to Pittaway et al. (2004, p.160) "the role of third parties operating within the network infrastructure, such as professional and trade associations is under-researched." Extant literature suggests formation of new industries is a social and political process and creating an industry association in the early years helps achieve cognitive and sociopolitical legitimacy among stakeholders (Aldrich and Fiol, 1994; Rao, 2002).

The industry associations such as Organic and Printed Electronics Association OE-A are not only playing an effective role for providing legitimacy at both macro and micro levels but they are actively involved in shaping industry development. When the technology first emerges, actors are unsure of its potential and future evolutions. Contestation and interaction are importance at early stages of the industry emergence (Kaplan and Tripsas, 2008). Industry associations, as the thesis elaborates, provide arenas for such interactions between producers, users and institutions that in turn impact actors' idiosyncratic interpretation of the technology, evaluative criteria and finally decisions and outcomes. These interactions and negotiations resolve cognitive and technological variations and pave the way for stabilisation and finally selection of the technology options. Scholarly literature normally associates convergence with institutions such as standard setting bodies and technical committee (Rosenkopf and Tushman, 1998; Kaplan and Tripsas, 2008). However, in the context of the thesis, the industry association was seen as an important institution for convergence of technological options, and collective identification of reverse salient and sense making.

9.2 Implications for Policy and Practice

The study, while discussing the emerging industry, provides important policy implications. Emerging technologies have a long gestation period and require substantial investment for a considerable period of time. In this context the normal venture capital model focused on short-term goals may not be a viable model for nurturing innovation in start-ups and commercialising the research results. This therefore requires designing projects and devising IP strategies that can facilitate collaborations, experimentation, and development of prototypes and contribute to the building of a value chain.

De-risking investments by facilitating development of pilot lines provides convergence around unproven processes as has been evident from the discussion on research and technology organisations. Though RTOs are important for facilitating innovation at regional level, however, more needs to be learned from the open innovation model such as that adopted by Holst Centre. Holst Centre has a global orientation and through its IP model ensures innovation appropriability for all its partners. This value creation influence its success and allows it to act as main orchestrator within the OPE space for both small and large firms.

Furthermore, many breakthrough technologies fail and never emerge as an industry. However, as discussed by Forbes and Kirsch (2011), the limitation with studies in this context is also somewhat related to the ephemeral and dispersed nature of records. This can be mitigated through appropriate mechanisms and interventions at the public level that ensure codification of the data and records at various levels.

The study entails implications at the managerial level as it points to the importance of designing collaborations characterised by reciprocity, interdependencies and flexibility in sharing IP. Most of the collaborations and alliances do not succeed, characterised by the restricted flow of knowledge among the parties owing to the risk of losing valuable IP-related benefits. The cases of TFE and Solvay clearly demonstrate the importance of expectation management, symbiosis, and developing mechanisms both at the inter-organisational and intra-organisational levels to facilitate joint learning as the main objective in this context is increasing the overall size of the pie rather than increasing individual share.

Furthermore, the study demonstrates that the entrepreneurial firm can be a market shaper and winner, provided that they develop a product oriented approach and create a business ecosystem. Timings and speed are two important considerations for entrepreneurial firms that are pursuing the objective of creating a market. Adopting an ecosystem model may result in faster progress, reducing uncertainties and resolving challenges associated with existing incumbent technologies. However, the emphasis should be on iteratively building a value proposition for an ecosystem, developing effective processes for value creation, enhancing legitimacy at both the venture level as well as industry level that facilitate development of shared vision and enhance the shadows of the future.

The success of an entrepreneurial venture is mostly associated with an individual rather than with collectives. Another important implication that can be derived from the study of an entrepreneurial venture is the diversity of experiences in the top management team of new ventures that contributed to the effectiveness of strategic performances in a dynamic environment.

The study provides empirical evidence of adopting a holistic approach that would enable incumbent firms investing in the early stages to introduce paradigmatic changes and avoid being locked out earlier. Furthermore, though dynamic capabilities are considered to be important for reconfiguration, however they tend to be path dependent and evolutionary in character whereas substitution is more drastic and may result in discarding existing capabilities in an untimely manner. Therefore, transformation in this context is an appropriate response.

