Aalto University
School of Business

The proliferation of a new-market disruptive innovation: case personal 3D printers

International Business
Master's thesis
Heljo Sauramo
2014

Department of Management Studies
Aalto University
School of Business

Aalto University
School of Business

Aalto University, P.O. BOX 11000, 00076 AALTO
www.aalto.fi

Abstract of master's thesis

Author Heljo Sauramo

Title of thesis The proliferation of a new-market disruptive innovation: case personal 3D printers

Degree Master's Degree

Degree programme International Business

Thesis advisor(s) Inês Peixoto, Markus Paukku

Year of approval 2014 **Number of pages** 128 **Language** English

Abstract

Ever since Clayton Christensen's 1997 book "The Innovator's Dilemma" on disruptive innovations, the theory has received considerable scholarly as well as business management attention, with some even calling it "groundbreaking". Its key premise – that entrant companies with products of inferior performance can displace established companies – continues to be a prominent subject of management and innovation research. Like any trailblazing theory, it has also stirred criticism and aroused alternative explanations, contributing to its ongoing evolution. There nevertheless exists a considerable amount of concrete examples in the literature of various products, companies and industries where an entrant company or product did indeed disrupt the established actors. Christensen (2000) found that such disruptive innovations tend to be smaller, simpler, cheaper, more reliable and convenient that established or preceding products, and still based on existing technologies.

These characteristics bring us to view the recent proliferation of personal 3D printers in a new light. Recent media attention has led some authors – and popular media – to consider 3D printing as a new disruptive technology, even though the technology has existed for a good quarter of a century. Also, disruption is a relative phenomenon, meaning that there must be an established product to disrupt. However, the recent expiry of certain patents and the birth of an open-source 3D printer project have led to the advent of a class of considerably low-priced, consumer-grade 3D printers. These seem to fit Christensen's (2000) characteristics of a typical disruptive innovation remarkably well, yet the notion of personal 3D printers as a potential disruptive innovation doesn't seem to have been researched in any detail and thus the knowledge on the phenomenon is scattered.

The purpose of this case study is to study the proliferation of personal printers in detail and address whether they can indeed be considered a disruptive innovation. This entails studying e.g. the factors leading to their advent, the differences between the personal printers and entry-level industrial ones, business models, unit sales, prices, market shares and industry revenue. Based on Christensen's (2000) suggestion, also the development of personal 3D printers' performance over time is charted and compared to entry-level industrial printers as well as assumed performance demands of the market.

My results indicate that personal 3D printers meet the general criteria for a (new-market) disruptive innovation, yet their proliferation has occurred in a fashion that doesn't cause immediate consequences for individual incumbent companies, even though the total 3D printer market has no doubt been disrupted by the new product and new entrants. The case supports the view of significant market expansion as a result of a disruptive innovation's entry.

Keywords disruptive innovations, open innovation, 3D printing, additive manufacturing

Aalto-yliopisto
Kauppakorkeakoulu

Aalto-yliopisto, PL 11000, 00076 AALTO
www.aalto.fi

Maisterintutkinnon tutkielman tiivistelmä

Tekijä Heljo Sauramo

Työn nimi The proliferation of a new-market disruptive innovation: case personal 3D printers

Tutkinto KTM

Koulutusohjelma International Business

Työn ohjaaja(t) Inês Peixoto, Markus Paukku

Hyväksymisvuosi 2014 **Sivumäärä** 128 **Kieli** Englanti

Tiivistelmä

Teoria mullistavista innovaatioista on nauttinut merkittävää huomiota sekä akateemisen tutkimuksen että liikkeenjohdon saralla aina Clayton Christensenin vuoden 1997 teoksesta "The Innovator's Dilemma" lähtien ja sitä on jopa kutsuttu uraauurtavaksi. Teoriassa on kyse siitä, että tulokasyritys, jolla on suorituskyvyltään heikompi tuote, voi syrjäyttää toimialan perinteiset yritykset. Teoria on edelleen näkyvästi esillä liikkeenjohdon ja innovaatioiden tutkimuksessa ja sille on esitetty kritiikkiä sekä vaihtoehtoisia selityksiä, joten teoria kehittyy jatkuvasti. Kirjallisuudessa on esitetty lukuisia konkreettisia esimerkkejä erilaisista tuotteista, yrityksistä ja toimialoista joissa tulokasyritys tai uusi tuote on todellakin mullistanut perinteiset toimijat. Christensenin (2000) mukaan tällainen mullistava innovaatio on tyypillisesti pienempi, yksinkertaisempi, edullisempi, luotettavampi ja kätevämpi käyttää kuin perinteiset tai edeltävät tuotteet, mutta silti se perustuu olemassa oleviin teknologioihin.

Nämä ominaispiirteet laittavat meidät näkemään viime aikoina yleistyneet 3d-kotitulostimet uudessa valossa. Viimeaikainen medianäkyvyys on johdattanut jotkut kirjoittajat ja valtavirtamedian pitämään 3d-tulostusta uutena mullistavana teknologiana, vaikka ko. teknologia on ollut olemassa jo yli neljännesvuosisadan. Lisäksi mullistava innovaatio on suhteellinen käsite, joten täytyy olla jokin olemassa oleva tuote jonka se syrjäyttää. Tiettyjen patenttien viimeaikainen raukeaminen ja erään open-source –lähtöisen 3D-tulostinprojektin kehittäminen ovat kuitenkin johtaneet uuden, huomattavan huokeahintaisen 3D-tulostinluokan syntymiseen. Tämä luokka näyttää sopivan huomattavan hyvin yhteen Christensenin (2000) käsitykseen tyypillisestä mullistavasta innovaatiosta. Tästä huolimatta 3D-kotitulostimia mahdollisena mullistavana innovaationa ei kaiketi ole tutkittu kovin tarkasti – jos ollenkaan – ja täten ilmiöön liittyvä tieto on hajanaista.

Tämän case-tutkimuksen tarkoituksena on näin ollen tutkia syvällisesti 3D-kotitulostimien yleistymistä ja selvittää josko ne voitaisiin tulkita mullistavaksi innovaatioksi. Tämän vuoksi on tarkoitus tutkia niiden yleistymisen taustatekijöitä, 3D-kotitulostimien ja perustason ammattilaistulostimien eroja, liiketoimintamalleja, hintoja, markkinaosuuksia ja toimialan liikevaihtoa. Christensenin (2000) suosituksen johdosta myös 3D-kotitulostimien suorituskyvyn kehittymistä ajan myötä analysoidaan kaavioilla ja verrataan perustason ammattilaistulostimiin sekä oletettuihin markkinoiden odotuksiin suorituskyvystä.

Työni tulokset osoittavat, että 3D-kotitulostimet täyttävät mullistavan (uuden markkinan) innovaation yleiset kriteerit, mutta niiden yleistyminen on kuitenkin tapahtunut tavalla joka ei aiheuta välittömiä seurauksia yksittäisille, perinteisille yrityksille. 3D-tulostimien markkinat ovat kuitenkin kokonaisuutena epäilemättä kokeneet mullistuksen uusien tuotteiden ja tulokasyritysten johdosta. Tämä case-tutkimus tukee näkemystä kokonaismarkkinan voimakkaasta laajenemisesta mullistavan innovaation markkinoilletulon seurauksena.

Avainsanat 3d-tulostus

INDEX

LIST OF FIGURES & TABLES

Acknowledgements

This thesis started as a spinoff of the Outlier Initiative by TEKES with my initial research efforts for the project funded by the Aalto School of Business. I feel indebted to my thesis advisors Markus Paukku and Inês Peixoto for their patience and insights that helped guide this thesis in the right direction. In addition, I would like to express my gratitude to Jukka Tuomi, Jouni Partanen, Sergei Chekurov, Ashish Mohite, Tapio Väistö, Ismo Mäkelä, Heidi Piili and the staff at Aalto ADDLAB in Espoo, Finland, for their valuable contributions to my work. Despite their busy schedules, some of them agreed to meet me several times in order to support me with my work. In addition to interviews, I was presented to a roomful of different 3D printers, explained how they function, and showed dozens of examples of 3D printed objects. A special thanks goes to Mr. Jukka Tuomi for borrowing me industry data sources that proved invaluable for this thesis.

I'm also grateful to the friendly staff at Aalto FabLab in Helsinki, who first introduced me to personal 3D printers and the world of Making. During the early stages of the research process, I had the good fortune to talk with several insightful people – such as Kivi Sotamaa – about 3D printing, which helped me learn about the topic in general. Further, my thanks go to the staff of IdeaScout Oy for facilitating an inspiring brainstorming session about 3D printing.

On a final note, I'd like to thank MakerBot Industries of Brooklyn, NY, for sending me complementary print samples from their 3D printers.

heljo.sauramo@alumni.aalto.fi

1. Introduction

"Those cheap printers are nothing but toys. They're not good for anything."

Overheard in a technology seminar from an experienced user of high-end additive manufacturing systems.

1.1. Background

3D printing – or *Additive Manufacturing*, AM, for a more professional term – is a manufacturing technology that has gained a lot of media visibility during the last few years. It refers to a process where an object is built from ground-up, layer-by-layer, based on three-dimensional computer designs. There are many different technologies and materials for achieving this: some of the most prominent ones employ plastic filament extruded through a nozzle (Fused Deposition Modeling, FDM), liquid resin hardened by a laser beam (stereolithography, SLA), or powder sintered by a laser (Selective Laser Sintering, SLS).

The physical applications of 3D printing are striking – ranging from titanium jaw bones, Rolls-Royce jet engine parts and printed chocolate to outlandish paper-layered 3D rings. The technology is even sometimes referred to as a third industrial revolution (The Economist, 2012) and as a technology that will change the world (D'Aveni, 2013). Such descriptions are anything but modest, and so has 3D printing's rise to the limelight even been considered as a bubble or hype (Gartner, 2013c). It has also been called a *disruptive technology* by some sources and industry experts (e.g. CSC, 2012), which brings us to the theoretical framework of this thesis.

The theory of disruptive innovations (originally disruptive *technologies*) has been used to explain competitive changes in a wide array of industries. Put simply, it refers to a phenomenon where an entrant company can displace an incumbent one with a seemingly inferior product. According to Schmidt & Druehl (2008 p.347), few terms in the recent literature on innovation management have been as widely used as the phrase "disruptive innovation". Not only has the theory itself gained significant prominence, but the phenomenon that it seeks to explain can potentially have major implications for any particular industry and for economy in general. For example, Gilbert (2003 p.32) stated that disruption has been and will continue to be a tremendous source of growth in the economy. Hence, I would consider the theory of disruptive innovations to be one of the most influential innovation theories. It has to be noted that disruptiveness can only be expressed relative to the business model of a company and its competitors (Christensen & Raynor 2003. p.232), making relativeness is the essence of a disruptive innovation. For this reason, we need to look deeper into 3D printing technology to discover where its disruptive potential may lie.

