Kilkki, Matti; Mäntylä, Martti; Karhu, Kimmo; Hämmäinen, Heikki; Ailisto, Heikki

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A disruption framework

Kalevi Kilkki[a,*], Martti Mäntylä[a], Kimmo Karhu[a], Heikki Hämmäinen[a], Heikki Ailisto[b]

[a] Aalto University, Espoo, Finland
[b] VTT Technical Research Centre of Finland, Finland

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ABSTRACT

One of the fundamental dilemmas of modern society is the unpredictable and problematic effect of rapid technological development. Sometimes the consequences are momentous not only on the level of a firm, but also on the level of an entire industry or society. This paper provides a framework to understand and assess such disruptions with a focus on the firm and industry levels. First, we give a generally applicable definition for a disruption as an event in which an agent must redesign its strategy to survive a change in the environment. Then we construct a layered model that spans from basic science to society and enables a systematic analysis of different types of disruption. The model also helps in analyzing the spread of innovations both vertically between layers and horizontally between industries. Thirdly, we introduce three main threats that may lead to a disruption and four basic strategies applicable when a disruption occurs. Finally, the framework is used to study four cases: GSM, GPS, the digitalization of photography, and 3D printing. The main contribution of this paper is the simple yet expressive model for understanding and analyzing the spread of industry-level disruptions through several layers and between industries.

1. Introduction

Innovation means different things to different people. However, for most of us innovation has a positive connotation. Disruption is, in turn, a negative term. Thus, there is a kind of internal conflict in the term disruptive innovation. Even more so with the term creative destruction, as coined by Joseph Schumpeter in 1942. Both terms leave open the question of whether the outcome will be socially beneficial or not; the terms hint that some entities will benefit while others will suffer. The role of new technologies in the redistribution of costs and benefits has been apparent from the early 19th century when Luddites fiercely protested the then new textile industry. The dilemma between the necessary actions needed for the continuous development of modern societies and the requests to maintain the status quo and to honor the old traditions has been a central topic in political, social, and economic forums during the last 200 years.

After Schumpeter (1950), discussion about the effects of innovations gradually gained momentum. Diffusion of innovations has been studied since early last century (Tarde, 1903/1969). The concept of the S-curve and adopter categorization by Rogers (1962/2003) has been widely used and referenced. Nevertheless, the terms *disruptive technology* and *disruptive innovation* were seldom used before Clayton Christensen published *The Innovator's Dilemma* in 1997. Per Google Scholar, the numbers of scholarly articles before 1997 mentioning “disruptive innovation” or “disruptive technology” were 51 and 58, respectively, whereas innovation, overall, was mentioned in close to 100,000 articles. Christensen's book created lots of debate about the nature of disruptions. The number of articles discussing disruptive innovations rose from the level of ten per year in the mid-nineties up to almost 3000 articles in 2015. Obviously, Christensen was able to identify and clarify the nature of an important idea.

Understandably, much of the existing literature focuses on disruptive innovation at the level of an individual technology or a single firm and often delves deep in the specific characteristics of the individual case. Yet historical examples show that truly significant disruptions affect also entire industries and even society: former industrial leaders may vanish and be replaced by new entrants, boundaries between formerly distinct industrial sectors may blur, and the new market conditions emerging from the disruption may require significant adaptations at the level of societies in terms of new institutions and regulation.

The main objective of this paper is to provide a simple yet expressive framework for studying and understanding disruptive changes especially at the level of entire industries. To achieve this, we develop conceptual definitions, a layered framework, and a classification of strategies to cope with different types of disruption. The primary viewpoint of the paper is a combination of technology, business, and consumer behavior. However, because we want to present a general

* Corresponding author at: Aalto University, Department of Communications and Networking, Konemiehentie 2, 02150 Espoo, Finland.
E-mail address: kalevi.kilkki@aalto.fi (K. Kilkki).

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framework, we also need to consider social and political processes, as well as scientific and applied research. All definitions and classifications are devised to be applicable on all layers from science to society. Before going to the details of the framework in Section 3, we present a literature review on disruptions in the next section. Additionally, in Section 4 several cases are then analyzed through the presented framework. Finally, the general findings of the cases are presented in Section 5 with a discussion about the need for further studies on business disruptions.

2. Literature review and the definition of disruption

Christensen's influence has been most prominent in technology-related business literature. Many books have discussed the interplay between technology and business. For instance, Berkun (2010, p. 62), Isaacson (2014, p. 288), Lessig (2008, p. 143), Naim (2014, p. 71), Norman (1998, p. 235), Rogers (1962/2003, 5th ed., p. 247), and Varian (2004, p. 26) approvingly reference Christensen's original thesis about disruptions. Typically, the attitude in such technical papers is that “disruptive” is a desirable trait, because the choice of the term suggests that the paper is presenting something important and possibly highly valuable. The greater the effect or the more disruptive the innovation, the better.

Christensen's original idea was that an excessive reliance on the known and presumed needs of current customers could be harmful when a novel technology disrupts the market. The conflict between old and new needs may lead to a situation in which the incumbents concentrate on serving the old needs while the new players capture a major portion of the market by serving new needs. However, Christensen's treatise in *The Innovator's Dilemma* has been criticized as cherry picking examples and for the lack of a general classification of disruptions, see Danneels (2004), King and Baatartogtokh (2015), Lepore (2014), Markides (2006), Sood and Tellis (2011), and Wadhwa (2015).

Moreover, some business literature about digital disruptions omits Christensen and the concept of disruption. For instance, Evans and Wurster (2000) use terms “blowup” and “deconstruction” to address those cases that Christensen would call disruptions. Similarly, Brynjolfsson and McAfee (2014) only refer to Schumpeter's creative destruction and use the word disruption only occasionally while Kelly (2016) discusses the significant future effects of novel technologies on our lives but does not mention Schumpeter or Christensen at all. Also these books do not stress the difference between *sustaining* and *disruptive* technologies; rather, they consider digitalization and its economic and social effects as a complex process that includes phases of gradual evolution and intermittent rapid changes.

Other kinds of terminology have also been used. *Discontinuous innovation* was widely used before disruptive technology became popular, see Anderson and Tushman (1990), Lynn et al. (1996), Veryzer (1998), and Kaplan (1999). Disruptive is a stronger and more tangible qualifier than discontinuous, which may explain the popularity of disruptive among many fields of inquiry. However, the events discussed under these two terms, disruptive and discontinuous innovations, are very similar.

