Exaptation and ecosystem entry: the case of 3D printing

Ahmad Beltagui[1], Ainurul Rosli[2] and Marina Candi[3,4]

[1]Operations and Information Management Dept., Aston Business School, Aston Triangle, Birmingham, B4 7ET, United Kingdom, a.beltagui@aston.ac.uk

[2]Brunel Business School, Brunel University London, Kingston Lane, Uxbridge, UB8 3PH United Kingdom, ainurul.rosli@brunel.ac.uk

[3]Center for Research on Innovation and Entrepreneurship, Reykjavik University School of Business, Mentavegur 1, 101 Reykjavik, Iceland, marina@ru.is

[4]University of Edinburgh Business School, Entrepreneurship and Innovation Group, 29 Buccleuch Place, Edinburgh, EH8 9JS, United Kingdom marina.candi@ed.ac.uk

Summary

Innovations are increasingly referred to using terms such as digital, disruptive and ecosystems. A case in point is 3D Printing, a set of manufacturing technologies that combine digital data with physical production. An ecosystem of interdependent companies has grown in support of these technologies, increasing the perceived potential to disrupt established firms and industries. Questions remain over how such ecosystems form and, particularly, how firms can enter into them. To address these questions, we examine the 3D Printing ecosystem and apply the lens of exaptation to understand the entry of firms into a newly forming ecosystem. Exaptation, a term originating from evolutionary biology, refers to the repurposing of technologies for novel functions. This research contributes to knowledge by showing that this functional shift can also be the basis for ecosystem entry. It argues that ecosystems take on a life of their own, resisting centralised control, and identifies five trajectories whereby exaptation allows firms to co-opt their existing capabilities to take a role within the new ecosystem: re-casting, re-packaging, re-integrating, re-inventing, re-designing.

Keywords: Exaptation; Ecosystem; 3D printing; Modularity; Digital Innovation

Track: Innovation

Word Count: 5245

1. Introduction

The terms *disruptive*, *digital* and *ecosystem* are often used hyperbolically to describe new innovations, but what these terms mean in practice and how to respond to them is unclear. Innovations are disruptive when they address unrecognized market needs and thus alter the competitive landscape (Christensen, 2006). They are digital when they combine Information Technology (IT) with physical and mechanical components to create complex and novel functionality (Candi and Beltagui, 2018). And innovation ecosystems describe complex, collaborative and co-operative interconnections between firms and innovations that cut across industry boundaries in unpredictable ways (Moore, 1993; Iansiti and Levien, 2004; Adner, 2017). An ecosystem's behavior results from aggregation of actions at lower levels and a concomitant resistance to top-down control, which makes it appear to take on a life of its own (Simon, 1996). The resulting conditions challenge how traditional industry structures and patterns of innovation are understood (Moore, 1996). For example, automotive producers face disruption from IT firms that use digital technologies and combine resources of other firms to develop autonomous vehicles. These IT firms co-opt technologies for new purposes, for example, the global positioning system that was developed for weapons guidance gained commercial use in consumer smart phones, generating geographic data that can now be used to guide autonomous vehicles. Such shifts in the functions of technologies are referred to as *exaptation*, a promising lens through which to understand the birth and growth of innovation ecosystems and disruption (Mokyr, 2000, 2002).

Exaptation is a term used by evolutionary biologists to describe features that are co-opted for alternative functions than those they have evolved to fill (Gould and Vrba, 1982). For example, feathers that evolved for temperature regulation later found a new function when their owners evolved the ability to fly. A similar process is evident in the repurposing of pharmaceuticals when unexpected side effects lead to a new market opportunity (Mastrogiorgio and Gilsing, 2016). Exaptation, therefore, offers a route to innovation by allowing a product or a component to be co-opted for a new function, potentially disrupting firms whose offerings satisfy that function (Garud et al., 2016). This may come about through serendipitous discovery (Garud et al., 2018), for example, when a module of a radar system was discovered to generate sufficient heat to cook food (Andriani and Carignani, 2014). Ecosystems, another concept originating in biology, are systems consisting of niches filled by plants or animals fulfilling particular functions such as those of predator and prey (Moore, 1993). Similarly, innovation ecosystems consist of businesses that act as customers or suppliers and seek to dominate or collaborate using their unique capabilities (Iansiti and Levien, 2004). For example, the personal computer (PC) ecosystem encompasses a web of hardware, software, consumer electronics and information suppliers (Moore, 1996; Autio and Thomas, 2014). Ecosystem leaders may create platforms for other firms to fill a niche, for example when Google, eBay or Amazon share resources to create a marketplace for products and software (Nambisan and Baron, 2013; Gawer and Cusumano, 2014). Or they may seek to capture value from ecosystem members and avoid competition and disruption from new entrants. Digital technologies can both disrupt and sustain ecosystem members. For example, the rise of digital cameras strengthened the position of lens producers while endangering film camera producers (Ho and Lee, 2015). Literature on disruption tends to focus on established ecosystems, such as the disruptive potential of successive generations of semiconductor technology within an established ecosystem (Adner and Kapoor, 2016). Although exaptation may create uncharted markets that grow into ecosystems, little is known about how exaptation influences ecosystem entry/exit and (Bonifati, 2010; Ching, 2016). To examine these gaps in knowledge, this research investigates the role of exaptation in the ecosystem forming around a digital innovation, focusing on the entry trajectories of ecosystem members.