3D printing technology is not new. The very first commercially available 3D printers were introduced already in 1987 by 3DSystems, Inc. with Stratasys, Inc. following suit in 1991 (Wohlers Associates, 2011b). Their machines were initially sold to larger R&D-based organizations that require high-quality objects and are able to afford a premium price (de Jong & de Bruijn, 2013). Not unlike computers, the technology has evolved from these early, prohibitively expensive industrial systems to more affordable desktop printers, and now in the latest phase to the ultra-low-priced personal ones. The term "3D printer" was originally used to refer to a particular class of small, desktop-fitting rapid prototyping machines – that saw daylight in circa 1996 – to distinguish them from the large, high-end rapid prototyping systems – put differently, a less costly variation of rapid prototyping technology (see e.g. Wohlers Associates, 2001). Potter (1997) described 3D printers as "the smaller, faster, cheaper siblings of conventional RP equipment". Also terms like "desktop rapid prototypers", "office modelers", "office rapid prototypers" and "concept modelers" have been used of these machines (See e.g. Ashley, 1995 & 1996; Huxley & Weisberg (2002); Plastics Technology, 1996; Potter, 1997; Beckert, 1998; Wohlers Associates, 2001). Since then, these printers have formed the low end of industrial printer manufacturers' model lineups. See Appendix "A" for more detailed definitions and Appendix "B" for examples of different 3D printers.

Recently, the most prominent development in 3D printing has been the advent of remarkably low-priced personal 3D printers. Thanks to a wave of open-source projects, starting with the RepRap printer and then the popular Makerbot, 3-D printing has fallen below $1000 and printers are found in schools, homes, and countless makerspaces (Anderson, 2012 p.234). Interestingly, it wasn't started by the biggest, leading companies with infinite resources, but an open innovation project involving university researchers and hobbyists around the world. Subsequently, this open-source printer project facilitated the birth of several entrant 3D printer manufacturers in garages and hobbyists' workspaces, creating a new product class of very affordable, simple and in certain aspects inferior 3D printers – again resembling the birth history of the personal computers. Today, the growth of their unit sales is nothing short of breathtaking and the segment seems to yield new ventures and models almost weekly.

A new product emerges, introduced by entrant companies, which lags in performance but has the potential to begin winning market share due to its low price and new product attributes. In the same way that PC's eventually caused minicomputers to fall by the wayside, the theory of disruptive innovations suggests that also these 3D printer entrants may be in a position to challenge or even displace the incumbent 3D printer manufacturers, which until fairly recently only manufactured considerably more expensive industrial-grade printers. And the best way for upstarts to attack established competitors is to disrupt them (Christensen & Raynor, 2003 p.32).

The phases that the 3D printer industry is going through are thus not novel and the theory of technology disruption provides a lens through which the phenomenon can be analyzed. In this thesis, I intend to introduce the reader to the process of disruptive innovation and its categories, examine the factors that have led to the advent of the personal 3D printers, and address whether the performance of this new class of personal machines has developed enough to disrupt the market of industrial entry-level 3D printers. The ultimate goal is to find out how well the personal 3D printers fit the theory of disruptive innovations, and if they form a potential or actual threat of displacement for the incumbent manufacturers.

1.2. Research gap and research questions

In his model of theory-building, Christensen (2006 p.41) suggests researchers to test the theory of disruptive innovations in a deductive fashion to see if the same correlations exist between attributes and outcomes in a different set of data than from which the hypothesized relationships were originally induced. Also Danneels (2004 p.250) encourages scholars to use the foundation provided by Christensen for theory-testing purposes. Despite the maturity of the technology, the core works in the research field of disruptive innovations do not seem to have addressed 3D printing, which may be due to the fact that it has risen to wider prominence only during the last few years.

However, the claim that 3D printing a disruptive technology in the sense that it will disrupt traditional manufacturing lacks in context, since disruption always occurs relative to another product, company or industry. Also, the actual disruptive aspect of 3D printing needs to be determined. Many authors have drawn comparisons between the first personal 3D printers and certain prior technologies and products – such as personal computers (see e.g. Gershenfeld, 2012; Malone & Lipson, 2007; Anderson, 2012; Wohlers Associates, 2011) and the first laser printer (Anderson, 2012). Interestingly, Christensen's (2000) theory of disruptive innovations is built on cases regarding these very same products – among many others, such as hard drives and steel mills. Thus, focusing on personal 3D printers with industrial ones as the assumed target of disruption offers seems to offer a natural direction to expand the theory of disruptive innovations.

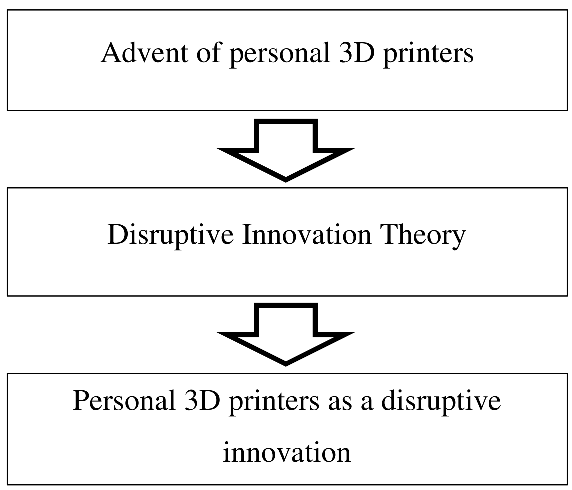


Figure 1. Research approach for the thesis.

Figure 1 illustrates the thesis' research approach, which I will address by following a set of research questions. The main research question is:

Can personal 3D printers be classified as a disruptive innovation?

I intend to tackle the question by providing answers for these subquestions:

1. *How is a disruptive innovation defined and how does it occur?*
2. *What factors have contributed to the advent of personal 3D printers?*
3. *How do personal 3D printers differ from entry-level industrial printers?*
4. *Is there evidence that personal 3D printers are displacing industrial printers?*

The conceptual commitments of the thesis relate to additive manufacturing, disruptive innovations, open innovations and startup companies. Following this introduction, I will discuss the relevant literature about disruptive innovations. Then I will address the key factors that have contributed to the birth of the personal 3D printer segment. Continuing from there, I will present the methodology for the study. Empirical findings will then be assembled and discussed, finally leading to conclusions and suggestions for further research. Remember the expert that I quoted in the beginning? At the end of this thesis, I will try to evaluate in the light of my findings if he was indeed right, wrong or something in between.

2. Literature review

The literature review consists mainly of the following articles relating to the theory of disruptive innovations (see Figure 2), in chronological order.

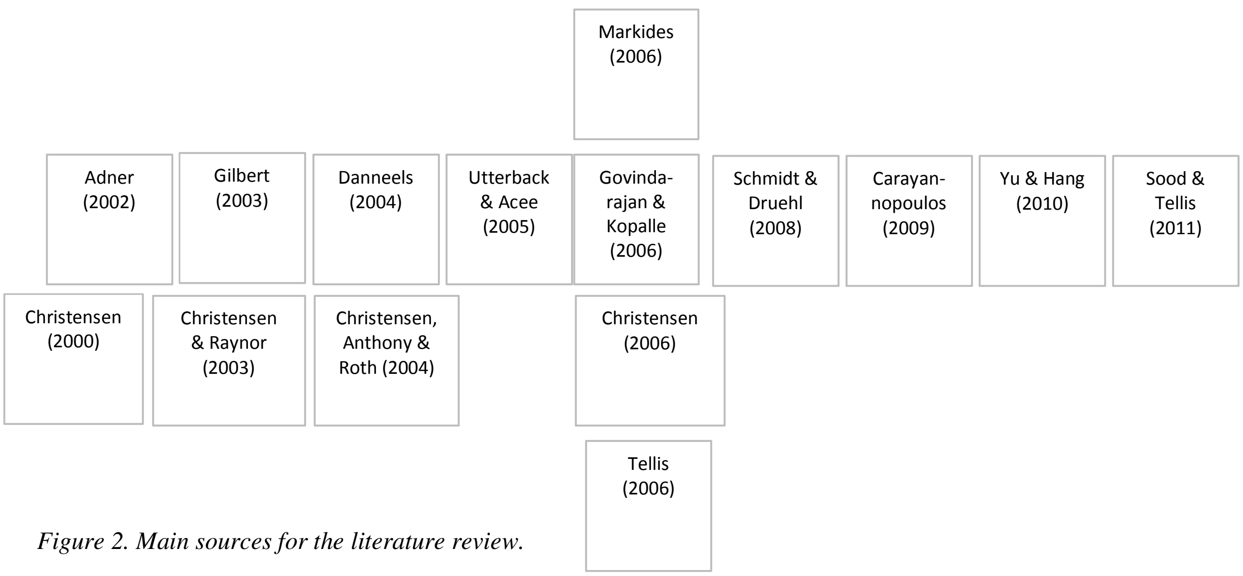


Figure 2. Main sources for the literature review.

2.1. General characteristics of a disruptive innovation

The Theory of Disruptive Innovations – or disruptive technology, as it was first called – builds fairly heavily on the work of Clayton M. Christensen, who popularized the theory, helped it rise to prominence and launched a significant amount of academic discussion around it. Christensen's first book on the topic, "The Innovator's Dilemma" (1997) articulated the basic theory of disruptive technology in a comprehensive and detailed manner (Yu & Hang, 2010 p. 436). Christensen further built on the theory by co-authoring the books "The Innovator's Solution" (2003) and "Seeing What's Next" (2004), along with numerous journal articles.

By identifying the possibility that technologies with inferior performance can displace established incumbents companies, his theory has had a profound effect on how to approach technology competition (Adner, 2002) and been cited extensively by scholars (Danneels, 2004). The theory has also created a significant impact on management practices and aroused plenty of rich debate within academia (Yu & Hang, 2010). Tellis (2006 p.34) calls Christensen's concept a highly praised and critical contribution to the strategy literature. The impact of his thesis has been enormous both in the business and academic communities (Tellis, 2006 p.34; Danneels, 2004 p.257). Schmidt & Druehl (2008 p.349) even called Christensen's work groundbreaking and seminal. It should be noted that in addition to Christensen (2000, 2006), Christensen & Raynor (2003) and Christensen et al (2004), also other authors have greatly contributed to the theory: Yu & Hang (2010 p.445) pointed out that the Disruptive Innovation Theory has been extensively studied in the extant literature. Next, I will introduce the reader to its basic premises of the theory.

The following is a summary of Christensen's (2000) work. He described the theory of disruptive technologies as a process, whereby an entrant company had developed a product that was inferior in performance compared to the incumbents' products, but also significantly cheaper to buy. Meanwhile, incumbent companies would make products that offered performance that actually exceeded the customers' needs in their primary attributes. The new disruptive product would only be just "good enough", filling the needs of the lowest customer segment on the market, but at a considerably lower price than the incumbent's product. Typically, the product would come with secondary performance attributes that appeal to customers. Eventually the disruptive technology product would improve in performance in the primary performance attribute to attract higher customer segments, while the incumbents would feel tempted to leave the low-margin segments for the entrant and migrate to even higher-margin ones. Christensen found many cases where the incumbent was eventually driven from the market altogether by the entrant, the products of which were at least initially inferior to the incumbents' ones in the primary performance attributes.