Various definitions of disruption can be found from literature. Sood and Tellis (2011) state that technology disruption occurs when a new technology exceeds the performance of the dominant technology on the primary dimension of performance. Similar definitions can be found in Govindarajan and Kopalle (2006), Schmidt and Druehl (2008), and Utterback and Acee (2005). Linton (2002) refers to Abernathy and Clark (1985) and states that “Disruptive innovations are based on a different technology base than current practice, thereby destroying the value of existing technical competencies.” Kassicieh et al. (2000), Kostoff et al. (2004), Rothaermel (2002), and Volberda et al. (2011) have provided similar definitions. According to Danneels (2004) “a disruptive technology is a technology that changes the bases of competition by changing the performance metrics along which firms compete.” Similar definitions are presented by Obal (2013) and Nagy et al. (2016). According to Walsh et al. (2002), Geoffrey Moore has noted in 1991: “disruptive technologies generate discontinuous innovations that require users/adopters to change their behavior in order to make use of the innovation.” Albors-Garrigos and Hervas-Oliver (2014), Lyytinen and Rose (2003), Bessant et al. (2010), Paap and Katz (2004), and Urban et al. (1996) have presented similar kinds of definitions. Sometimes disruptions are initiated by a new business model rather than by new technology, as discussed in Ghezzi et al. (2015), Pisano (2015), Sabatier et al. (2012), and Sosna et al. (2010). Finally, many articles (e.g., Kassicieh et al., 2002; Laplante et al., 2013; Markides, 2006 and Yu and Hang, 2010) discuss several aspects of disruptions without giving one clear definition.

In most of the definitions outlined above, the authors define disruption by searching for the common denominator in a set of disruptions. Instead, we take a conceptual approach that starts with the concept of disruption and aims to give a definition that is applicable for all fields, not only for the business sector. Cambridge Dictionaries Online (2017) gives the following definition for *disrupt*: to prevent something, especially a system, process, or event, from continuing as usual or as expected. An agent, when pursuing some predefined goals, makes intentional decisions and performs some actions that, in turn, affect other entities. Sometimes the effects are disruptive, either intentionally or unintentionally. Thus, a *disruptor* is an agent that disrupts the functioning of some other agents. Those disrupted agents can be called *disruptees*; see, e.g., Christensen (2013) and by Yu and Hang (2008). An agent can thus be a disruptor, a disruptee, or a neutral actor from the perspective of a disruption.

But not all entities are agents. In an ecosystem, a majority of entities stay passive without goals, expectations, or intentions. For instance, although money is an integral part of all business ecosystems, money in and of itself has no intentions; only the owner of the money has intentions. In our framework, *disruptive* is a property of a passive entity that mediates the effects from disruptors to disruptees. An ecosystem is, thus, a medium for disruptions. If one says that an ecosystem is disrupted due to an event, the actual claim is that so many agents in the ecosystem are disrupted that the event has a perceptible influence on the ecosystem as a whole.

As to the term *innovation*, Merriam-Webster (2017) gives two main definitions: 1) the introduction of something new, and 2) a new idea, method, or device. We prefer here the later meaning in which innovation refers to an actual object (e.g., charge-coupled device (CCD) that led to digital cameras) instead of the process initiated by an object. Moreover, we use the term *disruptive innovation* rather than *disruptive technology* because innovation is a broader concept and covers business, institutional, and user-generated innovations.

Thus, we propose the following definitions:

> An agent is *disrupted* when the agent must redesign its strategy to survive a change in the environment.
> From the perspective of a system, *disruption* is an event in which a substantial share of agents belonging to the system is disrupted.
> *A disruptive innovation* is a passive entity that mediates a disruption in a system.

3. Framework

As the literature review in the previous section demonstrated, numerous viewpoints and methods have been proposed to assess disruptive innovations. Typically, if someone wants to understand a disruption, she may start either with a specific viewpoint (say, strategic choices within a firm) or with a relevant book or a set of articles. In contrast, our aim is to build a framework that makes it possible to flexibly choose among different viewpoints and different methods and even use several of them in parallel. The framework consists of two parts: first, a model with six layers to assess the dynamics of disruptive

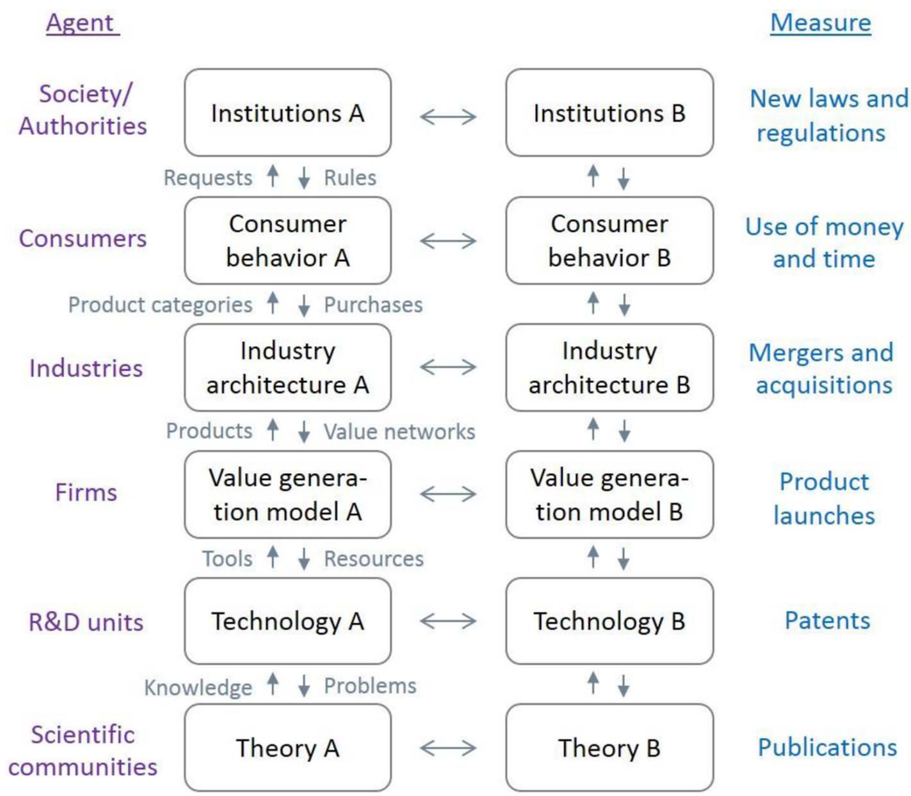

Fig. 1. A layered structure to illustrate the interactions in disruptive processes.
The boxes in the middle (theory, technology, etc.) represent potentially disruptive entities.

innovations and, secondly, a model with three types of threat and four types of strategic choice for a firm encountering a disruption.