The research setting is the ecosystem that has formed around three-dimensional printing (3DP), a set of additive manufacturing technologies that use computer control to create physical models directly from digital design models (Petrovic et al., 2011; Weller et al., 2015; Candi and Beltagui, 2018). The combination of hardware such as printers and components, software such as design tools, advanced materials such as liquid polymers and metal powders, and services such as direct manufacturing, leads to the recognition that 3DP is not a single technology but in fact forms the core of a digital innovation ecosystem (Piller et al., 2015). The origins of this ecosystem can be traced to the patents, granted in 1986 and 1992, respectively, to the current ecosystem leaders, 3D Systems and Stratasys. In recent years, the growth of this ecosystem has been rapid, capturing the public imagination amid claims of a new industrial revolution (Barnatt, 2016; Rüßmann et al., 2015) and incentivising a broad range of entrants. Debate centres on whether 3DP is currently, or could shortly become, disruptive to incumbents in established sectors, e.g. the rapid adoption of 3DP by major hearing aid producers and the subsequent impact on market position is discussed by D'Aveni (2015) and by Sandström (2016). The latter explains that, while 3DP has entered the hearing aid ecosystem, it has not altered the competitive landscape. This research focuses on the entry mechanism, specifically, how firms have entered the 3DP ecosystem, where they have come from and which ecosystem roles they take. Given the impossibility of defining ecosystem boundaries, a 3DP trade exhibition is used as a self-selected sample of ecosystem members. We uncover the exaptive trajectories that have allowed exhibiting firms to enter into the ecosystem.

2. Literature review

2.1 Exaptation

The term *exaptation* was proposed by evolutionary biologists as an alternative to *adaptation* (Gould and Vrba, 1982). Whereas the latter refer to features that develop for a specific function, such as larger lungs among Andean mountain people, exaptation refers to features that are later found to be useful for unintended functions (Mastrogiorgio and Gilsing, 2016). Innovation examples include the repurposing of specialist glass production technology for producing optical fibers (Cattani, 2005), compact discs, an audio recording technology, for data storage (Dew, 2007) and laser technologies for applications from barcode scanners to surgery (Bonifati, 2010). In each of these examples, there is a possibility to disrupt the incumbents and the technologies previously used for these applications. To the best of our knowledge, however, the interactions between ecosystems and exaptation have not been taken into account in the exaptation literature.

In the innovation literature, exaptation has been classified according to the level of effort required to convert from the original to a new function. This involves search processes across various ecosystem boundaries (Katila and Ahuja, 2002) where firms try to understand links with potential customers and social processes by which new functions are discovered (Bonifati, 2010). The interaction between an artefact and a context, often without a specific objective, may allow alternative functions and hence innovations to emerge. Following Baldwin and Clark's (2000) approach to decomposing artefacts into modules, Andriani and Carignani (2014) define exaptations according to whether the change of function is in a module (*internal exaptation*), the whole artefact (*external exaptation*) or both (*radical exaptation*). External exaptations may require little or no modification to occupy a new niche in a different ecosystem, whereas radical exaptations need substantial effort to build a new system architecture around a module. For example the tuberculosis drug Marsilid was marketed as an antidepressant when this unexpected side-effect was found, whereas the magnetron took years of development to go from a radar component to the core of the microwave oven (Andriani and Carignani, 2014). The literature thus far says little regarding the potential of these functional shifts to enable ecosystem entry.

2.2 Innovation ecosystems

Ecosystems are complex adaptive systems (Choi et al., 2001) characterized by interplay among actors and those of the whole system across indeterminate boundaries. They are often defined by a focal firm or platform and incorporate both value creation and appropriation mechanisms (Autio and Thomas, 2014). As the relationships among firms and their business partners have become richer, deeper and more crucial for business success, they have become more complex. This, in turn, requires alignment among a multilateral set of partners (Adner, 2017) and can influence firm evolution (Hannan and Freeman, 1977).

Along with other members of an ecosystem, who fill specific niches, ecosystem leaders play an important coordinating role. So called keystones help to create opportunities for others (Iansiti and Levien, 2004; Gawer and Cusumano, 2014) and profit, by providing goods and services while contributing to the overall health and diversity of the ecosystem (Nambisan, 2017). Other firms occupy a particular niche, satisfying both their own and the ecosystem's objectives (Nambisan and Baron, 2013; Dedehayir et al., 2016). As with biological ecosystems, these niches may be occupied by new entrants into an ecosystem, whose specialized capabilities and features may be co-opted for alternative functions. For example, studies of biotechnology firms reveal a range of entry trajectories based on how firms use their capabilities, which market opportunities they focus on and how they interact with other firms (Mangematin et al., 2003). Firms therefore follow different trajectories to enter an ecosystem according to their own strategic paths (Lee and Malerba, 2017). Those best suited to maintaining a niche may be those that are able to diversify and adapt their capabilities to different functions as ecosystems evolve, since they will have prior experience of adapting to different markets (Murmann and Frenken, 2006; Chen et al., 2012). Ecosystems that facilitate ease of entry allow competition and the possibility of disruption, so that firms survive by facing disruption and adapting to the continual threat of new entrants (Moore, 1996; Ansari and Krop, 2012). In contrast to the firm-centric view, an ecosystem perspective recognises that a variety of trajectories into an ecosystem are possible and that the positioning of actors, links and flows can shift. To understand this dynamic behaviour requires understanding complexity in the system, which has a modular composition and enables internal competition.

2.3 Modularity and ecosystem competition

Most radical innovations or new technologies follow a similar evolutionary pattern. As the technology matures, the supporting systems around it grow and create fertile ground for disruptions (Iansiti and Levien, 2004) and, thus, an ecosystem is born. Any artefact may be decomposed into a modular structure, with *integral innovation* focused on designing the artefact and *modular innovation* on improving constituent parts (Baldwin and Clark, 2000). The innovator initially focuses on integral innovation, building the entire architecture rather than specific modules. Initial success creates a platform for other firms to create both competing and complementary innovations (Gawer and Cusumano, 2014). When the complexity of the artefact becomes too great for a single firm to manage, others may focus on modular innovations. Specialized firms enter into specific stages of production and less specialized firms, unable to achieve economies of scale, exit (Kapoor, 2013). As the various elements of this growing ecosystem evolve, they become strongly functionally interdependent in a manner that makes customer demand dependent on the entire system, with little demand for components in isolation (Gawer and Henderson, 2007). In this way, product modularization is typically accompanied by disaggregation as specializations are accommodated. An exception that proves the rule is the integration of previously modularized bicycle drive trains by Shimano (Fixson and Park, 2008).