At this juncture, the key concepts of entrant and incumbent companies should be elaborated. The former are those firms that were new to the industry at that point of technology change, whereas the latter are firms that had been established in the industry prior to the advent of the new technology, practicing the prior technology. (Christensen, 2000 p.9) For my purposes, I will use "established firms" as a synonym for incumbents.

Christensen (2000) derived the original theory from historical data, primarily from the computer disk drive industry, along with several other products and industries such as hydraulic excavators, accounting programs, minicomputers, desktop computers (PCs), laptops, steel minimills, inkjet printers and small Honda motorcycles. He observed disruptive technologies mostly in B2B, but also in B2C markets. As Yu & Hang (2010 p. 437) and Markides (2006 p. 19) point out, Christensen & Raynor (2003) widened the application of the theory beyond physical products and technologies to include services and business model innovations as well.

Christensen & Raynor (2003 p.43) argue that many of the most profitable growth trajectories in history have been initiated by disruptive innovations. They also claim that the best way for upstarts to attack established competitors is to disrupt them (Ibid, p.32). Also, Govindarajan & Kopalle (2006 p. 12) separate disruptive innovations from other innovations by calling them strategically important innovations. Gilbert (2003 p.32) even argued that disruption has been and will continue to be a tremendous source of growth in the economy. However, it should be noted that most innovations are not disruptive. Many of the most important and most profitable innovations are actually sustaining innovations that take a good product or service and make it better. (Christensen et al, 2004 p.270) In contrast to sustaining innovations – which are often mastered by incumbents – Christensen & Raynor (2003 p.34) describe a disruptive innovation the following way:

> *"Disruptive innovations, in contrast, don't attempt to bring better products to established customers in existing markets. Rather, they disrupt and redefine that trajectory by introducing products and services that are not as good as currently available products. But disruptive technologies offer other benefits – typically, they are simpler, more convenient, and less expensive products that appeal to new or less-demanding customers."*

Christensen suggested that disruptive products tend to be smaller, simpler, cheaper, more reliable and convenient than established or preceding products. He also found that disruptive products generally offered lower margins and lower expected growth figures than existing products. (Christensen, 2000) It is important to note that a disruptive technology need not be principally novel or supreme in terms of performance or development. In fact, Christensen (2000 p. 215) elaborates:

> *"Historically, disruptive technologies involve no new technologies; rather, they consist of components built around proven technologies and put together in a novel product architecture that offers the customer a set of attributes never before available."*

Danneels (2004) suggested the following as the core of the definition of a disruptive technology: *A disruptive technology is a technology that changes the bases of competition by changing the performance metrics along which firms compete*. This is in line with Christensen's (2000) theory, whereby a key characteristic of a disruptive technology is that it heralds a change in the basis of competition. He claims that once the customers' demands in one functional aspect have been satisfied, their demand shifts to put greater emphasis on other aspects of the product that were previously considered secondary. (Christensen, 2000) Adner (2002 p.669) captured disruptive technology's dynamics in three aspects:

> *"Incumbent technologies that are displaced from the mainstream market by technologies that underperform them on the performance dimensions that are most important to mainstream consumers; mainstream consumers who shift their purchases to products based in the invading technology, even though those products offer inferior performance on key performance dimensions; and incumbent firms that do not react to disruptive technologies in a timely manner"*.

Christensen showed that technology disruption occurs when the performance improvement trajectory of the disruptive technology intersects with the trajectory of performance demanded by the market (Christensen, 2000 p.206; Yu & Hang, 2010 p. 436; Danneels, 2004 p. 249). At this point, the disruptive product will meet the demands of the mainstream market in the primary performance attribute. I will illustrate this process in the next section.

Christensen (2000) found that disruptive technologies typically have a lower sticker price per unit than products that are used in the mainstream, even though their cost in use is often higher. On the other hand, the price per unit of performance was in many of his cases higher, e.g. price per megabyte in disc drives and price per cubic yard of soil moved in hydraulic excavators. (Christensen, 2000 p. 214) Adner (2002) makes the connection between disruption and prices more prominent and claims that while disruption is enabled by sufficient (good enough) performance, it is enacted by price. He found the price to be a key mechanism in consumers shifting to the disruptive product. A lower absolute purchase price seems to be an inherent quality of a disruptive innovation also the way Christensen and his co-authors see it. However, several other researchers (see e.g. Utterback & Acee (2005); Govindarajan & Kopalle (2006); Schmidt & Druehl (2008); Sood & Tellis (2011); Carayannopoulos (2009) consider even a high-priced product as one category of disruptive innovations.

Christensen (2000 s.227) asserted that disruptive technology should be framed as a marketing challenge, not a technological one. While developing the theory further, Christensen & Raynor (2003) suggested that the moniker "disruptive technology" be replaced by "disruptive innovation" in order to avoid people twisting the concept to equate with words like "radical" or "breakthrough". Christensen (2006) admits that the phenomenon was originally named in a misleading way. Labeling it "disruptive technology" was in his words a mistake, since it is the disruptive business model in which the technology is deployed that paralyzes the incumbent leader – hence making it a business model problem, not a technology problem. (Christensen, 2006) These findings were supported by Yu & Hang (2010 p.437) who believed that "disruptive innovation" was a more appropriate term to describe the entire phenomenon, since it heavily involves business model innovations. Expressing it in terms of disruptive business models was considered by Christensen to be an important improvement to the theory. Further, Christensen (2006) concurred with the perception of Intel Corporation chair Andy Grove that the phenomenon should have been labeled as "Christensen Effect", in order to avoid the many confusing connotations of the term "disruptive" in the English language, such as "failure" and "radical" (Christensen, 2006).

Christensen's (2000) original work yielded anomalies, which he addressed in his later publications in order to improve the theory's explanatory power. One improvement in the definition was to view the concept of disruption as a relative phenomenon. According to Christensen, it is not an absolute phenomenon but can only be measured relative to the business model of another firm. An innovation that is disruptive relative to the business model of one firm can be sustaining relative to the business model of another. Relativity is a crucial concept in the theory of disruption. (Christensen, 2006) For example, selling computers over the Internet was a sustaining innovation for direct-sales pioneer Dell, but for retail-channel oriented Compaq, HP and IBM it was disruptive (Yu & Hang, 2010 p. 439).

Another important improvement in definition by Christensen (2006) is that of disruption as a process, not as a cataclysmic event. This observation is also supported by e.g. Yu & Hang (2010 p. 436) and Christensen & Raynor (2003 p.69). Observing a disruption take place may take a certain period of time before the effects are seen. Christensen & Raynor (2003 p.69) noted that even if the incumbent leader wouldn't be instantly killed by a disruption, the theory isn't false. They emphasize that the forces are operating all of the time in every industry, and while in some industries it may take decades for the forces to work their way through, in some cases it takes a few years. In many of Christensen's (2000) cases the incumbents nevertheless met their demise after being driven away from the market. As typical as it may be, it is not inevitable in the light of these findings.

In his original work, Christensen (2000) demonstrated how disruptive innovations captured the lowest customer segments of the incumbent companies' market. This approach was later amended by Christensen & Raynor (2003), who recognized two approaches to disruptive innovations; in addition to the low-end disruption, they coined the new-market disruption. The notion that a disruptive innovation could at least initially form an entirely new market was supported by e.g. Schmidt & Druehl (2008). In their theory, certain types of disruptive innovation would set off in a new market segment and encroachment of the incumbents segment would only occur at a later stage. In a similar fashion, Adner (2002) clearly distinguished between two market segments, making the implicit assumption that the disruptive product would initially be sold in a different market than the one it would at a later point expand to and take over. Also Govindarajan & Kopalle (2005, see 2006 p.13) argue that the innovation's new attributes and lower price may be valued by a new customer segment or the more price-sensitive mainstream market. So the true importance of disruptive technology – even in Christensen's conception of it – is not that it may displace established products. Rather, it is a powerful means for enlarging and broadening markets and providing new functionality. (Utterback & Acee, 2005 p.1)

In addition, Christensen (2000) strongly associates the phenomenon with management failure on behalf of the incumbents to identify competitive threats. When knowledgeable about the phenomenon, management can respond to the threat effectively, as Intel did with the disruptive Celeron microprocessor (Euchner, 2011; Christensen, 2006).

To summarize, a disruptive innovation need not necessarily capture the entire market or completely displace the incumbents. A disruptive product may also begin by expanding the market and forming a new segment of its own. Also, the possible encroachment may not begin instantly.

2.2. Categories of disruptive innovations

As we can imagine, the confusion in the definition of disruptive innovations leads to confusion about its categorization as well. Danneels (2004 p.250) notes that the concepts and mechanisms of the theory from earlier work are becoming increasingly "stretched", and it is therefore necessary for scholars to develop very careful definitions and classifications of types of technological change. Markides (2006 p.19) notes that over time, the same theory has been used to explain all kinds of disruptive innovations. He considers this to be a mistake, since different kinds of innovations have different competitive effects and produce different kinds of markets. He calls out for breaking the phenomenon down into finer categories and claims that only then can progress be made. (Markides, 2006 p.19) Also Carayannopoulos (2009 p. 435) suggested identifying and categorizing a number of different types of disruptive innovations.

In addition to the original set of disruptive innovations in Christensen (2000), Christensen & Raynor (2003 p.56-65) introduced a wide variety of additional examples ranging from e.g. Amazon.com for books, Black & Decker handheld power tools, Bloomberg financial news, community colleges, Canon photocopiers, catalog retailing to even 802.11 wi-fi networks as disruptive innovations. Markides (2006 p.24) underlines that while all of these may be equally disruptive to incumbent companies, they should be treated as distinct phenomena. Also Govindarajan & Kopalle (2006) argue that Christensen's examples differ from each other in the extent of how radical they are.

Christensen (2000 p.9) originally divided innovations into two categories: *sustaining* ones and *disrupting* ones. The first sustain the industry's rate of improvement in product performance and range in difficulty from *incremental* to *radical*. He found industry incumbents to typically lead in developing and adopting these sustaining innovations. Christensen et al (2004, p. 270) clarify that many of the most important and most profitable innovations are sustaining innovations that take a good product or service and make it better. On the other hand, the disrupting ones redefine performance trajectories, and they are often created by industry entrants (Christensen, 2000).

Christensen & Raynor (2003) refined Christensen's (2000) original theory by further dividing disruptive innovations into *low-end* and *new-market disruptions* – Christensen (2006) later noted these two to be fundamentally different phenomena. Figure 2 illustrates how Christensen and his co-authors have categorized sustaining and disruptive innovations in their works. It's important to note that few technologies or business ideas are intrinsically sustaining or disruptive in character. These are extremes in a continuum, and the disruptiveness of an innovation can only be described relative to various companies' business models, to customers, and to other technologies. Put differently, much depends on the implementation of an idea. (Christensen & Raynor, 2003 p. 32, 122)

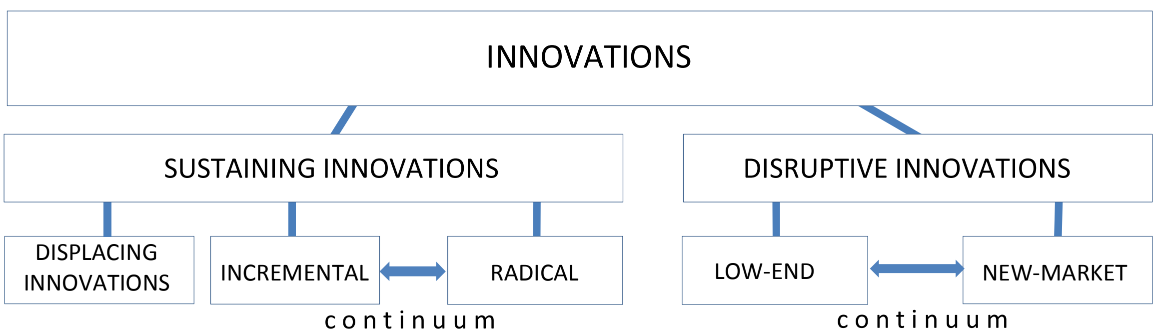


Figure 3. Innovation categories. Adapted from Christensen (2000); Christensen & Raynor (2003) & Christensen et al (2004).