3.1. A layered model

The main strength of the definitions presented in the previous section is that they are applicable independent of the particular nature and process of a disruption. The definitions can also be applied at any agent layer. These layers range from scientific research to the authorities defining the rules of the society as illustrated in Fig. 1. Scientific disruptions, called paradigm shifts by Thomas Kuhn (1962), may occur on the science layer; the discovery of the theory of evolution is a clear example. Even without a paradigm shift and grand disruptors, the accumulation of scientific knowledge enables technical inventions in the research and development (R&D) units of private companies and public organizations. On this layer, many important decisions are made on the level of middle managers that first identify the potential of an invention. As a result, a manager can become a disruptor within a firm by allocating resources from old technologies to develop a commercially successful invention, that is, an innovation.

On the layer of firms, the key decision maker when an innovation is brought to market is the Chief Executive Officer together with other top managers. Inside a firm, disruptive technologies typically require new skills and create a pressure to change the value generation models of the firm. Disruptions also occur because of the adoption of an established technology into a new business sector or because of a new combination of two or more old technologies as discussed by Arthur (2009) and Berkun (2010).

The effects of disruptions may diffuse through multiple layers including technology, business, and consumers as presented in Funk (2008). A disruption started by a new technology affects the value generation model of a firm that is then able to offer new products. The new product might pass the industry layer without any immediate disruptive effect on the industry architecture. However, if the product creates significant demand among consumers, technology push may turn into market pull and the disruption can diffuse back to the industry and firm layers with noticeable consequences. As an example, short message service (SMS) was adopted by consumers much more rapidly than what the service providers expected (Hillebrand, 2010). SMS demonstrated the urgent need for online social interaction that later led to the rise of social media applications.

On the lower layers (science, R&D, and firms), it is often possible to identify the disruptor, that is, a person or a group of persons, initiating a disruption by a new publication, patent, or product. These accomplishments can be used to measure the significance of a disruption. On the upper layers, the situation is fuzzier. On the industry layer, new products may cause changes in the structure of the value networks (see, e.g., Allee, 2000). Disruptions affect an industry by changing the relationships between different players and results in mergers, acquisitions, and bankruptcies that can be used as measures of the strength of a disruption.

Disruptive products can also prompt a momentous change in usage behavior. As a recent example, many consumers now spend at least several hours per day using their smartphones (Finley and Soikkeli, 2017). Additionally, other aspects of the smartphone innovation affect daily life. For example, smartphone applications collect and use a large amount of private information (often for targeted advertising purposes); thus, prompting user privacy concerns (Rainie, 2016). Those concerns create requests for regulating the behavior of enterprises and other organizations by means of new rules. Therefore, notable changes in regulation can be considered a strong indication of a disruption on some of the lower layers in Fig. 1. In extreme cases, a disruptive technology together with other social changes can even disrupt the social order of nations; the Arab Spring in 2010 is a notable example.

3.2. Firm-level strategies

As to business disruptions, the most critical decisions are usually made in firms. The main strategic choices for firms are illustrated in Fig. 2. There are three axes: industries, product quality, and the number

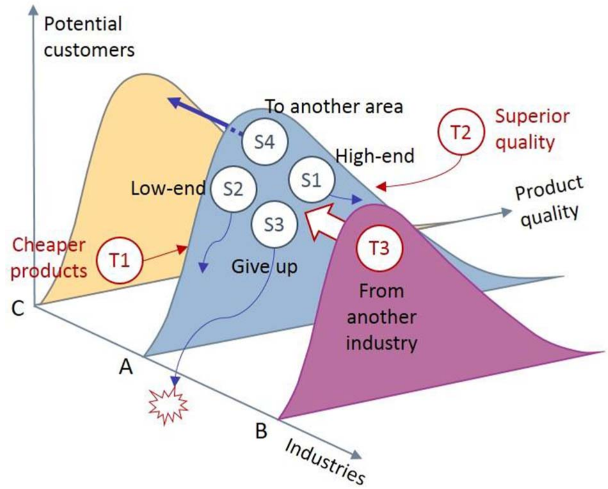

Fig. 2. Three industries (A–C), three threats (T1–T3), and four strategies for incumbent players in industry A (S1–S4). Threats are made by disruptors while disruptees need to select a strategy to cope with the effects of a disruption.

of potential customers. Different industries serve different customer needs by offering different types of products. Most customers have moderate product requirements while some customers are more demanding and willing to pay more than others. In a stable situation, a couple of firms usually dominate the largest customer segment with moderate requirements.

Now we can consider how a disruptive innovation affects the status quo. Three types of entrants pose different threats for the incumbents in industry A. New entrants armed with an innovation may invade the market by serving first the less demanding customers (threat T1). The entrant assumes it can improve the product quality so quickly that firms using the old technology cannot react quickly enough and thus lose the battle. This is the archetypal disruption in Christensen's model while the other threats can be viewed as extensions to that basic model. In the second type of threat (T2), the main competitive advantage of the entrant is superior quality demanded by high-end customers. If the price of the new product can be decreased quickly enough, the innovation may capture a major part of the market from the incumbents. Finally, the most serious threats often arise when another industry expands to the area of an established industry and threatens to change the business logic of the old industry (threat T3).