Mobility of individuals is quite common in emerging contexts and is used as a means to acquire capabilities. Furthermore, the literature suggests that individual cognition is important for the enactment of routines. This paradoxical situation demands managerial attention as to the impact of a key high level employee or group of employees exiting the organisation. It may risk losing competitive advantage owing to the transfer of higher level routines.

9.3 Limitations of the Present Study and Further Work

The present study is not without limitations. Emerging industries are characterised by their fast pace; they offer a small window of opportunity but generate large and diverse amounts of data. The project suffered from both time and financial constraints that did not allow for exploring a number of interesting but divergent emerging phenomena such as the growing importance of standards development during 2012 and its range of associated activities. This study however does set a foundation for future work in this direction in other emerging industries such as graphene.

Furthermore, the data collection was mainly confined to Europe; however, USA and Asia are two other active regions and contrasting them with Europe would give important insights regarding how breakthrough technologies are nurtured and shielded in different institutional contexts. Future studies can thus contribute to explaining heterogeneity in these geographical hotspots.

Though the present study employed qualitative methods underpinning the complexity associated with the study of routines, further investigation through the use of bibliometric and patent analysis would complement the initial work done in this study and would provide a holistic picture.

The study identified the important role played by adoption of a product orientation in the commercialisation success of an entrepreneurial firm. This theme provides a rich foundation for the business models and strategies that ensure commercialisation success for start-ups and small firms in the transition and emergent stage. However, the adoption of using single case limits its generalisability. The selected entrepreneurial firm demonstrated tremendous growth during the writing phase of this study. A longitudinal study in this regard will help in better understanding of the implications of creation of ecosystem in early stage of an industry and its evolution in later stages.

Another limitation of the study is that the cases selected have been success stories. A study based on failures and shakeouts in the emerging industry would have provided a rich insight but was beyond the scope of this research.

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Appendices

Appendix 1: Interview Protocol

Example of an Interview Protocol

Topic area	Broad Focus of questions
Introduction about the Organization and Technology	• Description of the organization. Its main area of concentration. Its position within the value chain of Printed/Organic Electronics. Its existing competence and, skill level of its employees • Description of how the technology has progressed and different from the existing one. How the *organisation* has used and is using the network to develop and commercialize the technology. • Standards setting practices for the technology and the role of *organisation* within the network. •
External Practices for Identifying and Accessing Knowledge	• What are the areas where there are challenges and how you are planning to solve them? • What triggers the need for external knowledge? • What are the practices adopted by *organisation* to identify and access the relevant new knowledge outside its organisational boundaries? • How were these practices developed and the role of management in developing these practices? • With whom and how frequently does the organization collaborate? Main reasons for collaboration. Are these partnership along the value chain, to test the proof of concept or with integrators • Are these collaborations developed to improve the existing capabilities and expertise (product/processes) or to explore new and unrelated areas. • How these collaboration pattern changed over the period of time.
Practices for Collaborations	To elaborate on inter-organisational practices, discussion was based on specific examples of collaborative projects that were in the public domain. • How partners are identified, selected, monitored for collaborations? • What are the activities /practices adopted for acquiring and transferring knowledge from partners in Collaborations? • What is the role of management in developing the practices for these collaborations? • Has the organization developed some practices to identify the dos and don’ts in collaborations? How are these disseminated within the *organisation*? • What is the impact of these collaborations on performance target set by *organisation*? • Are these collaboration repetitive? • What happens after the project ends. How is the collaboration evaluated? • What are potential risks of collaboration? • Regional, National. International Networks *organisation* associate with and why

Transferring knowledge back into organization	• How do you transfer or integrate the acquired knowledge into your organisation? • Do you use tools to facilitate knowledge transfer across the organisation?
Internal Practices for generating new knowledge	• What are the mechanisms developed by the organisation to facilitate development/exploration of new ideas by employees within *organsation*? • How is knowledge shared internally? • What are the practices that are used to select and prioritize projects and to allocate resources between them? • Are there any road maps prepared internally for future technology developments and sources used to produce these roadmaps.
Monitoring and benchmarking performance	• How does organisation set its targets? • How does the organsation monitor or evaluate its own performance?
Competitive and industry Environment	• How would you define competition within industry and across related industry? • How would you rate the pace of change in technology and market within the industry?
Organizational Structure	• How would you define the culture, structure, decision making process, incentive structure in your organization