Simply put, a new-market disruption is an innovation that enables a larger population of people who previously lacked the money or skill, to now begin buying and using a product and doing the job for themselves (Christensen and Raynor, 2003 p. 102). In contrast, low-end disruptions are those that attack the least-profitable and most overserved customers at the low end of the [incumbents'] original value network (Christensen & Raynor, 2003 p. 45). Interestingly, Christensen et al (2004 p.270) seem to closely associate the low-end approach to business model innovations. Since the notion of low-end disruptions seems to offer little beyond the original version of the theory I've already explained in detail, I will concentrate on the new-market ones, which clarify the theory greatly.

> *"We say that new-market disruptions compete with "nonconsumption" because new-market disruptive products are so much more affordable to own and simpler to use that they enable a whole new population of people to begin owning and using the product, and to do so in a more convenient setting. The personal computer and Sony's first battery-powered transistor pocket radio were new-market disruptions, in that their initial customers were new consumers – they had not owned or used the prior generation of products and services. Canon's desktop photocopiers were also a new-market disruption, in that they enabled people to begin conveniently making their own photocopies around the corner from their offices, rather than taking their originals to the corporate high-speed photocopy center where a technician had to run the job for them. When Canon made photocopying so convenient, people ended up making a lot more copies."* (Christensen & Raynor, 2003 p.45)

In other words, new-market disruption refers to a situation where potential customers are nonconsumers, or there is a new (nonconsuming) context. It forms new value networks [the third dimension in Figure 6] which constitute either new customers, or different situations in which a product can be used – enabled by improvements in simplicity, portability and product cost (Christensen & Raynor, 2003 p.44-45). And while new-market disruptive innovations lack the raw functionality of existing products, they bring new benefits such as convenience and customization (Christensen et al, 2004 p.7). Not unlike low-end disruptions, Christensen et al (2004, p. 7-8) note that new-market disruptions are always relatively low-priced, too, but not necessarily cheap on an absolute scale. The authors point out that the first mobile phones, PCs and cameras were expensive yet significantly more affordable than other available technological solutions.

In addition to the examples in quote above, Christensen et al (2004, p. xvii, 8) categorize the inexpensive Kodak Funsaver camera, Bell telephone, Xerox photocopier, Apple PC, eBay online marketplace as well as the first mobile phones as new-market disruptive innovations. The authors argue that they all created new growth by making it easier for people to do something that historically required deep expertise or great wealth. In addition, Christensen (2000, p.151-152; 2003) noted already in his earlier work that the 50cc Honda Supercub motorcycles created “a totally new market segment” and were thus a new-market disruption. Also the transistor was considered by Christensen et al (2004, p. 156) to have been a new-market disruptive innovation in the 1940s.

Furthermore, Christensen & Raynor (2003 p. 48, 60) considered inkjets printers to be a new-market disruption in relation to laser printers. Inkjet was slower than the laser jet, its resolution was worse, and its cost per printed page was higher. But the printer itself was smaller and potentially, much less expensive than the laser jet. (Christensen 2000 p.116) Curiously, Christensen and his co-authors didn’t classify laser printers as a disruptive technology; apparently lasers were more expensive and superior in performance to earlier dot-matrices, and as such sustaining technology. Also, Christensen & Raynor (2003 p.48, p.57 p.60) classified Canon tabletop photocopiers as a new-market disruption in relation to earlier technician-operated Xerox systems – which he again considered to be a new-market disruption, too, but in relation to the former technology which was offset printing.

At this juncture, it is worth noting that many disruptions already mentioned are actually hybrids that combine new-market and low-end approaches. One example of such a hybrid is Southwest Airlines, which offered low prices and initially targeted those passengers who would not have otherwise flown at all (Christensen & Raynor, 2003 p.47; Christensen et al, 2004 p. 137). Christensen & Raynor also define the Canon photocopiers, digital printing (locally used laser- and inkjet printers as opposed to offset printing) and Black & Decker consumer power tools as hybrids. As we will see more closely in the next section, low-end and new-market disruptions actually form a continuum and an innovation can thus find its place anywhere along it. In addition, it is preferable to compete against nonconsumption: only if nonconsumers aren’t available should one turn to low-end disruption. (Christensen & Raynor, 2003 p. 48, 288)

Christensen’s (2000) notion of *sustaining innovations* deserves more attention at this point. He defined them as improving the performance of established products, along the dimensions of performance that mainstream customers in major markets have historically valued. He also found most technological advances in a given industry to be sustaining in character, and to rarely cause the failure of leading firms. Established firms can usually implement them successfully. (Christensen, 2000 p. xv, 42) As previously mentioned, he further classified up-market sustaining innovations to fall on a continuum between *radical* and *incremental* improvements, later supplementing these with *displacement* innovations. The latter ones are innovations that target a specific piece of an industry's value chain. (Christensen et al, 2004 p. 10, 284-285)

By far the most significant debate in literature about categorization concerns the so-called "high-end" disruptive innovations, in which the performance and/or price of the innovation are deemed by many authors to be higher than that of incumbent products. Yu & Hang (2010 p.438) call such high-end disruption "a white space where Christensen's theory has not set foot". Christensen's approach is said to be limiting in that it ignores other discontinuous patterns of change by emphasizing only "attack from below", (Utterback, 1994; Acee, 2001; see Utterback & Acee, 2005 p. 1). While several authors recognize the existence of the category, terms and definitions vary.

Just like performance oversupply leads to overshot customers, Christensen et al (2004) admitted that there can be undershot customers, too, who do not consider a product's current performance adequate. While companies can create new-market disruptive innovations to reach nonconsumers; and launch low-end disruptive innovations or modular displacements to reach overshot customers; they can also launch *up-market sustaining innovations* to reach the undershot customers. (Christensen et al, 2004 p.4) In other words, Christensen and his co-authors classify high-end innovations as sustaining ones, not disruptive. In the same vein, Schmidt & Druehl (2008 p.348) associate "high-end encroachment" (taking sales away from the old product by means of a high-end innovation) only with sustaining innovations and "low-end encroachment" (taking sales by means of a low-end innovation) only with disruptive ones.

Further, Christensen & Raynor (2003 p.68) provide examples of technologies that they considered highly innovative yet not disruptive – such as the jet engine, which was a radical but sustaining innovation relative to the piston aircraft engine. HP's laser jet computer printer business was a sustaining technology relative to dot-matrix printers, a market dominated by Epson. The authors point out that the theory of disruption cannot explain these anomalies. Utterback & Acee (2005, p. 1) coined the term "high-end disruption" for such cases where a seemingly technologically superior technology disrupted industry incumbents' products, adding the cases of fuel injection replacing carburetors and electronic calculators replacing slide rules as further examples. Christensen (2006 p.50) confirms the cases of fuel injection and the electronic calculator as examples that disruption theory cannot account for. While Christensen acknowledges that some have suggested these as instances of high-end disruption, he nevertheless proposes that another mechanism of action has caused [industry] leaders to miss these high-end innovations (as he calls them) and that another category should be found for these anomalies. Schmidt & Druehl (2008 p. 362) concur with Christensen that they wouldn't classify the cases of calculator and fuel injection as disruptive, but examples of high-end encroachment (see "Patterns of diffusion") and sustaining innovations.

In addition to Utterback & Acee, also Govindarajan & Kopalle (2006 p.14) recognize the existence of low-end and high-end disruptive innovations. However, they use the latter term to describe innovations that have a higher price but not necessarily higher performance in primary product attributes. Instead, they consider high-end ones to be "more radical" – resembling the concept of radical disruptive innovations. In addition, to further complicate things, they distinguish a category of *non-disruptive radical innovations* which they associate with Christensen's concept of sustaining radical innovations. (Govindarajan & Kopalle, 2006)

Yu & Hang (2010 p.438) and Govindarajan & Kopalle (2006 p.15) classify cellular phones as a high-end disruptive innovation with an initially higher price. This is in contrast to aforementioned Christensen et al (2004) as well as Schmidt & Druehl (2008 p.348) who instead classified them as new-market disruptions: they point out that it took cell phones 25 years to actually begin disrupting land lines – by which time, I might add, their prices had already dropped significantly. Christensen et al (2004, p. 8) also considered cell phones to have been significantly more affordable and convenient than the only real alternative, multiple CB radios. Further, Schmidt & Druehl's (2008 p.359) conclusion is that there are exceptions to Christensen et al's (2004) rule that disruptive new-market innovations are low-priced. Markides (2006 p.22-23) classified mobile phones as a radical (new-to-the-world) innovation which may initially come with a higher price but become affordable later on.

In addition to the high-end disruptions, also the notion of "radical" disruptive innovations has aroused controversy in the literature. A *radical product innovation* was defined by Chandy & Tellis (2000) as a "new product that incorporates a substantially different core technology and provides substantially higher customer benefits relative to previous products in the industry". However, they did not classify these as disruptive. Govindarajan & Kopalle (2006 p.14) make an interesting contribution by attributing radicalness as a technology-based dimension of innovations, and the disruptiveness as a market-based dimension. In contrast, Christensen & Raynor (2003 p.143) strongly emphasize that disruptive innovations usually don't entail technological breakthroughs, but rather package available technologies in a disruptive business model. Along with simple, incremental ones, the authors considered dramatic, leapfrog innovations to be sustaining innovations.

Christensen et al (2004 p. 270) further elaborate that different or radical technology does not equal disruptive. The authors identified *radical sustaining innovations* to be at the complex end of the continuum of sustaining innovations. They found that these "great leaps forward" tend to be very complicated and expensive and only possible for incumbent companies (Christensen 2004 p.285) Christensen (2006 p. 42) underlines that the term "disruptive" should not be associated with connotations such as "radical". Also Smith (2005, p.214) commented in his book review that new product development professionals should adopt the definitions of sustaining and disruptive innovations and avoid the mistake of calling all radical innovations disruptive.