2.4 3D Printing

Two potential benefits have been identified in industrial and consumer contexts. In the first place, current industrial usage in industries such as aerospace, characterized by low volumes and high complexity, is positioned to benefit from lower costs, which can enable expansion. Processes such as Laser Selective Sintering (SLS), which use high power lasers to fuse metal powders into previously impossible shapes allow complete design freedom, reducing assembly, improving performance and reducing both weight and wasted material. The possibility for decentralization reduces the need for spare parts inventory and can thus improve responsiveness (Khajavi et al 2014). In the second place, 3DP is increasingly being adopted by consumers who value customized, co-created, experiential products (Vargo and Lusch, 2008) and are happy to invest effort to make their own. The expiry of patents such as the 1986 stereolithography patent and the introduction of low cost Fused Deposition Modelling (FDM), whereby spools of plastic filament can be melted and deposited in layers, has brought the price for entry level equipment below $1000. This, coupled with the rapid growth of open source communities such as the RepRap project (Raasch et al 2009) makes manufacturing in the home a realistic possibility. Websites exist for sharing digital design files (e.g. thingiverse.com) as well as the hardware to produce them, meaning that consumers can print almost anything, instead of buying mass-produced products off the shelf.

2.5 Research framework

The research investigates the question of how exaptation relates to entry of firms into a digital innovation ecosystem. To address this question, we build a conceptual framework around on one hand, the modular structure of complex systems (Baldwin and Clark, 2000), which helps identify different ecosystem roles (Dedehayir et al., 2016), and on the other hand, types of modular exaptation (Andriani and Carignani, 2014), which relate to innovative dynamics.

Inspired by Adner's (2017) concept of ecosystem as structure, we define three layers,, which form the first dimension in our theoretical framework. The first class of players in an ecosystem are integral innovators, i.e. the firms introducing core technology systems and defining the system architecture (Henderson and Clark, 1990), thereby taking a central role in the ecosystem. The second layer consists of modular innovators, for example producers of key components. The final layer consists of supporting innovators, such as content providers or firms that offer other complementary goods and services. These may not be unique to a given ecosystem, but help to attain network effects that support adoption of innovations.

Considering the relationship between exaptation and ecosystems, change to the function of an artefact is either associated with a change to internal module function (*radical exaptation*) or a more straightforward repositioning without much restructuring (*external exaptation*). These two categories comprise the second dimension of our theoretical framework. Taking the firm as the unit of analysis, exaptation may also entail a change of role within the system. Hence, we expand Andriani and Carignani's (2014) concept of modular exaptation to encompass a firm's capabilities and its ecosystem role. A core technology has potential value, but this value cannot be realized without necessary product architectures and modules, nor without the support of content generators, complementary products and a relevant regulatory framework.

3. Research Methods

3.1 Research Setting

We examine the three-dimensional printing (3DP) ecosystem. Studying the 3DP ecosystem at the present time makes sense for several reasons. Firstly, the origins and growth are clearly identified, from the first patent for stereolithography (STL), granted in 1986. Secondly, the expiry of these patents has enabled entry through exaptation. The co-existence of vastly different processes, applications and technologies within a single identifiable ecosystem provides a unique opportunity for investigation. Thirdly, while initial growth was slow, there has been rapid growth in recent years, partly attributable to the entry of new actors into the ecosystem. Global revenues for industrial 3D printers alone have grown from around $1bn in 2012 to almost $2.5bn in 2015, while growth in service revenues was 25% and 39% annually from 2010 to 2015 (Wohlers, 2016). Finally, 3DP combines mechanical, chemical and information technologies in a truly diverse ecosystem that facilitates entry from a variety of sources, helping to provide numerous examples of exaptation for study.

3.2 Case method

To understand this growth, multiple cases of entrants into the burgeoning ecosystem were examined. Multiple case studies are regarded as a useful way to build theory (Eisenhardt, 1989) and recent studies have used a narrative approach to implement such multiple case studies. For example, Franzoni and Sauermann (2014) use examples of online projects to contribute an understanding of crowd science and its role in innovation. They build an understanding of each crowd science project by constructing narratives using secondary data. Meanwhile Keupp et al. (2012) use narratives of foreign firms patenting in emerging economies and develop generalizable archetypes. Indeed, there have been calls for the use of archetypes and typologies to delineate such generalizable patterns among firms (Delbridge and Fiss, 2013; Snow and Ketchen, 2014). In response to these calls, the present research uses the framework outlined above as the basis for identifying archetypes describing the exaptive trajectories of ecosystem entrants. A comparative approach is used, whereby firms are categorized and examined as complete cases, rather than a set of variables (Ragin, 2014). The narrative approach helps us to understand the histories of each firm and to develop insights to explain their exaptation strategies.

3.3 Data sources and analysis

Sampling in an ecosystem is challenging because the complexity of interrelationships and cross-industry interactions make boundaries nearly impossible to define (Moore, 1996; Autio and Thomas, 2014). To overcome this challenge, a 3DP trade exhibition was identified, in which all participating firms can be considered to identify as part of the ecosystem. Having invested time and resources to exhibit their products or services at the exhibition, these firms recognize a market related to 3DP. Such firms include producers of 3D printers (i.e. integral innovators), producers and suppliers of materials, software and components such as electronics (i.e. modular innovators) and other complementary products or services, in some cases only very loosely related to 3DP, such as design and prototyping services that use 3DP, as well as services that support 3DP use, such as intellectual property lawyers or part finishing services (i.e. supporting innovators).