Appendix 2: Unstructured Interviews

Interviews	Major themes covered
Industry Association	• General comments on the technology, its challenges and evolution. • Historical Background and emergence of association. • Its evolution over the period of time. • Selection and role of board members. • Investigation of main activities such as: - Roadmapping activities - Working group practices - Demonstrator competition • Practices for creating demand-pull and evangelising of the technology.
Research and Technology Organisations (RTOs)	• Historical background related to the general interest in the technology. - Adopted Business Model. - Existing competencies. - Particular application focus and reasons for its selection. - Infrastructure and investments. - Evolution of organisation. • Collaboration practices. • Partners along the value chain and their motivation to collaborate with research organisation. • Practices for evangelising the industry with specific probes around industry association and standardisation. • General comments on technology and its evolution.

Appendix 3 Details of Interviews

S.No	Date	Pseudonyms/ Organisation	Type of Organisation	Interviewee Designation	Mode of Interview	Interview	Follow-up	Location of Interview
1	13-May-11	OLED Association	Intermediary	Managing Director	S	1		
2	06-Jun-11	Organisation N	Material Developer	CSO, Founder	S	1		
3	14-Jun-11	Organisation P	Material Developer	Vice President of Business Development	S	1		
4	18-Jul-11	New Display	Material and Device Developer	General Manager, VP Intellectual Property and CTO (group interview)	F	1		UK
5	25-Jul-11	Printable Electronics Technology Centre	Intermediary	Program Manager	F	1		Sedgefield UK
6	27-Jul-11	Organisation N	Material Developer	CSO, Founder	F		1	Europe
7	03-Aug-11	New Display	Material and Device Developer	Business Development Manager	F	1		UK
8	11-Aug-11	New Display	Material and Device Developer	Senior Scientist	F	1		UK
9	12-Aug-11	New Display	Material and Device Developer	Director-New Technology	F	1		UK
10	18-Aug-11	Solvay	Material Developer	Anonymous	F	1		Manchester
11	22-Aug-11	IDTechEx	Intermediary	Director	F	1		Cambridge UK
12	08-Sep-11	Organisation T	Device Developer	OLED Group Leader	F	1		UK
13	07-Sep-11	New Display	Material and Device Developer	Vice President	F	1		UK

14	12-Sep-11	Holst Centre	Intermediary	Program Manager	F	1		Eindhoven Netherlands
15	12-Sep-11	Holst Centre	Intermediary	Project Manager	F	1		Eindhoven Netherlands
16	14-Sep-11	Organisation L	Device Developer	General Manager	F	1		Dresden Germany
17	14-Sep-11	Organisation V	Equipment Provider	Program Manager Research and Innovation	F	1		Dresden Germany
18	15-Sep-11	IPMS	Intermediary	Director	F	1		Dresden Germany
19	16-Sep-11	Organic Electronics Saxony	Intermediary	Business Manager	F	1		Dresden Germany
20	20-Sep-11	New Display	Material and Device Developer	Business Development Manager	F	1		UK
21	20-Sep-11	New Display	Material and Device Developer	Senior Scientist	F	1		UK
22	23-Sep-11	ESPKTN	Intermediary	Director and Operations (group interview)	F	1		Birmingham UK
23	06-Oct-11	Organisation D	Material Developer	New Product Development	S	1		
24	13-Oct-11	TSB	Intermediary	Lead Technologist; Electronics, Photonics & Electrical Systems	F	1		Manchester UK
25	02-Nov-11	OE-A	Intermediary	Managing Director	F	1		Frankfurt Germnay
26	04-Nov-11	Organisation PT	Integrator	Chief Operating Officer	F	1		UK
27	16-Nov-11	New Display	Material and Device Developer	Vice President	F	1		UK