When the entrant generates threat T1, established players have a motive to move upwards on the scale of product quality (High-end strategy, S1). Even if the firm will likely lose market share, gross margins are typically higher in the upper product categories. However, there is rarely enough room in the upper segment for all established players. The situation is even more problematic when a strong entrant enters the market with a high-quality product (T2). In principle, established players may move downwards by reducing costs, diminishing product variety and lowering quality (Low-end strategy, S2). From an organizational viewpoint, this kind of move is uncomfortable, because it threatens the position and status of some integral parts of the organization including R&D and advanced customer support. But doing nothing is also a strategy; it likely results in a bankruptcy or in a voluntary exit from the business (S3). Finally, some firms move to another industry (S4). Different strategies may lead to different kinds of interaction with agents on the other layers illustrated in Fig. 1: low-end strategy (S1) leads to a change in the interaction with consumers, high-end strategy (S2) requires investments in R&D, and moving to another industry (S4) changes the firm's position in the business ecosystem.

4. Case examples

In this section we check the feasibility of our framework by assessing some major disruptions. In 1439, the introduction of movable type printing created a massive disruption that affected the rise of modern society. Many agents, particularly state leaders had to make critical strategic decisions whether to embrace or suppress the usage of the innovation. The Turkish Sultan decided to effectively ban printing, and therefore helped maintain a status quo in Turkish society for centuries, but hindered intellectual and economic advancement. On the other hand, the Catholic Church accepted the printing press and thus helped spur the transition from the Middle Ages to the Renaissance and New Age – but also enabled the Reformation and Protestantism. This major disruption demanded critical strategic decisions on the highest layer of the society. For instance, in 1589, Queen Elisabeth I declined to grant a patent for a knitting machine, because she was afraid that knitting machines would create political instability (Acemoglu and Robinson, 2013, p. 182). There were no firms or industries to support the spreading of the invention, only individuals. In general, the spreading of innovations was defined primarily by the institutions adopted by different nations.

As to modern technology, the computer, and more generally information technology, has produced major disruptions that can be evaluated by using available data sources. For instance, many Internet and web-enabled services have disrupted conventional businesses: first CD-ROM technology and later Wikipedia have disrupted the encyclopedia business (see, e.g., Anderson, 2009). Similarly, Uber is causing tremors in the taxi business and Airbnb in the hotel business. In a certain sense, all these examples started with low prices (threat 1 in Fig. 2), but at the same time they offered additional benefits unavailable in the conventional model. In these cases, new entrants started within a certain field (like Amazon in books) but then expanded to other fields of business (see, e.g., Rothman, 2017). More disruptors are emerging due to the continuing effects of Moore's law and the development of machine learning and artificial intelligence.

In the following case analysis, we use our framework to analyze a few industries more closely using both quantitative and qualitative approaches. As explained in Section 3.1., disruptions leave their mark in databases covering publications, patents, products sales, usage of applications, stock prices, mergers and acquisitions, and regulatory decisions. Thus for the quantitative approach, we collect and plot the yearly development of some of these variables (see Figs. 3, 4, 5, and 9) and use them as proxies for indicating strength and timing of innovation activity at specific layer in our framework (refer to the right-hand side of Fig. 1). The primary data sources in the figures are: articles: IEEE Xplore (2017), patents: United States Patent and Trademark Office (2017), books: Amazon.com (2017), stock prices: Yahoo (2017), and the share of mobile phone features in Finland: Riikonen et al. (2015).

For the qualitative analysis, we collected the main events in selected case industries and built a synthesizing illustration by positioning the events over time on the horizontal axis and according to layers of our framework on the vertical axis (see Figs. 6, 7, and 8). We present our case analysis in three parts. First, we utilize our framework using quantitative, and second, qualitative approach to consider the development of mobile phones, GPS, and digital photography. These cases illustrate how the effects of innovations spread between industries. They also provide a useful set of occurrences to demonstrate the usefulness of the framework with (mostly past) business disruptions. Third, we use 3D printing as an example of a potential future disruptive innovation that is still in the early phase of development.

4.1. Quantitative analysis of GSM, GPS, and digital photography: timing and scale of disruptions

Over the last 30 years mobile phones have had dramatic effects on everyday life all over the world. The first generation mobile phones using analog technology were cumbersome and expensive and were not widely adopted by consumers. The first truly successful mobile technology was GSM (Global System for Mobile Communications). Fig. 3

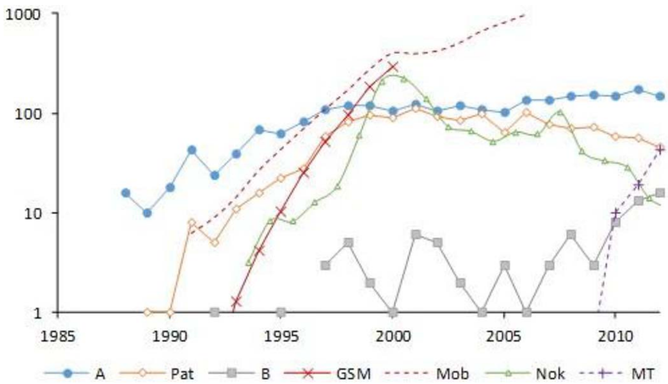

Fig. 3. The history of GSM in numbers. A: the number of articles per year with *GSM* in abstract); B: the number of books published per year with GSM in title; Pat: the number of patents filed per year based on granted patents 6/2017 with *GSM* in abstract; GSM: the number of GSM phones sold per year (millions, source: Häikiö, 2001, p. 179); Mob: the number of mobile phones sold per year (millions); Nok: the market capitalization of Nokia (billions of Euros, source: Nokia's annual reports); MT: the share of mobile phones with multi-touch screens in Finland (%).

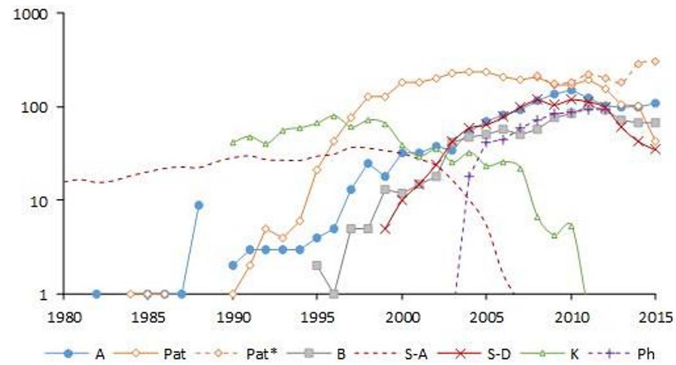

Fig. 5. The history of digital photography in numbers. A: the number of articles in per year with *digital photography* or *digital camera* in abstract, B: the number of books published per year with *digital photography* in title; Pat: the number of patents filed per year based on granted patents 6/2017, *Digital photography* or *digital camera* in abstract; Pat*: the estimated number of filed patents per year, estimated based on the granted patents by 6/2017; S-A: the number of analog cameras sold per year (millions, source: CIPA, 2017); S-D: the number of digital cameras sold per year (millions, source: CIPA, 2017); K: the stock price of Kodak ($ US); Ph: the share of mobile phones with camera in Finland (%).