The TCT (originally Time Compression Technologies) trade exhibition has been held in the UK for over a decade and has steadily grown in size as the ecosystem has grown. It includes a broad range of participants, ranging from large, multinational firms to small local firms. It also includes firms from a variety of backgrounds and offering a wide range of products and services, in line with the diversity of the growing 3DP ecosystem. In total, 104 firms that met the criterion of exaptive entry were selected for analysis. Of interest for the purpose of this study were those firms that have entered into the ecosystem from outside. Therefore, start-ups formed within the ecosystem were excluded from the sample examined.

The sample, as shown in Table 1, has an over-representation of local firms, with 54 of the 104 being UK-based, meaning that this sample captures a localized ecosystem. However, the representation of other nations—particularly the US—demonstrates the global overlap. Almost half (49) of the firms in the sample were founded before the first 3DP patent in 1986. For these firms in particular, capabilities have been leveraged and updated over time in order to respond to the opportunities identified in 3DP. The diversity of starting capabilities highlights the diversity of opportunities in this kind of digital innovation ecosystem.

Insert Table 1 here

Each of the three authors attended the exhibition on at least one occasion, with the first author attending in three successive years (2015, 2016, 2017). This helped us to understand the firms and their products. Additionally, a set of questions was prepared in order to gain insights from the exhibitors. The questions focused on capabilities (e.g. “what does your company do?”), exaptation (e.g. “how did your company get into 3DP?”) and the ecosystem (e.g. “who do you collaborate with?”). These structured conversations contributed to an understanding of secondary data collected through online sources. We developed a database of the companies, capturing key details and including evidence in the form of quotations. We used company websites to establish general information and decide on inclusion in the sample. Next we examined profiles on LinkedIn and other social media sites, to help establish details on company history. Then we examined third-party sources, including news reports, industry publications and official records for triangulation and to complete our understanding of the firms’ trajectories. Coding was conducted systematically within the database. To maintain the reliability of the analyses, two of the authors actively developed the database, discussing their interpretations and supporting selections based on quotations used as evidence. The third author was able to act as an outsider (Evered and Louis, 1981), reviewing the results from a critical perspective.

Firms were categorized according to the theoretical framework. The numbers of firms falling in each category are shown in Table 2. The category of integral innovation/external exaptation is not feasible, since it means entering into a central role in the ecosystem (e.g. producing 3D printers) without modifying capabilities (i.e. having previously been a producer of 3D printers)—so without exaptation. This also highlights why it did not make sense to include start-ups in our sample, since a change of ecosystem and change of function cannot be clearly seen. The other notable feature of this table is that around two-thirds of firms fall under the external exaptation dimension. This is most likely because this dimension implies little or no modification to capabilities; such firms find demand for their existing offerings within the 3DP ecosystem, without having to go through the niche construction phase inherent in radical exaptation (Andriani and Carignani, 2014).

Insert Table 2 here

5. Findings

The 3DP ecosystem offers many opportunities for new entrants to offer specialised products and services and in doing so, helping to increase the size and diversity of the ecosystem they enter. As shown in Table 3, five archetypes were identified, which illustrate the trajectories that these entrants take into the ecosystem.

Insert Table 3 here

Re-Integration refers to firms that have leveraged their existing capabilities to position themselves centrally, by building 3D printers. Their ability to do so is supported by openness, both in terms of expired patents leaving scope for innovation and in the willingness of individuals to share designs that can help others to create products. In common with open-source software ecosystems, communities collaborate in designing products, including desktop 3D printers. The ease with which companies have been able to enter the 3DP ecosystem as Re-Integrators is rapidly leading to the commoditization of desktop 3D printers and possible saturation within the hobbyist market. This is evidenced by companies such as 3D Systems and Autodesk discontinuing their desktop printers in recent years. The openness that is evident in the realm of polymer based 3DP is not as prevalent in metal 3DP, where technology is closely guarded and quality tightly controlled. While it is indeed possible for new entrants to use their capabilities to develop 3D printers, this is where competition is greatest, either due to price or technical requirements.

Companies from diverse industries exploit new opportunities in the modular innovation layer of the 3DP ecosystem. *Re-Casters* have found ways for their existing products to serve a new purpose in the 3DP ecosystem, essentially re-casting the role of these products. Material producers have found ready niches in the 3DP ecosystem by leveraging effective research, manufacturing and quality control to offer polymer and metal products. *Re-Inventors*, on the other hand, spot opportunities to adapt their products or create new ones. For example, identifying synergies between musical instrument strings and filaments used for desktop 3DP demonstrates how capabilities are re-invented to create new narratives. Several firms have re-invented themselves over a long history, for example, what began as mining companies in Sweden and the Netherlands in the 19th century have become R&D focused producers of raw materials, which see the 3DP ecosystem as a new market opportunity.

In the supporting layer, many of the offerings that support other industries enjoy demand in the 3DP ecosystem. These include industrial processes such as finishing, testing and cleaning as well as legal and other professional services. Additionally, products such as measurement and 3D scanning tools require no adaptation, but are in demand because 3DP increases their value. We label firms that identify such opportunities as *Re-Packagers*. For these firms, 3DP users may represent a small market, but rewards may ensue from being the first to enter a new growing ecosystem. For example, BOC a chemical company that produces inert gases, works with its customers including 3D printer manufacturers, helping it to find a new market. Finally, we identify those firms that build new offerings to support the 3DP ecosystem. We label this trajectory *Re-Designing*, partly because one of the main offerings we observe among firms belonging to this archetype is the use of 3DP to design and make products. Not only 3D printer manufacturers, but casting houses, design consultancies, material producers and almost any firm with engineering capacity seems able to contribute in this area.