28	16-Nov-11	New Display	Material and Device Developer	Director Research	F	1		UK
29	25-Nov-11	Technology Consultant	Consultancy	Technology Consultant	F	1		Runcorn Warrington
30	06-Dec-11	IPMS	Intermediary	Head of Business Unit Microdisplays and Sensors	S	1		
31	07-Dec-11	New Display	Material and Device Developer	Director-New Technology	F	1		UK
32	07-Dec-11	New Display	Material and Device Developer	Group Leader	F	1		UK
33	12-Dec-11	OMIC	Intermediary	Professor and Knowledge Transfer Manager (group interview)	F	1		Manchester UK
34	13-Dec-11	Solvay	Material Developer	Senior Vice President	F	1		Brussels Belgium
35	13-Dec-11	EU	Intermediary	Project Officer in unit G5 photonics	F	1		Brussels Belgium
36	14-Dec-11	New Display	Material and Device Developer	General Manager	F	1		UK
37	11-Jan-11	Organisation E	Component Provider	COO	F	1		Manchester
38	13-Jan-12	Thin Film Electronics	Integrator	CEO	F	1		Oslo
39	13-Jan-00	Thin Film Electronics	Integrator	CFO	F	1		Oslo
40	16-Jan-12	Organisation C	Equipment Provider	Vice President	F	1		Europe
41	17-Jan-12	Organisation H	Material Developer	Global Technical director Display and semiconductor	F	1		Europe
42	18-Jan-12	Organisation PO	Component Provider	Managing Director	F	1		Europe

43	23-Jan-12	Organisation NL	Product Developer	VP	F	1		UK
44	23-Jan-12	Organisation NL	Product Developer	Director of Process Operations and Technology Transfer	F	1		UK
45	23-Jan-12	Organisation NL	Product Developer	Technology Manager	F	1		UK
46	23-Jan-12	Organisation NL	Product Developer	Research Manager	F	1		UK
47	23-Jan-12	Organisation NL	Product Developer	IP Manager	F	1		UK
48	23-Jan-12	Organisation NL	Product Developer	HR Manager	F	1		UK
49	01-Feb-12	Organisation E	Component Provider	COO	S	1		
50	03-Feb-12	Organisation DLR	Customer	Head of Ideas Development	F	1		UK
51	08-Feb-12	New Display	Material and Device Developer	CTO	F	1		UK
52	08-Feb-12	New Display	Material and Device Developer	Senior Scientist	F	1		UK
53	10-Feb-12	CIKC	Intermediary	Director	F	1		Cambridge UK
54	14-Feb-12	Printable Electronics Technology Centre	Intermediary	Director	F	1		Sedgefield UK
55	17-Feb-12	Organisation NL	Product Developer	Display Design Manager	F	1		UK
56	17-Feb-12	Organisation NL	Product Developer	Research Manager	F	1		UK
57	17-Feb-12	Organisation NL	Product Developer	Director of Display Application	F	1		UK
58	20-Feb-12	Organisation M	Material Developer	Senior Director	F	1		UK
59	20-Feb-12	Organisation M	Material Developer	R&D Director	F	1		UK
60	20-Feb-12	Organisation M	Material Developer	Senior Manager	F	1		UK

61	23-Feb-12	New Display	Material and Device Developer	Director Research	F	1		UK
62	23-Feb-12	New Display	Material and Device Developer	VP Intellectual Property	F	1		UK
63	24-Feb-12	IPMS	Intermediary	Director	S		1	
64	02-Mar-12	COPE	University	Director	S	1		
65	13-Mar-12	Organisation PE	Component Provider	Business Development Director	F	1		UK
66	15-Mar-12	Princeton University	University	Professor	S	1		
67	22-Mar-12	Tampere University	University	Professor	S	1		
68	26-Mar-12	Organisation PT	Integrator	Chief Operating Officer	F		1	UK
69	29-Mar-12	Organisation I	Material Developer	Scientific Expert	F	1		UK
70	02-Apr-12	Holst Centre	Intermediary	OPV Group	S	1		
71	03-Apr-12	CSEM	Intermediary	Section Head Polymer Optoelectronics	S	1		
72	03-Apr-12	Welsh Centre for Printing and Coating	Intermediary	Professor	F	1		Swansea UK
73	16-Apr-12	Solvay	Material Developer	Senior Executive Vice President	F	1		Brusesels Belgium
74	16-Apr-12	Solvay	Material Developer	Technical Marketing Manager	F	1		Brussels Belgium
75	16-Apr-12	Solvay	Material Developer	Organic Electronics Manager	F	1		Brussels Belgium
76	16-Apr-12	Solvay	Material Developer	Future Businesses Investment Manager	F	1		Brussels Belgium
77	18-Apr-12	Organisation PV	Producer	Technical Development Director	S	1		
78	02-May-12	VTT	Intermediary	Key Account Manager	S	1		