illustrates the three phases of GSM development: first, the relatively quiet years until 1994, then the phase of rapid development from 1995 to 2000, and finally a stagnant phase when the main development effort moved from GSM to the next generations of mobile technology (3G, 4G, and 5G). In the case of GSM, the number of scientific articles started to rise several years before successful businesses, because mobile service providers and device vendors were aware of the necessity of the change from analog to digital technology. Still, the number of US patents remained low (partly because other technologies were adopted in US). Even though the main actors in the mobile ecosystem were prepared for the change induced by GSM, they did not anticipate the dramatic increase of demand illustrated in Fig. 3. The sudden change in the mobile phone business gave an opportunity for Nokia to rise from a small player to a global mobile phone giant in a couple of years (illustrated by the stock value in Fig. 3).

At the same time as GSM, two other technologies were in the phase of rapid development: digital photographing and GPS (Global Positioning System). Figs. 3, 4, and 5 reveal similarities in the development of GSM, digital photographing, and GPS but also some notable differences. In the case of GPS, a lot of patent applications were filed already over 10 years before GPS became popular in consumer devices because of the usage of GPS in other fields. With digital photographing the lag between patents and sales was roughly 6 years, whereas with GSM it was less than five years. The lag between sales and patents illustrates how innovation propagates, with some delay, from the

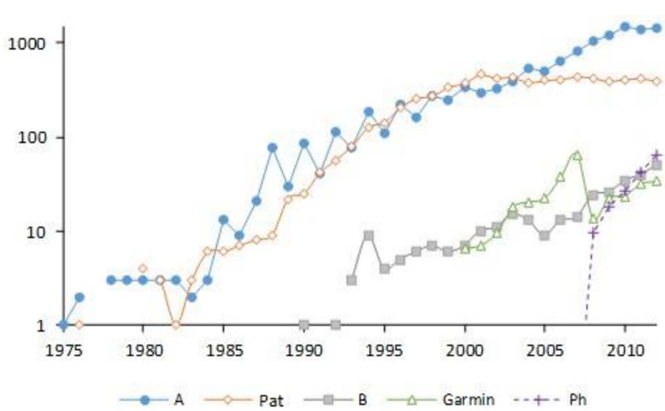

Fig. 4. The history of GPS in numbers. A: the number of articles per year with *GPS* in abstract; B: the number of books published per year with GPS in title; Pat: the number of patents filed per year, based on granted patents 6/2017, *GPS* in abstract; Garmin: the stock price of Garmin Ltd. ($ US); Ph: the share of mobile phones with GPS in Finland (%).

scientific communities and R&D unit layers up to the firms and consumers layers. It seems that also speed, i.e., a small delay and sharp angle, in addition to the scale of change contribute to the disruptiveness.

The advance of digital photography disruption is manifested in the decline of yearly sales of film cameras and the increase in the sales of digital cameras. The number of film cameras sold peaked in 1998, when 36 million units were sold (CIPA, 2017). In 1999, sales began a constant decline and in less than ten years sales dropped below a million units per year. During the same period the sales of digital cameras reached 100 million units. Since then, sales of digital cameras have declined to 35 million units because the next wave of digital photography entered the scene, namely the smartphone (see MT in Fig. 3). Smartphone sales in 2015 reached 1.4 billion units. This serves as an illustrative example of successive waves of disruptions enabled by convergent developments in other fields, which will be explored in more detail in the qualitative analysis.

4.2. Qualitative analysis of GSM, GPS, and digital photography: entanglement of disruptions

Digital technology has created several disruptions in the telecom sector. All established telecom firms have had to make major strategic decisions: first in the fixed network area and then in mobile network and device area. Nokia was a disruptor in the first phase but was itself later disrupted by the software and Internet enabled smartphones made by Apple and Google (see Nokia's stock value and the share of multi-touch phones in Fig. 3). As a strategic consequence, Nokia was forced to sell its phone business to Microsoft in 2013. Apart from the disruptive developments within the industry, mobile communications have had significant disruptive effects on other fields, including GPS devices and cameras, which we will examine more closely.

The history of GPS is illustrated in Fig. 6. Whereas photography emerged as a device-driven technology, satellite navigation required massive investments in satellite systems and is therefore necessarily government-driven. The early phases in the 1960s (Sputnik 1, TRANSIT system) were driven by military interests. Because of the tragedy of Korean Air Lines Flight KAL007 the US government allowed limited civilian use (e.g., maritime, aviation) when the first GPS satellite was launched in 1989. This event opened the GPS device market. The first device firms Magellan and Garmin exploited military synergies (and the government subsidized satellites) while entering the non-military personal navigators industry (threat T3 to traditional navigation firms).

The GPS market got a major boost due to the improvements in GPS

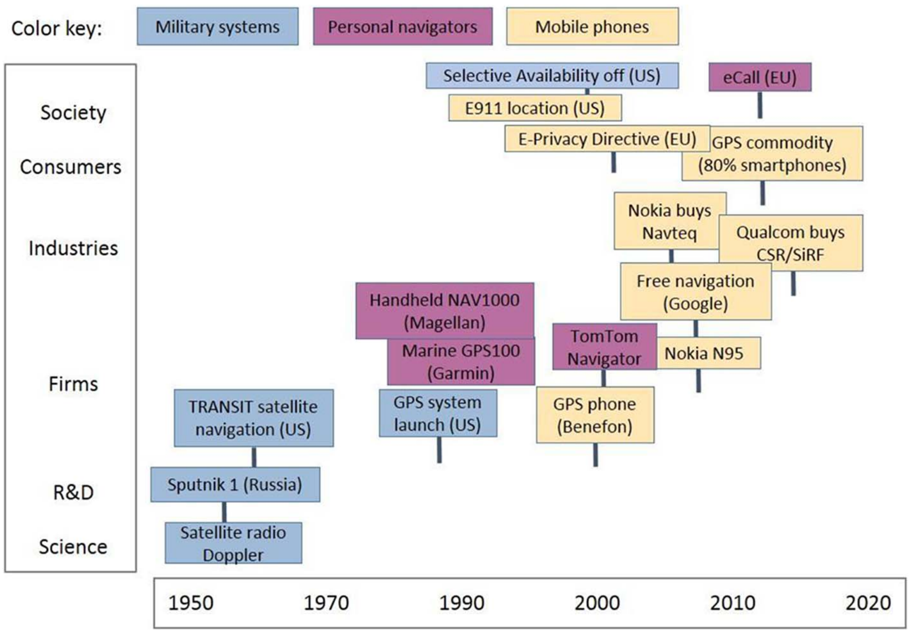

Fig. 6. Milestones of GPS satellite navigation.