6. Discussion

This research responds to calls for a closer empirical examination of exaptation (Garud et al, 2016) and a lack of knowledge on ecosystem dynamics (Autio et al., 2018), by examining the 3D Printing ecosystem. It reveals the use of exaptation in support of firms' ecosystem entry, contributing to knowledge in several ways.

Firstly, it highlights the emergent nature of ecosystems and illustrates how this characteristic makes ecosystems resistant to control. This idea contrasts with the research emphasis on the role of ecosystem leaders in supporting or dominating their ecosystems (Iansiti and Levien, 2004). Just as complexity in natural systems leads to self-organization or "design without a Designer" (Simon, 1996, pg.34), it should be no surprise that an innovation ecosystem can develop a life of its own, beyond the control of the firms within it (Hannan and Freeman, 1984).

Secondly, it demonstrates how innovations and ecosystem entry are often due to serendipity, as opposed to deliberate strategic effort (Garud et al., 2018). We find evidence of firms stumbling upon opportunities to repurpose their existing technologies and capabilities by creating 3DP related products or services. Crucially, we see this as a means of entry into the 3DP ecosystem, which consequently leads to competition within the system. For example, initial partnerships may lead a supplier to identify a potential opportunity, whereby they compete with their customers.

Thirdly, the research draws on Andriani and Carignani's (2014) modular exaptation model to develop a framework of five archetypal entry trajectories: re-casting, re-packaging, re-integrating, re-inventing and re-designing (see Table 3). These archetypes of exaptation are based on the distinction between external exaptation and radical exaptation (Andriani and Carignani, 2014). The former implies that an artefact changes function with little or no modification to the internal, modular design. As shown in Table 3, firms may see the growing ecosystem as a new market opportunity for components that are generally useful, allowing them to occupy a niche that may be different from their traditional one (e.g OEM in computer ecosystem acts as supplier in 3DP ecosystem). In contrast, radical exaptation demands often considerable efforts at niche construction, whereby the module and artefact are both redeveloped in order to build on capabilities to occupy a niche (e.g. developer of design software may become producer of 3D printers). The opportunities identified by these firms contribute to a growing, healthy and diverse ecosystem. Their entry, however, creates threats to the incumbent members of the ecosystem.

As observed in prior studies, industries tend to evolve away from vertical integration as technology development moves from the architecture to more specialized, modular and potentially incremental innovations (Fixson and Park, 2008). The threat of disruption potentially increases when the importance of modules becomes more important (Ho and Lee, 2015), so perhaps the efforts to vertically integrate through mergers and acquisitions may help in avoiding a fate similar to IBM, which ceded control of its ecosystem when suppliers such as Microsoft and Intel became more important (Moore, 1993; Fine, 1998).

7 Implications for Practice

The rise in the digitally connected and smart products has an impact on new technologies as it will in turn make them more closely connected parts of complex technology ecosystems. Ecosystem leaders play a vital role in the ecosystem development by creating platforms for smaller firms, as highlighted in this research. The diversity of small firms that involve in re-casting, re-packaging, re-integrating, re-inventing and re-designing their products and services resulting diversity, and an indicator of a healthy ecosystem. It acts as a source of growth as small firms find niches in the ecosystem, and also a source of potential threat for larger firms (Moore, 1993; Fine, 1998).

Our findings provide some suggestions to help managers to take action. Firstly, managers need to be aware that they might be able to reframe their firm's capabilities to create new narratives that can provide limitless possibilities of new ecosystem entry for growth potential. Although firms entering into a new ecosystem may have a less central role, there is a need for firms to balance the objectives of the ecosystem with their own (Nambisan and Baron, 2013; Autio et al., 2018), and to be aware of their role within the new ecosystem they are entering.

Secondly, managers must take a broad perspective in recognising the sources of threats, which come from both 'big fish' and 'little fish'. By cultivating the ecosystem, either through attempts to dominate or support others, they create more attractive propositions for larger firms from outside of the ecosystem. The complexity of ecosystems creates opportunities and threats from an almost infinite number of sources. The first step, however, is to consider that these challenges come from outside of the current market or industry (Moore, 1996) and that the digital nature of future technologies only widens the scope of ecosystems and sources of disruption, and make each firms to have a slice of a bigger pie.

For firms in a variety of companies, 3DP presents opportunities and potential challenges. The implication of viewing 3DP as an ecosystem is that these opportunities and challenges are much broader than may be expected. Service extensions allow some companies to reach new markets without need for substantial innovations. For example, companies that produce materials and software may simply market their offerings towards 3DP customers. For many other firms, however, capabilities in manufacturing, distribution, software development, materials and most importantly product design can be leveraged to create innovations that lead to the 3DP ecosystem. Therefore, managers should think carefully about whether 3DP is a threat or an opportunity, even if it seems completely unconnected. Threats arise where 3DP offers alternative manufacturing opportunities that reduce the size of the market for traditional processes. Meanwhile the openness of technology in the desktop, polymer processing 3DP area offers many opportunities. Indeed the number of competitors leads to questions about sustainability and profitability, but entrants into this space that are able to offer advantages based on leveraging their current capabilities stand to gain.

References

Adner, R. 2017. Ecosystem as structure: An actionable construct for strategy. *Journal of Management*, *43*(1), 39-58.

Adner, R., Kapoor, R. 2016. Innovation ecosystems and the pace of substitution: Re-examining technology S-curves. *Strategic Management Journal*, 37(4), 625–648.

Andriani, P., Carignani, G., 2014. Modular exaptation: a missing link in the synthesis of artificial form. *Research Policy,* 43(9), 1608-1620.

Ansari, S., Krop, P. 2012. Incumbent performance in the face of a radical innovation: Towards a framework for incumbent challenger dynamics. Research Policy, 41(8), 1357–1374.