Markides (2006 p.19) makes a distinction between a *disruptive technological innovation*, *disruptive business-model innovation* as well as a *disruptive product (new-to-the-world) innovation*. In contrast to Christensen and his co-authors, the third category he discovered consisted of *radical product innovations* which create disruptive *new-to-the-world products* – for example the car, television, PCs, VCRs, and mobile phones. They are disruptive to producers because the markets they create undermine the competences and complementary assets on which existing competitors have built their success. (Markides, 2006 p.22) Christensen (2006 p.48) noted that many of the innovations Markides cites as new to the world were really not, such as the PC and the mobile phone. Christensen adds that most innovations can be expressed relative to a preceding form of the same. He nevertheless gives recognition to Markides' notion of ''new to the world'' innovations and admits that he didn't consider this classification carefully enough. Where an innovation cannot be described relative to a preexisting product or technology, we can say it indeed was new to the world. (Christensen, 2006 p. 48)

Further, Caraynnopoulos (2009) introduced four types of disruptive technologies/innovations: *radical, architectural, modular (component)* and *incremental*, classified in four sections of a table with two dimensions – challenging of existing modular or architectural knowledge, both or neither of them. She classified a desktop PC as a *disruptive architectural innovation*, because it represented a reconfiguration of existing components, and the electronic calculator as a *radical disruptive innovation*, since it has both significantly different component as well as architecture dimensions, and thus the scientific principles on which it operates differ substantially from the slide rule it replaced. (Carayannopoulos, 2009) Christensen (2000 p.15, 215) notes that disruptive technologies – such as those in the disk drive industry – have proven technology/components but a novel product architecture.

In a somewhat similar fashion, Sood & Tellis (2011 p.340-341) allocate technologies in three categories: *platform*, *design* and *component* innovations. The first is based on a unique scientific principle, the second on (new) linkages or layout within same scientific principle and the third on (new) materials or parts within same scientific principle. For example, the authors classified 3.5" disk drives to be design innovation relative to the 5.25" drives. Curiously, they classify digital cameras as "platform" technologies, that is, as the most fundamental disruptive technologies, while Carayannopoulos (2009) sees them merely as modular innovations. These design and component innovations lead to performance improvement over time of the actual platform technology (Sood & Tellis, 2008 p. 340). While the authors admitted that disruption may occur in design and component innovations, they only included platform technologies in their search for disruptive innovations. (p.344, 352) In addition, these seem to equate to radically new technologies, which Christensen and his co-authors clearly categorize as sustaining innovations. This difference in defining a disruptive innovation may explain why Sood & Tellis' (2011) results cannot confirm many of Christensen and his co-authors' findings.

Interestingly, Utterback & Acee (2005 p.14) made a similar observation about fuel injection, which "represented an architectural change in the fuel delivery systems as well as a change to the system components when compared to carburetion." They call it a disruptive technology as it differed dramatically from the incumbent carburetor-based technology. Thus, Carayannopoulos' category of radical disruptive innovations could also account for Christensen's (2006) anomalies (calculator, fuel injection) mentioned above.

To summarize, innovations and disruptive innovations can be divided into different categories. Sustaining innovations can be either incremental or radical, and incumbents usually fair well with them. In contrast, disruptive innovations can be low-end or new-market ones, depending on the initial set of customers. Disruptive innovations are typically low-priced and have a low performance, although many authors suggest high-end innovations can be disruptive, too. Often such innovations (such as the cell phone) are initially expensive, and begin really disrupting the market only once their prices have gone down over time, and are thus not at odds with the perception of disruptive innovations as low-priced. Also radical innovations have been suggested to be disruptive. Literature suggests that disruptive innovations are architectural innovations, using known components in a new arrangement. A highly innovative and disruptive product is not necessarily a disruptive innovation as such.

2.3. Process of disruption

2.3.1 Basic model explained

Christensen (2000) originally illustrated the process of disruption by comparing the performance development trajectories of an incumbent technology and the entrant/disruptive one. In his model, Christensen assumes that the performance of both the incumbent and the entrant product improves over time – which explains the ascending solid lines (Christensen et al, 2004 p.xvi). Figure 4 presents a simplistic, early version of the model.

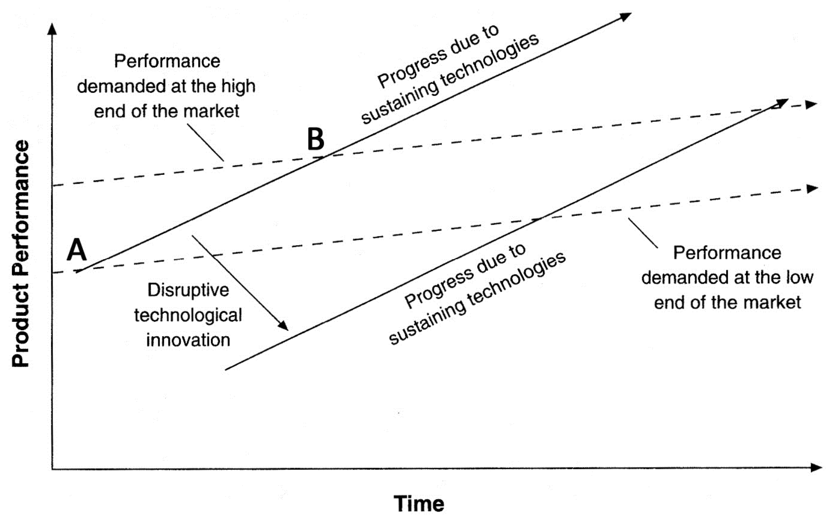


Figure 4. The Impact of Sustaining and Disruptive Technological Change. Christensen (2000, p. xvi)

The trajectory on the left depicts the incumbent's offering, whereas the one on the right is the new, entrant offering. The dotted lines represent the scale of product performance the market demands and is able to use (Christensen et al, 2004 p.xvi). In most industries, a market is made up of many different groups of customers, who can be classified by how demanding they are. At the high end of a market are demanding customers who have very tough problems to solve. At the low end of the market are less demanding customers who have relatively fewer or less complex requirements to satisfy. These "tiers" are illustrated by the dotted lines and the great majority of customers is somewhere in the middle. This majority of customers is termed the core of the market, or the mainstream customer. (Christensen et al, 2004 p. 9; 277-278) As we shall see, it is this concept of mainstream that plays a key role in the process of disruption.

Figure 5 shows basically the same thing, while better visualizing the point where the disruptive product develops to become "good enough" for the mainstream market, and thus begins to seriously threaten the incumbent. It is important to note that the disruption does not occur with the introduction of the disruptive innovation. Only when the disruptive innovation's trajectory of performance development intersects with the trajectory of performance demanded by the *core* or the *mainstream* of the market, the actual disruption is said to occur – marked by the little star in Figure 5 (see e.g. Adner, 2002; Yu & Hang, 2010).

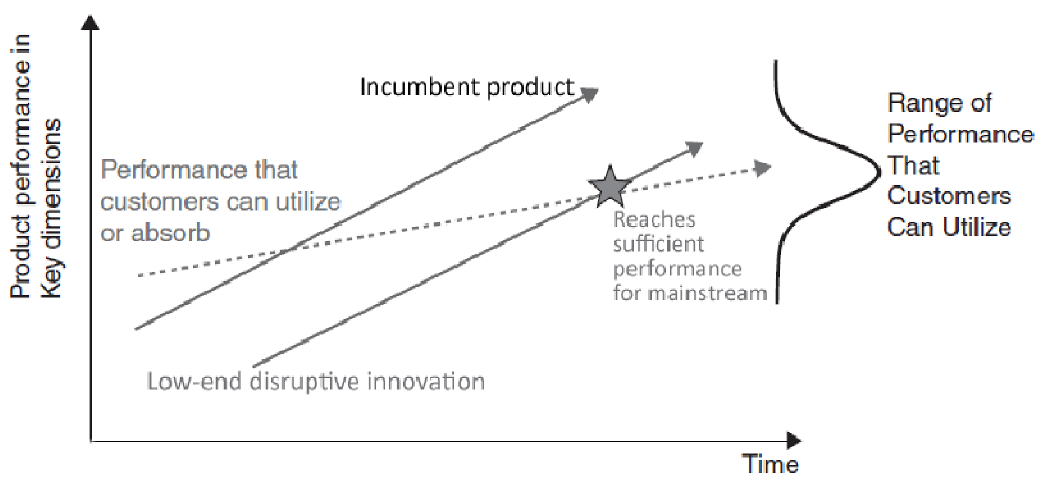


Figure 5. The Disruptive Innovation Model. Modified from Yu & Hang (2010) and Christensen & Raynor (2003 p.33).

At that stage, a significant amount of incumbents' customers begin migrating to the disruptive product. As we saw earlier, the process may even take years or decades. It took twenty-five years for wireless telephony [cell phones] to seriously begin to erode the wireline business

(Christensen et al, 2004 p.43) and well over 30 years for minicomputer makers to develop a sustaining lead in revenues in relation to incumbent mainframe computer manufacturers. Disruption is thus not an immediate phenomenon — it can take years and even decades before the upstart business encroaches heavily on the established market. (Gilbert, 2003 p. 29, 27)

The initial market segment of the disruptive innovation is often called a “niche” segment (see e.g. Carayannopoulos, 2009; Sood & Tellis, 2011; Yu & Hang, 2010; Govindarajan & Kopalle, 2006) or “marginal market” (Danneels, 2004). Adner (2002, p. 679) found this entry point to consist of lower-end consumers. The mainstream and niche segments have similar needs but differ in their preferences: the mainstream segment favors the primary [performance] dimension, whereas the niche segment favors the secondary dimension (Sood & Tellis, 2011; Schmidt & Druehl, 2008). Initially, the disruptive innovation is not good enough to meet the performance requirements of the core market in the attribute that matters to them most. However, they are typically more affordable and simpler to use [secondary attributes] than products in the incumbent’s product portfolio. The disruptive innovators aggressively move up-market on their own sustaining improvement trajectories as they pursue more attractive profit margins. Ultimately, when the disruptive innovation is good enough to meet the needs of larger swaths of the incumbents customers, the incumbent is forced further up-market or out of the market entirely. (Christensen et al 2004 p.279) In other words, the disruptive product’s initial market consists of customers who value the secondary attribute; only once the product develops to become good enough also in the primary performance attribute, does it become attractive to the mainstream of the incumbent’s customers as well.

Disruptive technologies generally improve at a parallel pace with established ones – their performance trajectories do not intersect (Christensen, 2000, p.51). In other words, they don’t necessarily improve to surpass the performance of the prior technology. They generally do not, and need not. (Christensen, 2006, p.50) In contrast, Sood & Tellis (2011 p. 342, p.347) define technology disruption as a situation where the performances of the new technology actually crosses the performance of the dominant technology on the primary dimension of performance. They formed performance trajectories on e.g. desktop printers – using print resolution as an attribute – and found that while inkjet printers were initially inferior to other technologies such as laser and dot-matrix, they improved over time to surpass all of them. To clarify, Christensen (2000, 2006) does not expect or determine that the performance of the disruptive product should ever exceed that of the incumbents’ ones, yet he doesn’t rule it out.