accuracy in 2000 when the US government removed Selective Availability. As one consequence, it became clear that GPS would be superior in outdoor positioning compared to triangulation technologies of GSM mobile networks. Mobile operators and mobile phone manufacturers became interested, and Benefon launched the first GPS-enabled phone in 2001. The emergence of smartphones with GPS (see Fig. 4) partly explains the financial difficulties of Garmin (specialized in navigation devices) as well as the acquisitions of Navteq (specialized in navigation maps) by Nokia (2007) and CSR/SiRF (specialized in GPS microchips) by Qualcomm (2015).

As to the consumer layer, GPS did not have any noticeable effect on purchase decisions of mobile phones in the period of 2004–2013 (Kekolahti et al., 2016). Thus, it seems that GPS did not disrupt the mobile phone market. On the other hand, none of the big GPS personal navigator vendors (e.g., Garmin, Magellan, and TomTom) could enter the mainstream mobile phone industry and instead remained specialized in their narrow segment. Overall, as witnessed by the societal impacts of regulation (emergency call positioning such as E911 and eCall, privacy rulings such as E-Privacy) and commoditization of smartphones (due to government satellite subsidy and Google's free navigation strategy), GPS is an example of full penetration through the vertical layers of our framework.

The origins of digital photography (Fig. 7) can be traced to basic technological research in the 1960s, leading to the invention of the fundamental component, the CCD image sensor in 1969. A completely digital camera nevertheless required the converging development of many other technologies (such as the development of processors and algorithms for image processing and large memory chips for storing the images); thus, the first digital cameras arrived to the market only around the end of the 1980s. During the 1990s, digital cameras were chiefly aimed at the high-end market of professional photography, corresponding with threat T2 of Fig. 2 against traditional analog photography. However, digital cameras soon expanded in volumes to low-end market as well (T1) as illustrated by sharp rise in sales in Fig. 5. The impact of this disruption proved to be disastrous to established firms of the market, culminating in the bankruptcy of Kodak in 2012 (strategy S3).

The low-end market was further fueled when the first mobile phones with embedded cameras entered the market. The almost simultaneous adoption of 3G mobile networks ensured that camera phones had sufficient communications capabilities to disrupt established photography, even though the picture quality and other characteristics of the first camera phones were relatively modest. For instance, the share of phones with camera increased from 21% in 2005 to 65% in 2009 in Finland (Kivi et al., 2012). The availability of a camera was one of the few features that had a discernible positive effect on the sales of mobile phone models between 2004 and 2007 (Kekolahti et al., 2016). By 2008, Nokia had become the world's largest camera manufacturer. Thus, Nokia and other mainstream camera phone manufacturers posed the threats T1 and T3 of Fig. 2 against traditional digital photography. In our layered framework, this illustrates a horizontal spread of innovation from one industry to another. Once established, camera phones enjoyed significantly larger economies of scale compared to traditional digital cameras.

By that time, however, the next wave of the digital photography disruption was already apparent. Powered by rapidly developing cloud data storage, websites for storing and sharing digital photographs appeared in the mid-2000s and were eventually integrated in the growing empires of Web giants such as Google (Flickr) and Facebook (Instagram). With this, the value of photographs moved from cameras and phones to social media sites that made the photographs available to other users (threat T3 against smartphone business). This has led to new user behaviors such as using photography to document all kinds of happenings (not just memorable events) or to communicate in peer groups (e.g., the "selfie" phenomenon). In our layered framework, this illustrates a vertical spread of innovation from a lower level upwards. The emergence of these behaviors has also raised social issues, such as the balance of freedom of expression and personal privacy.

4.3. *3D printing—a future disruptive innovation?*

The basic idea of 3D printing, to create 3-dimensional shapes by stacking 2-dimensional cross sections, can be traced to ancient humans; this is how much of Neolithic pottery was created before the invention of the potter's wheel. Nevertheless, the birth of modern 3D printing took place in late 1980s and early 1990s with the invention and patenting of the first practical technologies, such as stereolithography (SLA), selective laser sintering (SLS), and fuel deposition modelling (FDM) (see Fig. 8). Much of the 1990s were characterized by rapid progress with new materials and processes being continuously introduced to increase the range of parts that could be created. Powered by these inventions, the market developed rapidly under the parallel forces of creative