Ansari, S. S., Garud, R., Kumaraswamy, A. 2016. The disruptor's dilemma: TiVo and the U.S. television ecosystem. *Strategic Management Journal*, 37(9), 1829–1853.

Autio E, Thomas, L.D.W. 2014. Innovation Ecosystems, in Dodgson,M., Gann, D.M., Phillips, N. (eds) T*he Oxford handbook of innovation management*, pp.204-228, Oxford University Press: Oxford.

Autio, E., Nambisan, S., Thomas L.D.W, Wright, M. 2018. Digital affordances, spatial affordances, and the genesis of entrepreneurial ecosystems, Strategic Entrepreneurship Journal, 12, 72-95.

Baldwin, C.Y., Clark, K.B. 2000. *Design rules: The power of modularity* (Vol. 1). MIT press: Cambridge, MA.

Bandyopadhyay, A., Gualtieri, T. P., & Bose, S. 2015. Global Engineering and Additive Manufacturing. In Bandyopadhay,A. and Bose,S. (Eds.), *Additive Manufacturing*. CRC Press: Boca Raton, FL.

Barnatt, C. 2016. *3D-Printing*, 3rd edition, CreateSpace: Charleston, SC.

Bonifati, G. 2010. 'More is different', exaptation and uncertainty: three foundational concepts for a complexity theory of innovation. *Economics of Innovation and New Technology*, *19*(8), 743-760.

Candi, M, Beltagui, A 2018. Effective use of 3D printing in the innovation process" *Technovation,* DOI:10.1016/j.technovation.2018.05.002

Cattani, G., 2005. Preadaptation, firm heterogeneity, and technological performance: a study on the evolution of fiber optics, 1970–1995. *Organization Science*, 16(6), 563-580.

Ching, K. 2016. Exaptation dynamics and entrepreneurial performance: evidence from the Internet video industry. *Industrial and Corporate Change*, *25*(1), 181-198.

Choi, T. Y., Dooley, K. J., Rungtusanatham, M. 2001. Supply networks and complex adaptive systems: Control versus emergence. Journal of Operations Management, 19(3), 351–366.

Christensen, C. M. 1997. *Innovator's Dilemma: When new technologies cause great firms to fail*. Harvard Business School Press, Boston, MA.

Christensen, C. M. 2006. The ongoing process of building a theory of disruption. *Journal of Product Innovation Management*, 23(1), 39–55.D'Aveni, 2015

D'Aveni, R. 2015. The 3-D Printing Revolution. *Harvard Business Review*, 93(3), 41–48.

Dedehayir, O., Mäkinen, S.J., Ortt, J.R. 2016. Roles during innovation ecosystem genesis: a literature review. *Technological Forecasting and Social Change*. DOI:10.1016/j.techfore.2016.11.028

Delbridge, R., Fiss, P.C. 2013. Styles of theorizing and the social organization of knowledge, *Academy of Management Review,* 38 (3), 325-331.

Dew, N. 2007. Pre-adaptation, exaptation and technology speciation: a comment on Cattani (2006). *Industrial and Corporate Change*, *16*(1), 155-160.

Dew, N., Sarasvathy, S.D. 2016. Exaptation and niche construction: behavioral insights for an evolutionary theory. *Industrial and Corporate Change*, *25*(1), 167-179.

Evered, R., Louis, M.R., 1981. Alternative perspectives in the organizational sciences: “inquiry from the inside” and “inquiry from the outside”. *Academy of Management Review*, 6(3), 385-395.

Fine, C.H. (1998) *Clockspeed: winning industry control in the age of temporary advantage*. Perseus Books, Reading, MA.

Fixson, S. K., Park, J. K. 2008. The power of integrality: Linkages between product architecture, innovation, and industry structure. *Research Policy*, 37(8), 1296–1316.

Franzoni, C., Sauermann, H., 2014. Crowd science: The organization of scientific research in open collaborative projects. *Research Policy*, 43(1), 1-20.

Garud, R., Gehman, J. and Giuliani, A.P., 2016. Technological exaptation: a narrative approach. *Industrial and Corporate Change*, 25(1), 149-166.

Garud, R., Gehman, J. and Giuliani, A.P. 2018. Serendipity arrangements for exapting science-based innovations. *Academy of Management Perspectives*, *32*(1), 125-140.

Gawer, A., Cusumano, M. A. 2014. Industry platforms and ecosystem innovation. *Journal of Product Innovation Management*, 31(3), 417–433.

Gawer, A., Henderson, R. 2007. Platform owner entry and innovation in complementary markets: Evidence from Intel. *Journal of Economics and Management Strategy*, 16(1), 1–34.

Gould, S.J., Vrba, E.S. 1982. Exaptation—a missing term in the science of form. *Paleobiology*, *8*(1), 4-15.

Hannan, M.T., Freeman, J. 1977. The population ecology of organizations. *American Journal of Sociology*, 82(5), 929-964.

Hannan, M.T., Freeman, J., 1984. Structural inertia and organizational change. *American Sociological Review*, 49(2), 149-164.

Henderson, R. M., Clark, K. B. 1990. Architectural innovation: The reconfiguration of existing product technologies and the failure of established firms. *Administrative Science Quarterly*, 35, 9–31.

Ho, J. C., Lee, C.-S. 2015. A typology of technological change: Technological paradigm theory with validation and generalization from case studies. *Technological Forecasting and Social Change*, 97, 128–139.

Iansiti, M., Levien, R. 2004, March. Strategy as Ecology. *Harvard Business Review.*, 82(3), 68-81.

Jick, T.D. 1979. Mixing qualitative and quantitative methods: Triangulation in action. *Administrative science quarterly*, *24*(4),602-611.