It is also worth noting that Christensen et al (2004 p.48) define the disruptive innovation's improvement trajectory as sustaining (incremental), relative to its prior market position. The improvement cycle begins once the disruptive product gains a foothold in new or low-end markets. The previously not-good-enough technology eventually improves enough to intersect with the needs of more demanding customers. When that happens, the disruptors are on a path that will ultimately crush the incumbents. (Christensen & Raynor, 2003, p.34)

2.3.2. Performance oversupply

In Christensen's (e.g. 2000, p.183 & p.213) theory, the key driver for disruption is *performance oversupply*, the condition in which the rate of performance improvement provided by [an existing] technology exceeds the actual needs of the market. Companies innovate faster than customers' lives change. In other words, what people are looking to get done remains remarkably consistent, but products always improve. Thus, products eventually become too good, eventually overshooting the performance that some of their customers can use, and leading to performance oversupply. Christensen et al (2004, p. 12)

In other words, the incumbent's product or service offering has developed to offer such a high level of performance that some customers can no longer fully utilize it, or find it unnecessary, or can't justify its high price. These customers are ripe for a new product that offers just enough performance for their needs at a noticeably lower price point. When performance oversupply occurs, it creates an opportunity for a disruptive technology to emerge and subsequently to invade established markets from below (Christensen, 2000 p.183 & p.213). Historically, performance oversupply opens the door for simpler, less expensive, and more convenient – and almost always disruptive – technologies to enter. (Ibid, 2000 s.213)

This oversupply/overshooting begins at the bottom of the market and then creeps upward, but does not concern all customers at once (Christensen et al 2004 p.12). In other words, it progresses incrementally one customer tier at a time. If we return to Figure 4, the incumbent technology is overshooting the needs of the lowest tier of customers in the far left of the graph at point "A". Similarly, at point "B", the technology has developed far enough to overshoot the needs of even the highest-demanding customers.

Performance oversupply also triggers a fundamental change in the basis of competition in the product's market: the rank-ordering of the criteria by which customers choose one product or service over another will change. (Christensen, 2000 p.183 & p.213) In fact, it is a key characteristic of a disruptive technology is that it heralds a change in the basis of competition (Christensen, 2000 p.190). He observed from many markets how the product attributes demanded by the market evolved in phases, starting from *functionality* and evolving to *reliability* and *convenience* and finally to *price*, after the demand for each of the previous attributes had been adequately fulfilled. (Christensen, 2000; p. 189-190) Christensen et al (2004 p.12) took this a little bit further. They claimed that after functionality and reliability have become good enough, the next dimensions along which companies can compete relate to *ease of use* – how flexible and easy it is to use a product *(convenience),* how squarely a product lines up with individual customers' idiosyncratic jobs *(customization)*, and how much it costs to use a product *(price).*

Note that "good enough" is the key phrase that is used to describe the threshold performance requirement of the core market in a certain attribute (see e.g. Christensen et al, 2004, p. 279). When the functionality and reliability of products overshoot customer needs, then convenience, customization and low prices become what are not good enough (Christensen et al, 2004 p.18). To summarize: generally, once the performance level demanded of a particular attribute has been achieved, customers indicate their satiation by being less willing to pay a premium price for continued improvement in that particular attribute. Hence, performance oversupply triggers a shift in the basis of competition, and the criteria used by customers to choose one product over another changes to attributes for which market demands are not yet satisfied. (Christensen 2000 p. 187) As a result, disruption redefines performance trajectories (Ibid, p.9).

To illustrate, Christensen (2000 p.184) charted the performance of earlier 5,25" computer disk drives with newer, physically smaller and cheaper 3,5" inch drives and discovered that the earlier technology, while superior in absolute capacity, began falling by the wayside with the advent of the newer generation of drives. He assumed that the market demand for capacity was satiated – and, in fact, exceeded – so other attributes that were less satisfactory [such as physical size, power consumption and absolute price] came to be more highly valued by the market, thereby leading to new trajectories of product performance compared to market demands. (Christensen, 2000; p. 184-185) Specifically, in the desktop PC marketplace between 1986 and 1988, the smallness of the drive began to matter more than other features. The smaller 3.5-inch drive allowed computer manufacturers to reduce the size, or desktop footprint, of their machines. This was the first redefinition of the vertical axis – from capacity to physical size – and it was triggered by performance oversupply in capacity. While the 3.5" drives did provide less capacity than the 5.25" ones, they were both perfectly adequate for the desktop PC market Christensen (2000, p. 184; 186-187)

Adner (2002) analyzed the same disk drive industry context as Christensen above. He complemented Christensen's notion of performance oversupply with the logic of decreasing marginal utility, in other words, a decreasing willingness to pay for performance improvements. (Adner, 2002 p.685) As consumers' requirements are exceeded, they derive positive but decreasing marginal utility from further performance improvements. Put differently, as performance exceeds requirements, price increases in importance. (Adner, 2002 p.674) Based on his analysis, he suggested that instead of a new found appreciation for previously marginal (performance) attributes, the essential aspect of consumer choice which allows for disruptive displacement may be consumers' decreasing marginal utility from performance improvements (Adner, 2002). He found that this decreasing customer marginal utility and a lower absolute price were the key factors driving customer's choice for the disruptive product (the 3.5" disk drive), and not so much the other secondary product performance attributes.

Thus, Adner (2002 p. 686) considers the price at which the invader offers its product to be critical to a disruptive outcome. For this to happen, the product may be technically inferior but it must nonetheless be satisfactory and have a sufficiently lower price than rivals. In the disk drive case, Adner found that while the 5.25" drives offered greater absolute capacity at a better price/performance ratio, it was the lower absolute unit price of the 3,5" drives that allowed the latter to overcome the competition. Thus, consumers with sufficiently satisfied functional requirements are more concerned with differences in absolute unit price than with differences in price/performance points. (Adner, 2002 p.684) He concluded that when consumers face diminishing marginal returns to performance improvements, technologies that offer lower relative performance at lower price become increasingly attractive.

It's important to note that both Christensen (2000) and Adner (2002 p.684) share the view of the disruptive product as lower-priced and inferior in the primary performance attribute compared to the incumbent product. Markides (2006 p.20) found price to be one of the critical performance attributes emphasized by many new (disruptive) business models, while Sood & Tellis (2011) found the hazard of disruption (for both firm and technology) to be higher if a new technology is priced lower than the dominant technology at entry. We may thus assume that a low price is a strong contributor for the success of a disruptive innovation. On a final note, performance oversupply may be more relevant in a low-end disruption scenario than in a new-market one, since nonconsumers (in a new-market disruption) are by definition not overserved by current products (see Christensen et al, 2004 p.4).

2.3.3. Asymmetry of motivation

In addition to performance oversupply, asymmetry of motivation – as explained by Christensen et al (2003, 2004) – is claimed to be an important enabling factor for disruption. Industry leaders are always motivated to go up-market, and almost never motivated to defend the new or low-end markets that the disruptors find attractive – it is this phenomenon that Christensen & Raynor (2003, p.35) call *asymmetric motivation*. Disruptive attackers/entrants can take advantage of asymmetries of motivation. The expression refers to a situation where one firm wants to do something that another firm specifically does *not* want to do (italics by author). (Christensen et al, 2004 p.37-38)

More specifically, it applies to a case where the customer set of an entrant's initial market appear to the incumbent as either undesirable or nonexistent due to its small size. This shields the entrants from competitive response, because the incumbents simply aren't interested in defending that market. Christensen et al (2004 p. 115) also mentions differences in target customers and business models as examples of asymmetries that disruptive entrants can take advantage of. What looks like a highly attractive opportunity to the entrant, continues to look relatively unattractive to the incumbent – hence the asymmetric motivation. As the disruptive attackers have the incentive to continue to make inroads into the low end of the market, the incumbents on the other hand retreat to higher tiers and cede it to the entrant altogether. The incumbent may even view this as a positive development, since it allows it to concentrate on more profitable up-market segments and leave the least attractive customers behind. Even if the incumbents would later find the low-end market large enough to be attractive, asymmetric motivation would still hinder their response since they would typically require a different business model and need to acquire new skills quickly. (Christensen et al, 2004 p.37-42)

Successful low-end disruption requires having a shield of asymmetric motivation, which leads to incumbents fleeing from disruptive incursions at the low-end of their markets (Ibid, p.240). Note that while low-end disruptions motivate the incumbents to flee the attack, new-market disruptions induce incumbents to ignore the attackers. The disruptive [new-market] innovation doesn't invade the mainstream market; rather, it pulls customers out of the mainstream value network into the new one because these customers find it more convenient to use the new product. (Christensen & Raynor 2003 p. 46) In other words, the authors associate incumbents fleeing upmarket in particular with low-end disruption.

Entrants are motivated to serve the very customers incumbents are motivated not to serve. The motivations are simply different – asymmetric. The entrants can create a new market or attack the lower tiers of a market almost free from interference from an incumbent that views the opportunities as unattractive. Thus, the end may come swiftly to the incumbent. (Christensen et al, 2004 p.42-44) A sign of such asymmetries' existence is when the companies take completely different actions that nevertheless make sense to both of them. Asymmetries are at work, when one company calls an industry "unprofitable" while another firm calls that market "important". Naturally, the sizes of the companies matter: a meaningful growth opportunity for a Fortune 50 company will be very different than the one for a start-up. (Christensen et al, 2004 p.44)

Adner (2002) also addressed the notion of asymmetries as drivers of disruption by introducing the concepts of *preference overlap* and *preference (a)symmetry* between market segments. The former refers to the extent to which development activity that is valued in one segment (entrant's one) is also valued in another segment (incumbent's one). The latter describes the symmetry of this overlap, the relative size of the functional 'shadows' that segments cast on each other. (Adner, 2002, p.669) (A)symmetry would refer to a situation where one firm would have a product that is attractive to both firms' segments, whereas its competitor would be confined to its home segment (Ibid, p. 685-686). As was the case with Christensen's notion of asymmetric motivation, also preference asymmetry shapes firms' incentives to compete for new market segments. Increasing overlap between market segments means greater incentive to enter rival's markets. When preference overlap is asymmetric, the firm whose technology is relevant to a larger number of consumers has greater incentive to invade. (Adner, 2002 p.670) Christensen (2006 p.44-45) considered Adner's (2002) notion of asymmetric motivation as an important insight – a much clearer definition of the causal mechanism underlying the disruption process.

Adner (2002) based his findings on a computer simulation which was applied to the hard disk drive (HDD) industry. He found a preference overlap and asymmetry to exist between the entrant 3.5" and incumbent 5.25" disk drive market segments. In addition to its original segment – notebook computers – the 3.5" drive was found to be useful by the desktop computer segment as well (due to e.g. its lower absolute price), but not vice versa. The evaluation criteria of desktop users were subsumed by the criteria of notebook users. Hence, he found asymmetric preferences to be an enabling factor for disruption by the smaller drive. In Adner's simulation, the incumbent desktop HDD manufacturer was subsequently driven further and further upmarket by a combination of market incentives and competitive threats, thus verifying Christensen's findings. (Adner, 2002 p. 683) To summarize, the degree of preference overlap and -asymmetry between segments provides an explanation for the differing incentives for companies to compete in new market segments. (Adner, 2002)

On the other hand, a firm is more likely to be noticed and categorized as a competitor, and its activities scrutinized by a firm's strategists when the markets of the two firms overlap substantially (Chen, 1996; Porac et al., 1995; see Carayannopoulos, 2009). Limited market overlap between the young firm and the large incumbent it will eventually challenge will consequently make the young firm's activities less likely to be noticed by the incumbent (Carayannopoulos, 2009).