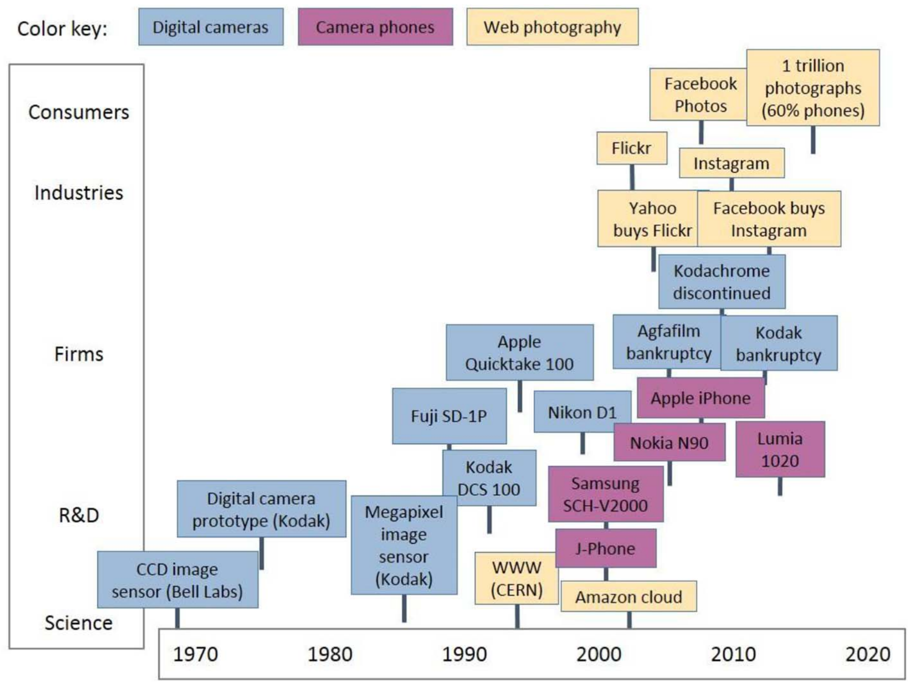

Fig. 7. Milestones of digital photography.

destruction and rapid consolidation. By the new millennium, industrial 3D printing was well established in design offices and had started to make inroads in actual manufacturing (initial threat T3 against traditional manufacturing).

A second wave of the disruption commenced in the mid-2000s, when the first printers aimed at consumer markets appeared (initial threat T3 against industrial manufacturing); this coincided with the expiration of some of the core patents from the 1980s. Akin to the development of web photography, this development gained speed from social media and the web economy being built around it. In particular, crowdsourcing spurred the rapid development of many new entrants competing to create printer kits for consumers. The growing consumer market also opened the door for Internet-enabled 3D printing app stores, sites specializing in publishing 3D-designs. Inevitably, social concerns have also appeared, such as the appearance of the Defence Distributed website specializing in 3D-printable gun designs. After some controversy, it discontinued its offering in 2013.

As to the disruptiveness of 3D printing, the most surprising observation in Fig. 9 is that all the metrics (articles, patents, books, sales, and the stock price of 3D Systems) accelerated within a relatively short period of time (2010–2014) after a long quiet period. The quickness of the change indicates that other sectors and industries may be unprepared for the possible disruptive effects of 3D printing. Whether 3D printing turns out be a genuinely disruptive technology akin to the web remains to be seen; though the rise during the last 5 years appears promising.

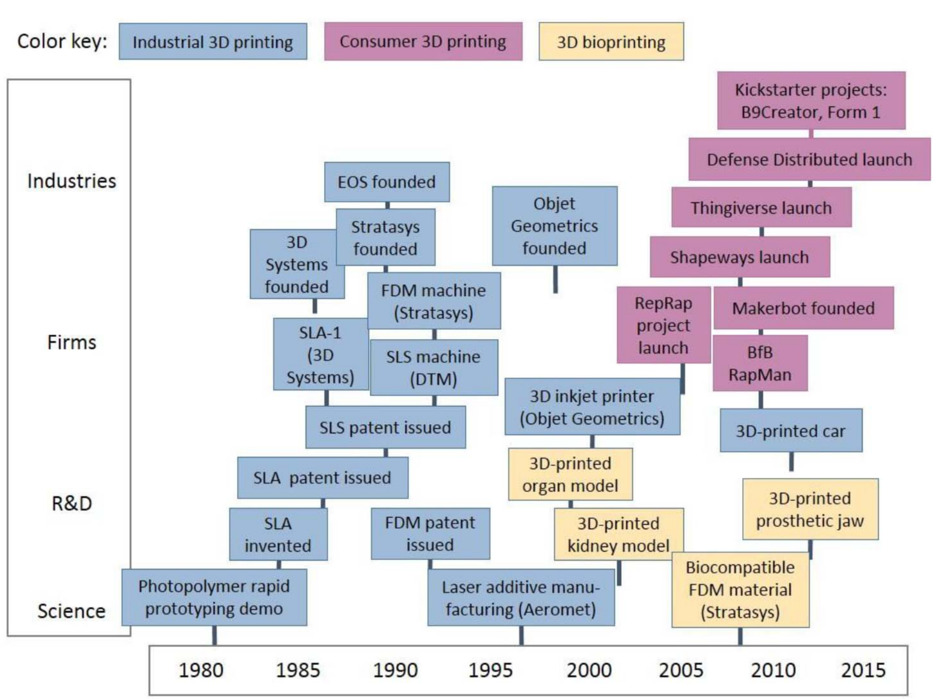

Fig. 8. Milestones of 3D printing.

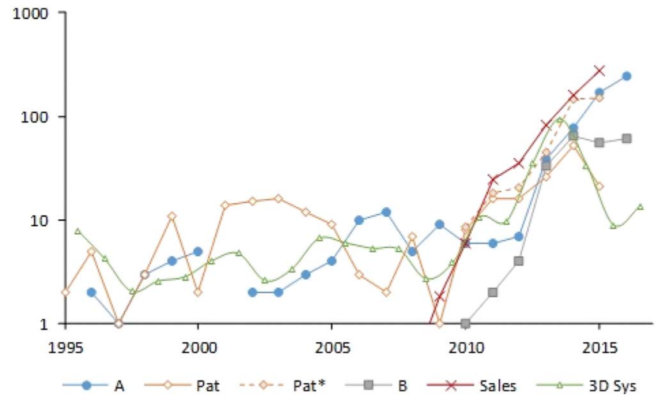

Fig. 9. The history of 3D printing in numbers. A: the number of articles per year with *3D printing* in abstract; B: the number of books published per year; Pat: the number of patents filed per year based on granted patents 6/2017, *3D printing* or *solid freeform fabrication* in abstract; Pat*: the estimated number of filed patents per year, estimated based on the granted patents by 6/2017; sales: the number of 3D printers sold per year (thousands, source: www.3ders.org, 2016); 3D Sys: the stock price of 3D Systems ($ US).

5. Discussion

The main contribution of this paper is a simple yet expressive model for assessing industry-level disruptions. More specifically, our framework helps to understand how a disruptive innovation propagates between layers, from science to society, and how it may spread from one industry to another. In this section we discuss the spreading of disruptive innovations from three perspectives: vertical vs. horizontal direction, entanglement with other innovations, and specific role of so-called generic disruptors. To conclude, we also discuss practical implications and provide avenues for future research.