Kapoor, R., 2013. Persistence of integration in the face of specialization: How firms navigated the winds of disintegration and shaped the architecture of the semiconductor industry. *Organization Science*, *24*(4), 1195-1213.

Keller, A., Hüsig, S. 2009. Ex ante identification of disruptive innovations in the software industry applied to web applications: The case of Microsoft’s vs. Google’s office applications. *Technological Forecasting and Social Change*, 76(8), 1044–1054.

Keupp, M.M., Friesike, S., von Zedtwitz, M., 2012. How do foreign firms patent in emerging economies with weak appropriability regimes? Archetypes and motives. *Research Policy*, 41(8), 1422-1439.

Katila, R., Ahuja, G. 2002. Something old, something new: A longitudinal study of search behavior and new product introduction. *Academy of Management Journal*, *45*(6), 1183-1194.

Lane, D.A. 2011. Complexity and innovation dynamics

Lee, K., Malerba, F. 2017. Catch-up cycles and changes in industrial leadership: Windows of opportunity and responses of firms and countries in the evolution of sectoral systems. *Research Policy*, 46(2), 338-351.

Levin S.A. 1998. Ecosystems and the biosphere as Complex Adaptive Systems. *Ecosystems*, 1, 431-436.

Li, J.F., Garnsey, E. 2014. Policy-driven ecosystems for new vaccine development. Technovation, 34(12), 762-772.

Lucas, H. C., Goh, J. M. 2009. Disruptive technology: How Kodak missed the digital photography revolution. *Journal of Strategic Information Systems*, 18(1), 46–55.

Mangematin, V., Lemari, S., Boissin, J. P., Catherine, D., Corolleur, F., Coronini, R., Trommetter, M. 2003. Development of SMEs and heterogeneity of trajectories: The case of biotechnology in France. *Research Policy*, 32(4): 621–638.

Mastrogiorgio, M., Gilsing, V., 2016. Innovation through exaptation and its determinants: The role of technological complexity, analogy making & patent scope. *Research Policy*, 45(7), 1419-1435.

Mokyr, J., 2000. Evolutionary Phenomena in technological change. In J. Ziman (ed.), Technological innovation as an evolutionary process. Cambridge University Press: Cambridge.

Mokyr, J., 2002. The gifts of Athena: Historical origins of the knowledge economy, Princeton University Press: Princeton, NJ.

Moore, J.F. 1993. Predators and prey: a new ecology of competition. *Harvard Business Review*, *71*(3), 75-86.

Moore, J.F. 1996.*The death of competition: leadership and strategy in the age of business ecosystems*. Harper Business: New York,NY.

Murmann, J.P., Frenken, K., 2006. Toward a systematic framework for research on dominant designs, technological innovations, and industrial change. *Research Policy*, 35(7), 925-952.

Müller, A, Karevska, S. 2016. How will 3D printing make your company the strongest link in the value chain? Ernst and Young, Mannheim, Germany.

Nambisan, S., Baron, R.A., 2013. Entrepreneurship in innovation ecosystems: entrepreneurs' self-regulatory processes and their implications for new venture success. *Entrepreneurship Theory and Practice*, 37(5), 1071-1097.

Nambisan, S. 2017. Digital entrepreneurship: Toward a digital technology perspective of entrepreneurship, Entrepreneurship Theory and Practice, 41(6), 1029-1055.

Oh, D.S., Phillips, F., Park, S., Lee, E. 2016. Innovation ecosystems: A critical examination. *Technovation*, *54*, 1-6.

Parry, M. E., Kawakami, T. 2016. The Encroachment Speed of Potentially Disruptive Innovations with Indirect Network Externalities: The Case of E-Readers. *Journal of Product Innovation Management*, 34(2): 141-158.

Petrovic, V., Vicente Haro Gonzalez, J., Jorda Ferrando, O., Delgado Gordillo, J., Ramon Blasco Puchades, J., Portoles Grinan, L. 2011. Additive layered manufacturing: sectors of industrial application shown through case studies. *International Journal of Production Research*, 49(4), 1061-1079.

Piller, F. T., Weller, C., Kleer, R. 2015. Business Models with Additive Business Models with Additive Manufacturing—Opportunities and Challenges from the Perspective of Economics and Management. Advances in Production Technology: 39–48.

Ragin, C.C., 2014. *The comparative method: Moving beyond qualitative and quantitative strategies*. Univ of California Press, Oakland, CA.

Rüßmann, M., Lorenz, M., Gerbert, P., Waldner, M., Justus, J, Engel, P. Harnisch, M. 2015. Industry 4.0 The future of productivity and growth in manufacturing industries, Boston Consulting Group: Munich.

Sandström, C. G. 2016. The non-disruptive emergence of an ecosystem for 3D Printing - Insights from the hearing aid industry's transition 1989-2008. *Technological Forecasting and Social Change*, 102, 160–168.

Simon, H.A. 1996. *The sciences of the artificial*, 2nd ed., MIT Press: Cambridge, MA.

Snihur, Y., Thomas, L.D., Burgelman, R.A. 2018. An ecosystem-level process model of business model disruption: The disruptor's gambit. *Journal of Management Studies*. DOI:10.1111/joms.12343

Snow, C.C., Ketchen, D.J., 2014. Typology-driven theorizing: A response to Delbridge and Fiss. *Academy of Management Review*, 39(2), 231-233.

Teece, D.J. 2010. Business models, business strategy and innovation. *Long Range Planning*, *43*(2-3), 172-194.

Weller, C., Kleer, R., Piller, F.T. 2015. Economic implications of 3D printing: Market structure models in light of additive manufacturing revisited. *International Journal of Production Economics*, 164, 43-56.

West, J., Kuk, G. 2016. The complementarity of openness: How MakerBot leveraged Thingiverse in 3D printing. *Technological Forecasting and Social Change*, 102, 169–181.