79	11-May-12	Organisation PV	Producer	Technical Development Director	S		1	
80	22-May-12	Technology Consultant	Consultancy	Technology Consultant	F		1	Manchester UK
81	22-May-12	Organisation PV	Producer	Technical Development Director	S		1	
82	25-May-12	Organisation B	Material Developer	Director Printed Electronics BASF future Business	F	1		Europe
83	25-May-12	CSEM	Intermediary	Section Head Polymer Optoelectronics	F		1	Basel Switzerland
84	29-May-12	Solvay	Material Developer	Senior Vice President Group Innovation Champion	T	1		
85	11-Jun-12	Liverpool University	University	Senior Lecturer	F	1		Liverpool
86	14-Jun-12	Organisation C	Equipment Provider	Director of Projects	T	1		
87	19-Jun-12	Organisation P	Material Developer	CEO	F	1		Munich Germany
88	20-Jun-12	Chemnitz University	University	Professor	F	1		Munich Germany
89	20-Jun-12	Organisation PP	OEM	General Manager	F	1		Munich Germany
90	20-Jun-12	Printable Electronics Technology Centre	Intermediary	Director	F		1	Munich Germany
91	02-Jul-12	Organisation E	Device Developer	Chief Operating Officer	F	1		UK
92	02-Jul-12	New Display	Material and Device Developer	General Manager	F		1	UK
93	04-Jul-12	Organisation PV	Producer	Technical Development Director	S		1	

94	05-Jul-12	Organisation PH	OEM	Public Private Innovation Partnership	F	1		Europe
95	06-Jul-12	Organisation PO	Product Developer	CTO	F	1		Europe
96	11-Jul-12	TFE Ecosystem Partner 3	Component Provider	Co-Founder and Head of Business	S	1		
97	13-Jul-12	Respondent CW	Consultancy		F	1		UK
98	18-Jul-12	New Display	Material and Device Developer	CTO	F		1	UK
99	18-Jul-12	New Display	Material and Device Developer	Group Leader	F		1	UK
100	19-Jul-12	OMIC	Intermediary	Professor	F		1	Manchester UK
101	19-Jul-12	OMIC	Intermediary	Knowledge Transfer Manager	F		1	Manchester UK
102	19-Jul-12	Organisation F	Equipment Provider	CEO	T	1		
103	23-Jul-12	New Display	Material and Device Developer	Senior Scientist	T		1	
104	24-Jul-12	Organisation E	Device Developer	Chief Operating Officer	S		1	
105	30-Jul-12	Organisation M	Equipment Provider	CEO	S	1		
106	01-Aug-12	OMIC	Intermediary	Knowledge Transfer Manager	F		1	Manchester UK
107	03-Aug-12	New Display	Material and Device Developer	Director Research	S		1	
108	09-Aug-12	Solvay	Material Developer	Manager External academic relationship	T	1		
109	20-Sep-12	Organisation NL	Product Developer	Ex CEO	F	1		Manchester UK
110	19-Oct-12	Thin Film Electronics	Integrator	CEO	S		1	

111	04-Dec-12	Organisation NL	Product Developer	Ex CEO	F	1		UK
112	18-Feb-13	Thin Film Electronics	Integrator	Chief Technology Officer	F	1		Linkoping/ Sweden
113	18-Feb-13	TFE Ecosystem Partner 2	Intermediaries	Department Manager	F	1		Norrkoping Sweden
114	22-Feb-13	Organisation PT	Integrator	Chief Operating Officer	S		1	
115	01-Mar-13	Solvay	Material Developer	OPV Scientist 1	S	1		
116	15-Mar-13	Respondent MH		Respondent MH	F	1		UK
117	20-Mar-13	Thin Film Electronics	Integrator	CEO	S		1	
118	28-Mar-13	Thin Film Electronics	Integrator	EVP Sales and Business Development	S	1		
119	28-Mar-13	TFE Ecosystem Partner 1	Intermediary	VP Director of Electronic Materials and Device Lab	S	1		
120	04-Apr-13	TFE Technical Advisory Council	University	Professor	S	1		
121	16-May-13	University of Bangor	University	Professors (group discussion)	F	1		Bangor
122	24-Jul-13	Organisation PO	Component Provider	Head of Applications	S	1		
123	23-Sep-13	Organisation N	Equipment Provider	Vice President Marketing	F	1		London
124	18-Oct-13	Organisation PV	Producer	Business Development Manager	S	1		
125	25-Oct-13	Organisation PV	Producer	Technology Officer	S	1		
126	30-Oct-13	Organisation PV	Producer	Senior Director R&D	S	1		
127	19-Feb-15	Solvay	Material Developer	Senior Executive Vice President	S		1	