Earlier research on spreading of innovation has mainly come in two streams. Diffusion of innovation research (e.g., Rogers, 2003, Wejnert, 2002) has looked at how a particular innovation is spread and adopted among group of actors in a social system. In terms of our framework, this stream of research has mainly focused on spreading of innovation within one layer, be it firms or consumers. Second, technology transfer research has looked at policies to promote innovation transfer from academia to industry (for a review, see Bozeman et al., 2015). In our model, this corresponds to spreading from scientific layer up to industries layer. Our framework extends these research streams by providing a systemic perspective on spreading of innovation between the entire stack of layers (vertically) and also between industries (horizontally). As an example, CCD image sensor technology, after propagating from academia to the industry layer, later spread from the original camera industry to another, namely the smartphone industry, disrupting the original receiving industry.

Although we have traced the roots of the three cases to several specific scientific discoveries or technological innovations, all cases were the result of many convergent technological developments, without which they would not have been successful. Apart from image sensors, the breakthrough in digital photography also depended on the general progress of microelectronics and embedded computing, making possible the image processing and storage required for the complete camera package. Later it gained further momentum from a convergence with the mobile phone and cloud-based Internet service disruptions. Correspondingly, the spreading of GPS to mobile phones created the need for more user-friendly maps and cloud-based Internet service. This contributed to another disruption where Internet and software driven firms such as Google and Apple produced smartphones and platforms that were able to challenge and replace the traditional mobile phone firms such as Nokia (Kekolahti et al., 2016). Likewise, although the original birth of 3D printing depended critically on the invention of suitable materials and processes, the later development of consumer 3D printing benefited from a convergence of relevant information and communications technologies (such as inkjet printer heads repurposed for 3D printing, and the Internet). These findings are in line with the earlier research that has noted how digital technology enable distributed and combinatorial innovation (Yoo et al., 2012). The layered framework we have presented contributes to the existing research by providing an instrument to track the paths how preceding developments and disruptions interact with the current disruption both vertically between layers and horizontally between industries.

How does the entanglement of disruptions take place? Earlier research on service innovation (Barrett et al., 2015) and digital innovation (Yoo et al., 2012) has emphasized the role of pervasive digital technologies. This is confirmed by our study. A common characteristic of the disruption case studies is that their path was significantly changed due to their crossover with Internet technology. Internet-based photo services are now the dominant form of sharing photographs among families and peer groups (after showing photographs directly from the phone screen to others). Likewise, the progress of consumer 3D printing is linked with the Internet economy through the symbiotic progress of 3D model app stores and increasingly web-enabled 3D printing services. This supports the view that the Internet specifically is a generic enabler and disruptor that has the power to alter the course of other disruptive developments once they become entangled with it (Lyytinen and Rose, 2003). From the industry-level perspective of our study, a generic disruptor may also act as a bridge allowing the spreading of disruptions from one industry to another.

Regarding practical implications, the Internet appears to have a similar role as steam power had in the first industrial revolution and electrification in the second, lending some credence to the view that we are now witnessing the third (or according to some, fourth) industrial revolution through the development of the Internet of Things (IoT). We believe our framework is especially suitable for analyzing developments, such as IoT, in which several layers, from science to society are involved, and impacts are typically felt across several industry sectors. In a networked economy, managers need to be aware of generic disruptors, not only technologies, but also social or business innovations that may spread from another industry. While these disruptions may pose a threat, there are ways to counter them (see Fig. 2).

Our research opens up several future research possibilities. First, the distributed and combinatorial nature of disruptive innovations calls for future research on diffusion of innovation, to understand how entangled innovations and practices are simultaneously diffused in a social system fueling the adoption of each other. Further, as Yoo et al. (2012, p. 1403) point out, innovations "will not simply spread but will mutate and evolve as they spread." Second, our preliminary quantitative analysis also calls for future research on the temporal aspects of disruptive innovations. One interesting temporal aspect to look at is the successive disruptions across industries, such as in the case of digital photography. Additionally, future research could examine the relationship between diffusion time (from science to products) on the disruptiveness of an innovation. In other words, it is potentially not only the scale, but also speed that together determine the disruptiveness of an innovation.

Conflicts of interest

None.

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Kalevi Kilkki is a university lecturer in the Department of Communications and

Networking in Aalto University, Finland. He worked at Telecom Finland in 1990–95 and Nokia Research Center 1995–2008 as a research scientist in the area of Quality of Service in the Internet and in mobile networks. During the last eight years, his main research topics have been Quality of Experience, customer behavior and economic models in communications ecosystems.

Martti Mäntylä is Professor of Information Technology at the Aalto University since 1987, where his work focuses on digitalization of industry. In 2009–2013 he was Chief Strategy Officer of EIT Digital, the Knowledge and Innovation Community (KIC) in digitalization of the European Institute for Innovations and Technology (EIT). In 1999–2008, he was Director of the Helsinki Institute for Information Technology (HIIT), a joint research centre of Helsinki University of Technology and University of Helsinki. Mäntylä obtained his Dr.Sc. in computer science from the Helsinki University of Technology in 1983.

Kimmo Karhu is Postdoctoral Researcher in the Department of Computer Science at the Aalto University. His recent doctoral thesis analyses open platform strategizing and digital tactics in mobile ecosystems. Currently, he works as a project coordinator for the Digital Disruption of Industry –project, a six-year project funded by the Strategic Research Council (SRC) at the Academy of Finland.

Heikki Hämmäinen is professor of Network Economics at Department of Communications and Networking, Aalto University, Finland. He has MSc (1984) and PhD (1991) in Computer Science from Helsinki University of Technology. His main research interests are in techno-economics and regulation of mobile services and networks. Special topics recently include measurement and analysis of mobile usage, value networks of flexible Internet access, and diffusion of Internet protocols in mobile. He is active in several journal and conference duties.

Heikki Ailisto, research professor, is responsible for Internet of Things/Industrial internet research in VTT. His research interests include ubiquitous computing, context awareness, and IoT. Currently Ailisto is the leader of Productivity with IoT research programme inside VTT. He is also a member in the steering board of a national industrial internet program. Heikki Ailisto has authored and co-authored more than 100 journal and conference papers, holds five patents and he is a member of IEEE. Ailisto holds a Dr. Tech and eMBA degrees.