Wohlers. 2016. *Wohlers Report 2016 - 3D Printing and Additive Manufacturing State of the Industry Annual Worldwide Progress Report*, Wohlers Associates Inc.: Fort Collins, CO.

Wozniak, S., Smith, G. 2006. *iWoz: from computer geek to cult icon: how I invented the personal computer, co-founded Apple, and had fun doing it*, W.W.Norton and Co.: New York, NY.

Table 1 — Descriptive statistics for firms in sample.

1a - Firms by country		
UK	54	51.9%
USA	17	16.3%
China	8	7.7%
Germany	7	6.7%
Japan	4	3.8%
Netherlands	3	2.9%
Denmark	2	1.9%
Italy	2	1.9%
Spain	2	1.9%
Canada	2	1.9%
Others	3	2.9%
Total	104	100%

1b - Firms by founded date		
Before 1900	4	3.8%
1900-1949	13	12.5%
1950-1979	18	17.3%
1980-1999	42	40.4%
2000-2009	19	18.3%
2010	3	2.9%
2011	1	1.0%
2012	1	1.0%
2013	2	1.9%
2014	1	1.0%
Total	104	100%

1c - Firms by main capabilities		
Manufacturing	21	20.2%
Design/Product Development	13	12.5%
Other Industrial Services	12	11.5%
Electronics	10	9.6%
Design and Manufacturing	9	8.7%
Distribution	9	8.7%
Polymers	8	7.7%
Lasers	7	6.7%
Software (CAD/CAM)	7	6.7%
Metal Powders	3	2.9%
Software (general)	3	2.9%
Professional Services	2	1.9%
Total	104	100%

Table 2 — Firms in sample by category according to theoretical framework

	integral innovation	modular innovation	supporting innovation
external exaptation	0 (0%)	30 (29%)	36 (35%)
radical exaptation	18 (17%)	7 (7%)	13 (13%)

Table 3 —Five archetypes of trajectories of entry into the 3DP ecosystem including selected examples taken from the 104 firms analysed.

	Integral Innovator	Modular Innovator	Supporting Innovator
External exaptation	No observation in this category.	Archetype: **RE-CASTING** Firms belonging to this archetype have **re-cast** their existing product/service lines to create offerings that support the 3DP ecosystem. Examples: • A materials company with long-term expertise in polymers and composites set up **Advanc3d Materials** to develop powders and 3D filaments for 3DP. • An electronics company, specializing in touch screens and digital pens, **Wacom** has sought to target its products at 3DP users, by partnering with service providers to offer an end-to-end solution. • A high-tech enterprise specializing in researching, developing, producing and operating degradable polymer materials, such as PLA and Polymorph, **SHINEDATA** own three different R&D centers, which specialize in material syntheses, modification and application.	Archetype: **RE-PACKAGING** Firms belonging to this archetype have **re-packaged** their existing product/service lines to serve the 3DP ecosystem, e.g. technical or professional services. Examples: • A safety consulting and certification company, which participated in the safety analysis of many of the 20th century's new technologies, most notably the public adoption of electricity and the drafting of safety standards for electrical devices and components, **UL** has turned its expertise to addressing safety concerns around 3DP. • Building on a foundation of expertise in industrial cleaning, **Quill Vogue** has developed a range of portable, enclosed, jet water cleaners for post-processing 3D printed parts, including cleaning and removal of support material. • A producer of testing machinery, **Testometric** identified 3DP as a growing industry and potential market for material and product testing. They have begun to promote their products to 3DP companies, which have similar requirements to other manufacturers.
Radical exaptation	Archetype: **RE-INTEGRATING** Firms belonging to this archetype have used their existing capabilities as the basis for building core systems, i.e., 3D printers, thereby creating a **revised integral** innovation. Examples: • Previously involved in the 3DP ecosystem as a supplier, **Ricoh** has now taken a position as an original equipment manufacturer (OEM). • Building on the foundation of the expertise and technologies associated with the production of bearings, **3D Platform** has developed large scale 3D printers. • A producer of CAD software, **Autodesk** launched its desktop SLA 3D printer, Ember. The printer was developed as an open source project, with the product and material information available online. Autodesk also owns the Instructables online DIY community platform, where users share designs for 3DP and other projects.	Archetype: **RE-INVENTING** Firms belonging to this archetype have used their existing capabilities as the basis for **re-inventing** themselves by developing new offerings that support the 3DP ecosystem (e.g., 3D printing/scanning services and materials). Examples: • Previously a producer of musical instrument strings, **Plastink** has exploited its expertise to take a position as a manufacturer of materials for 3DP. • A developer of safety glass, primarily for transport applications, Safeglass was founded to commercialize the outputs of its polymer materials research and set up **3DPrintWorks**. 3DPrint Works applies capabilities in polymer R&D to the development of 3DP filaments, as well as operating a 3D printing bureau service. • An electronics company, specializing in printed circuit board production and prototyping, **Tracks Laser & Electronics** has developed laser- based methods to produce 3D print circuit boards, which are presented to electronics manufacturers in general, including 3DP companies.	Archetype: **RE-DESIGNING** Firms belonging to this archetype have used their existing capabilities to **re-design** their offerings to serve the 3DP ecosystem. Examples: • A producer of 3D printed molds for casting, **3Dealise** uses design engineering and Ex-One sand 3D printers to deliver a service to its customers, which runs parallel to its core business of casting. • Formed when the founders discovered that 3DP was the best solution for making casings for a small batch of products they were producing. **We Do 3D Printing** now offers a 3D printing bureau service including design and batch production as well as reselling spare parts for desktop printers. • A producer of enclosed boxes for cleaning and finishing manufactured parts, **Inert** developed a solution for 3D printing factories to provide a constant and clean environment (enclosure) to produce a quality product.