2.3.4. New-market disruption process

Let us now take a closer look at how the category of new-market disruption as coined by Christensen & Raynor (2003) fits into the process. In Figure 6, the authors added a third dimension to the original Disruptive Innovation Model we saw earlier (see Figures 4 and 5). This third axis, if you like, represents *new customers* and *new contexts of consumption* [italics added], in other words, new value networks. These constitute either new customers who previously lacked the money or skills to buy and use the product, or different situations in which a product can be used – enabled by improvements in simplicity, portability and product cost. (Christensen & Raynor, 2003 p.43-44)

Here, the disruptive innovation targets non-consuming people, who are not incumbents' customers *per se*, or such contexts where the product is not yet being used. New-market disruptive innovations can occur when characteristics of existing products limit the number of potential consumers or force consumption to take place in inconvenient, centralized settings (Christensen et al 2004, p.xvii).

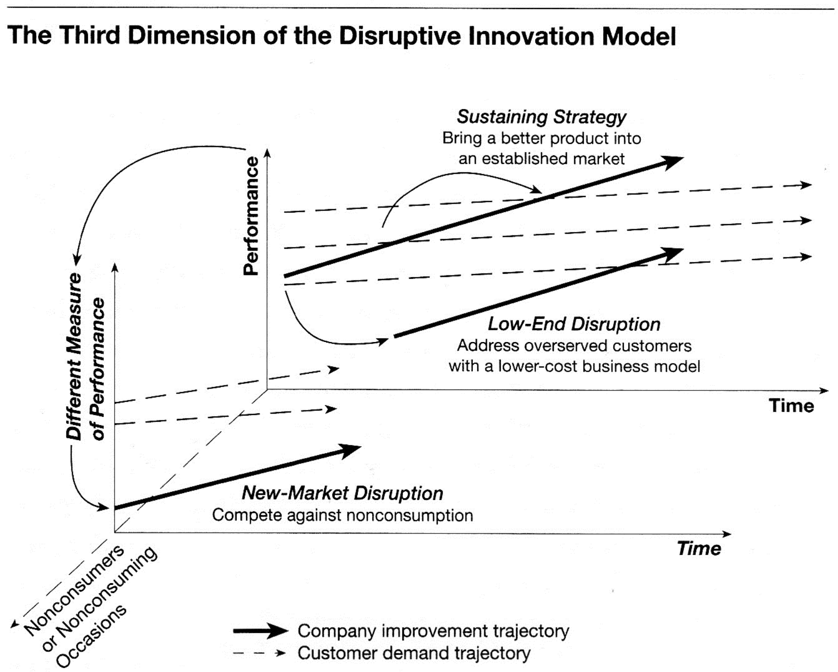


Figure 6. The third dimension of the Disruptive Innovation Model (Christensen & Raynor, 2003 p.44 & Christensen et al, 2004)

Notice how the attribute of product performance in the new context of consumption is different from what is valued in the original value network (Christensen & Raynor, 2003 p.45), explaining the additional vertical axis. In other words, non-consuming customers may value different things than the incumbents' existing ones to begin with. Note that different value networks can emerge at varying distances from the original one along the new third dimension of the diagram (Christensen & Raynor, 2003 p.45). Hence, it is useful to think of low-end and new market disruptive innovations as ends along a continuum (Christensen et al (2004 p.17).

According to Christensen & Raynor (2003 p.45), although new-market disruptions initially compete against nonconsumption in their unique value network, as their performance improves, they ultimately become *good enough* (italics added) to pull customers out of the original value network into the new one, starting with the least-demanding tier. In other words, while its first set of customers consists of nonconsumers, the new-market disruptive innovation continues to improve in performance and eventually moves to encroach on the incumbents' customers. This perception is shared by Schmidt & Druehl (2008). However, both Schmidt & Druehl and Gilbert (2003) emphasize that this process may take a considerable amount of time. While the original model (Figure 4 & 5) only illustrated the primary performance attribute, this version makes the role of the secondary attributes more prevalent and underlines them as a part of new-market disruptive innovations.

Because new-market disruptions compete against nonconsumption, the incumbent leaders feel little threat until the disruption is in its final stages. In fact, when the disruptors begin pulling customers out of the low end of the original value network, it actually feels good to the leading firms, as it seems to them they are replacing low-margin segments with higher-margin ones by moving up-market. (Christensen & Raynor 2003 p.46) Hence, a new-market disruption may even be more hazardous to the incumbents than the low-end disruption of the original model. Indeed, in Schmidt & Druehl's (2008) model, a new-market disruption initially takes no sales away from the old product while a low-end disruption on the other hand immediately steps on the toes of the incumbent. And even if some sales are impacted, the new product sells to low-end customers who are not that highly valued anyway, since they have such low willingness to pay (Schmidt & Druehl, 2008 p.351). And sure enough, Christensen et al (2004 p.8) argue that new-market disruptive innovations have the greatest potential for long-term industry change. Also, Christensen et al (2004 p.7 & 147, 157) strongly emphasize that competing against nonconsumption is easier – besides not eliciting strong competitive responses, there is a lower acceptance hurdle since the alternative for many customers may be to have no product at all.

2.3.5. Deriving the performance trajectories

I will now discuss how Christensen (2000) derived the straight, linear trajectories of performance demanded and performance improvement that his models are built on. These trajectories were initially based on the computer disk drive industry. More specifically, he collected data about successive generations of disk drives between 1975-1994 – from 14 inch to 8", 5.25", 3.5", 2.5" and finally to 1.8" drives, respectively, the number referring to drives' physical sizes. Although each new generation was at the time of introduction inferior to the standard drive size in terms of e.g. absolute memory capacity in megabytes, they were found to show a steady rate of improvement over time. (see Christensen, 2000 p.8, 15, 16,17, 24, 25, 26, 52) According to Christensen (2006 p.40) the original data from the disk drive industry was a complete census, not a statistical sample, and thus included every disk drive model out there in a given year.

The trajectory of performance *demanded* by the market was derived by Christensen (2000) by defining the disk drive capacity available with a *median*-priced computer on the market, so as to reflect the customers' demand. The trajectory of performance supplied was on the other hand measured as unweighted *average* capacity of all disk drives of each category introduced for sale for each year. Note that neither the capacity demanded or supplied represented the highest ones available, but typical examples. The raw data for these trajectories was acquired mainly from industry publications such as Disk/Trend. (Christensen, 2000 p. 18, 24-25, 144-145) As the previously mentioned concept of performance oversupply suggests, the performance offered by disk drives typically exceeded what the market appeared to demand. Christensen (2000, p.108-109) notes that the disk drive graph, if relabeled, would equally well summarize the computer industry as they have parallel histories. Empirically, demand trajectories are straight lines when charted on a logarithmic scale, suggesting our ability to utilize improvement increase at an exponential pace – though a pace that is shallower than the trajectory of technological progress (Christensen & Raynor, 2003 p.65).

Similarly, in another example of the excavator market, the performance demanded by the market was determined by the average bucket sizes of machines purchased by different types of contractors, and they were also found to show an increasing trend. Concurrently, the charted development trajectory of maximum available bucket size served to illustrate the continuous improvement in performance offered by disruptive innovation, the new hydraulic excavators. The calculations were based on data from e.g. industry experts. (Christensen, 2000 p.66 & 74)

Christensen also compared the performance of HP's laserjet printers with disruptive new inkjet ones. In this case he chose printing speed in pages per minute as the primary performance attribute and found ascending yet parallel performance trajectories in time for both technologies. While he did not graph the market demand trajectory for speed in this example, he subjectively estimated the printers to be "good enough" for the personal desktop computing market – students, professionals and other un-networked users of desktop computers. Data was acquired from HP product brochures of various years. (Christensen, 2000 p.115-117)

Further, Christensen provided guidance into identifying disruptive technologies in the form of a hypothetical case study of an electric car. To find out whether such a vehicle poses a legitimate disruptive threat to companies making gasoline-powered automobiles, Christensen suggested graphing the trajectories of performance improvement demanded in the market versus the performance improvement supplied by the technology, in other words creating a trajectory map similar to the one of the disk drive industry. He claims that such charts are the best method he knows for identifying disruptive technologies. (Christensen, 2000 p. 206)

The first step in making this chart involves finding out current mainstream market needs and comparing them with the current capacity of electric vehicles. Christensen (2000 p.208) chose three attributes by which he graphed the performance trajectories of electric vehicles: top speed, range, and acceleration. Christensen referred to observations that auto users demanded a minimum cruising range of 125-150 miles, whereas most electric vehicles only offered 50-80 miles' range at the time. Christensen notes that if the performance demanded/offered trajectories are parallel, then electric vehicles are unlikely to become factors in the mainstream market; but if the technology will progress faster than the pace of improvement demanded in the market, then the threat of disruption is real. (Christensen, 2000 p. 206-207)
The essential question is whether the trajectory of electric vehicle performance will ever intersect the trajectory of *market* demands. He continues that it is nonessential whether the trajectories of two *technologies* meet. While Christensen admits that electric vehicles may never perform as well as gasoline-powered cars, he contends that the question is wrong. (Christensen, 2000 p.209, italics by author)

Christensen & Raynor (2003 p. 93) claim that at a fundamental level, the things that people want to accomplish in their lives don't change quickly. Following this, they argue, the trajectories of improvement that customers can utilize in any given application or tier of the market tend to be quite flat. In other words, the graphed trajectory of performance demanded may be fairly small in slope. Contrary to his findings from the fast-paced disk drive industry, in his case example of the electric vehicle Christensen (2000 p.208) determined the performance demanded to be indeed constant over time in all three performance attributes. He justified the flat demand trajectories with regulatory, economic and geographical considerations (Christensen, 2000 p.207).

Contrary to Christensen's models, Tellis (2006) – based on a study of 23 technologies across six markets – didn't find the performance paths of most technologies in their sample to be linear or easily predictable, but punctuated by irregular jumps in performance. He observed that performance paths of rival technologies follow irregular step functions, may never intersect, or may intersect multiple times. Thus, he did not see the straight linear patterns with constant slope that one sees in examples of disruptive technology. (Tellis, 2006 p.36 & p.38) Danneels (2004 p.251) argues that while using trajectory charts is fairly straightforward for ex post case studies, ex ante predictions involve predicting what performance the market will demand along various dimensions and what performance levels technologies will be able to supply. He claims that it is not entirely clear what methods exist for such predictions. (Danneels, 2004) Then again, Christensen (2000, p.220-221) does admit that the historical rate of performance improvement is, of course, no guarantee that the future rate can be maintained. While these authors question the use of trajectory charts for predictive purposes, for the context of this thesis even a retrospective view of the market is perfectly adequate.