128	25-Feb-15	Solvay	Material Developer	OPV Scientist 2	T	1		
129	02-Mar-15	COPE	University	Director	S		1	
130	04-Mar-15	Solvay	Material Developer	Organic Electronics Manager	T		1	
131	19-Mar-15	Respondent DG			T			
132	24-Mar-15	Solvay	Material Developer	Head of Functional Nano metrial Advanced Laboratory	T	1		
133	02-Apr-15	COPE	University	Director	S		1	
Total Number of Interviews (inclusive of follow ups) conducted are 133						**108**	**25**	

Table Keys

10	Interviews informing chapter 6 (TFE)
16	Interviews informing Chapter 7 Solvay
34	Interviews informing Chapter 5 and Chapter 8
F	Face to face
S	Skype
T	Telco

Appendix 4: Participants information sheet

MANCHESTER
1824

The University of Manchester

“Internal and External Knowledge Creating Processes for Innovation”

Participant Information Sheet

You are being invited to take part in a research study. Before you decide it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully and discuss it with others if you wish. Please ask if there is anything that is not clear or if you would like more information. Take time to decide whether or not you wish to take part. Thank you for reading this.

Who will conduct the research?

Ambarin Asad Khan

Manchester Business School

University of Manchester

Booth Street West

Manchester

M15 6PB

Title of the Research

““Internal and External knowledge creating processes for innovation”

What is the aim of the research?

The research aims at identifying the configurations of routines, practices, processes and that are employed by organizations in the innovation process.

Why have I been chosen?

You have been chosen for the interview because of the valuable role played by you or the department during the development of the product as also indicated by the business unit head and therefore can provide valuable information on the process

You have been chosen to participate in the survey due to your experience of being involved in the innovation processes in your organization.

What would I be asked to do if I took part?

During an interview, you will be asked to provide details on the practices and processes that are used in the development of a particular product.

For the survey, you will be asked questions regarding the managerial practices, organization structure and competitive environment in relation to the innovation processes.

What happens to the data collected?

The data collected from interviews and survey will be used to identify best practices for innovation prevalent within organizations and how they differ among different sectors.

How is confidentiality maintained?

The data collected will be completely anonymous by never revealing the company and interviewee/ respondent's names. All possible measures will be taken to keep the identity of organizations confidential.

What happens if I do not want to take part or if I change my mind?

It is up to you to decide whether or not to take part. If you do decide to take part you will be given this information sheet to keep and be asked to sign a consent form. If you decide to take part you are still free to withdraw at any time without giving a reason and without detriment to yourself

Will I be paid for participating in the research?

There is no monetary compensation for participating in the research

What is the duration of the research?

The duration of your participation in the research will last for about 1 hour for one interview. It is possible that, in few occasions, there will be follow-up questions in the analysis phase to clarify the information gathered during the interview.

Subsequently, following the interview phase, a survey will be carried out, which will require you, or another person in your organisation identified by you, to fill in a questionnaire.

Where will the research be conducted?

The research will be conducted on the work site of interviewees and participants.

Will the outcomes of the research be published?

The outcomes of the research will be published in the final PhD thesis report.

Contact for further information

Contact: Ambarin Asad Khan

Mobile: 0044 7817513312

Email: ambarinasad.khan@postgrad.mbs.ac.uk

What if something goes wrong?

Please contact the main researcher using the information provided above.

If a participant wants to make a formal complaint about the conduct of the research they should contact the Head of the Research Office, Christie Building, University of Manchester, Oxford Road, Manchester, M13 9PL.