In Christensen's cases often only one or two performance dimensions dominate the customer's choice. For instance, in his focal example of disk drives, size and capacity are the dominant choice criteria. However, in many cases the number of performance dimensions is much higher, and customers trade them off against each other, making for a complex and recursive set of variables. For instance, for cars, key performance dimensions include speed, range, acceleration, styling, convenience of fueling, fuel efficiency, weight, towing capacity, crash safety, reliability, maintenance, durability, noise, vibration, theft risk, pollution, purchase and operating costs, and so forth. The multitude of relevant performance dimensions and their complex interrelationships may make the use of trajectory diagrams challenging. (Danneels 2004 p.249) This is supported by Schmidt & Druehl (2008 p. 354) in relation to their scenarios of disk drives' diffusion. They admit that real-life problems may be more complex, possibly including more than two key performance attributes.

2.3.6. Patterns of diffusion

Schmidt & Druehl (2008 p.348) introduced a complementary framework to Christensen & Raynor's (2003) work. While taking the categorization of innovations as given, they went a bit further to study the actual process and discovered different patterns of diffusion, or forms of *encroachment* (new product taking sales away from the old product) for each of them. They argued that new-market disruptions can follow either a pattern of *fringe-market low-end encroachment* or a *detached-market low-end encroachment*. Low-end disruptions on the other hand would diffuse by an *immediate low-end encroachment*. Sustaining innovations would follow a pattern of *high-end encroachment*. (Schmidt & Druehl, 2008) The authors illustrated these diffusion patterns by charting five market segments for various types of computer disk drives, sorting them by customer willingness to pay from highest to lowest ("mainframe" being highest and "specialty" segment being lowest).

The fringe-market low-end encroachment refers to a situation where the preferences of the first market segment the innovation opens are only incrementally different from the incumbent's one. The new market is defined to be on the fringe of the old market if buyers in this new market would have bought the current (old) product if only the old product were a little less expensive. (Schmidt & Druehl, 2008 p. 351) The incumbent's segment and the fringe-market are thus considered to be adjacent to one another. In the initial situation, the old product has priced itself out of the lower segments of the market, inhabiting only the higher segments. In this scenario, *after* opening up a new fringe market, the innovation begins encroaching on the low end of the old product market and diffusing upward toward the high end. (Schmidt & Druehl, 2008 p.363, italics added)

The authors classify the original buyers of 5.25" inch disk drives (the PC market) to be a fringe market in relation to the 8 inch drives' market (mainframe and midrange), and argued that the 5.25" disk drives followed the above mentioned pattern of encroachment. They also considered Southwest Airlines to have followed a fringe-market encroachment pattern, since it apparently didn't take a large reduction in airfares to begin by first converting the fringe-market – people who otherwise would've driven – to customers. Southwest then encroached upward. (Schmidt & Druehl, 2008, p.348, 357, p.362-363)

In the detached-market low-end encroachment scenario, the innovation also first opens up a new "detached" market, but there the preferences and needs of the first new customers are dramatically different (negatively correlated) from those of existing low-end customers. The new product still ultimately first encroaches on the low end of the old product market *before* diffusing upward toward the high end. In their example of a disk drive of the smallest size and least capacity, the new "specialty" market segment so highly values the alternate attribute [compactness] that it is actually willing to pay a high price for it – but the drive would have too little capacity to be of much good for any other segment. This effectively makes the remaining market segments "detached" from one another. In this scenario, the negative correlation in preferences between the remaining segments is so dramatic that the prices and volumes of the products on the opposite ends have no impact on each other. The segments are dramatically different in their willingness to pay for a certain attribute. (Schmidt & Druehl, 2008 p.358-359, 363)

It should be noted that the detached-market scenario allows for a higher price. Besides the miniature disk drive, the authors classify Sony's portable transistor radios and TVs as examples sold first to "detached" customers who valued portability. They also found mobile phones to follow a similar pattern. All of these innovations were initially expensive. (Schmidt & Druehl, 2008 p.361, 369) However, the authors admit that their hypothetical example of the miniature disk drive in this scenario was undesirable and unfeasible. Still, this pattern perhaps best explains how low-end disruption is possible even if a product is initially expensive. By the time the innovation proceeds from the new market to encroach on the incumbent's market, it has become considerable cheaper. (Schmift & Druehl, 2008 p. 359)

Also in the fringe-market scenario, there seems to be a certain degree of negative correlation between the segments' preferences. The low-end segment valued a disk drive's size over capacity and vice versa. Further, the authors found a number of Christensen & Raynor's (2003) 75 cases of disruptive innovations to be situations where the old high-quality product was used in a centralized location and a "low-quality" new product was targeted directly toward more local end users. In effect, these represent situations where segments' preferences are negatively correlated. For example, in the case of Xerox copiers encroaching on offset printing, the new segment of local users accepted much lower quality copies in favor of convenience. Following this, the authors consider a negative correlation in segments' preferences to be lucrative for fringe-market and detached-market encroachment, meaning, for a new-market disruptive innovation. The immediate low-end encroachment pattern on the other hand refers to a situation where there is no negative correlation in preferences between the segments. (Schmidt & Druehl, 2008 p.357, 364)

In terms of high-end encroachment, Schmidt & Druehl (2008 p. 362) classify the cases of calculator and fuel injection as examples of high-end encroachment, which diffused downward toward the low-end of the market. Their description of the process of diffusion is similar to that of Utterback & Acee (2005 p.9), who illustrate the possibility of a disruptive attack from above. They presented an example in which a higher performing and higher priced innovation is introduced into leading established market segments and later moves towards the mass market. Diffusion of, for example, fuel injection started with the luxury and sports car segments and then migrated into other segments. The first use of electronic calculators was in the scientific community. Later, simpler, less expensive and portable models expanded the total market by creating new segments, which later included the mass market. Utterback & Acee (2005 p.15) This process of high-end disruption seems to flow in a pattern exactly opposite to low-end disruptions.

Furthermore, also Sood & Tellis (2011 p.341) addressed the disruption process by identifying two types of "attacks": *lower* and *upper attacks*. A lower attack – which they call a "potentially disruptive technology" – occurs when, at the time of its entry, a new technology performs worse than the dominant technology on the primary dimension of performance. An upper attack occurs when, at the time of its entry, a new technology performs better than the dominant technology on the primary dimension of performance. The authors argued that a lower attack rarely disrupts firms; in fact it reduces the risk of disruption (Sood & Tellis, 2011 p.352). However, they did not consider price in their definitions of lower and higher attacks. This is contrast to e.g. Schmidt & Druehl (2008 p. 354-355) who consider a high-end encroachment to have a high price and generally a low price in low-end encroachment. Also Govindarajan & Kopalle (2006) associate a high-end disruption with a higher price and a low-end disruption with a low price. Interestingly, Sood & Tellis (2011 p. 352) found *ex post* that technologies that adopted a lower attack were not cheaper than older technologies. This and several other discrepancies may have lead Sood & Tellis (2011) to draw very different conclusions of disruption than most other authors.

Schmidt & Druehl (2008 p.348-349) discovered that a disruptive innovation's diffusion process is actually less disruptive initially than that of a sustaining innovation, and may not cause the incumbents' sales to drop for a good while. They found a sustaining innovation such as a new microprocessor generation to have an instant impact on the sales of the current technology (see Figure 7). However, in the disk drive industry, sales of previous drive technologies continued to grow even as the sales of the newer drives ramped up. For example, the 5.25" drive wasn't initially very disruptive to the previous 8 inch generation. (Schmidt & Druehl, 2008 p. 349) The reason for this phenomenon, the authors argue, is that the 5.25" drive first opened up a new low-end market for desktop computers before diffusing up-market. But only as the 5.25" drive's capacity was upgraded over time did it begin to encroach on (i.e. to displace) the old larger drive. This encroachment first occurred at the low end of the old drive's market (mid-range computers) where customers were more price-sensitive and were less driven by a need for capacity as compared with the high-end market (mainframe computers). In other words, it was a new-market disruption; the desktop computers were a new market segment, and the initial market of the new drive. (Schmidt & Druehl, 2008 p. 349-351) Also Adner (2002) mathematically modelled a delay of time periods before the disruptor expands to another market segment.

Although Christensen (2000 p.146) originally named successive generations of disk drives as low-end disruptive innovations, he noted that the 5.25" and 3.5" drives also facilitated the emergence of new value networks. For example, the later 3.5" drives were initially sold in the emerging portables market before encroaching on the desktop market, and the miniature 1.3" HP Kittyhawk drive initially targeted non-consuming contexts and new markets such as PDAs and Nintendo gaming consoles (Christensen, 2000 p.20-23, 146-149 ; Gilbert, 2003). Thus, some of the novel low-priced drives had features of a new-market disruption as well, essentially making them hybrids.

In Figure 7, two distinctly different diffusion patterns are illustrated – the unit sales for successive generations of microprocessors (a sustaining innovation) and those of disk drives (a disruptive innovation) (Schmidt & Druehl, 2008). While the authors call the successive generations of microprocessors sustaining innovations, they claim that they have a disruptive impact on the sales of the previous generation. And sure enough, compared with the way the P-4 processor disrupted the P-3 in terms of sales figures, the 3.5 inch drive wasn't at the outset very disruptive to the 5.25" generation. (Schmidt &Druehl, 2008)

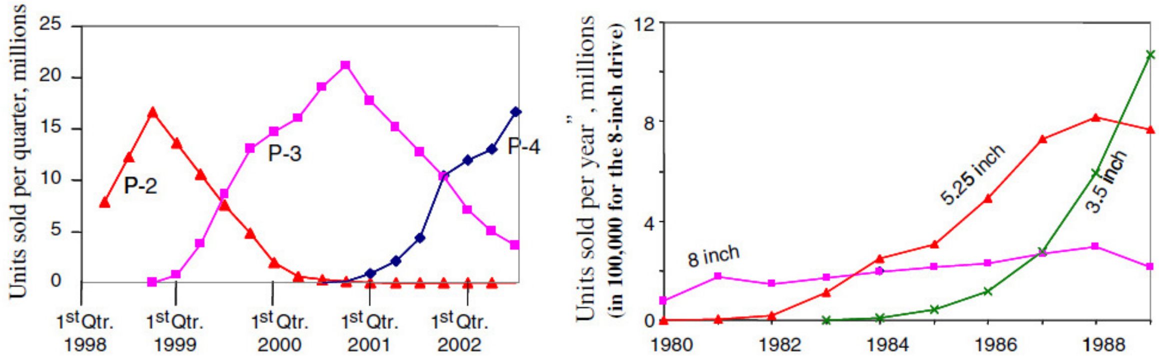


Figure 7. Sales of successive generations of microprocessors and disk drives (Schmidt & Druehl, 2008). Microprocessor data from Dataquest, Inc (2003) and disk-drive data from Christensen (1992).

Thus, the microprocessor example represents an innovation that is disruptive to sales of the old product right from the outset but is not a disruptive innovation (per Christensen's (1997/2000) definition) whereas the disk-drive example represents an innovation that is not very disruptive initially but is in fact a disruptive innovation. The authors support Christensen's (1997/2000) perception that a disruptive innovation may have a nondisruptive nature in the short run and thus cause the incumbents to fail to take action. (Schmidt & Druehl, 2008 p. p. 349) Their finding are supported by Yu & Hang (2010 p. 439), who argue that a technological innovation that has superior performance in key dimensions with a relatively low-cost structure (they used a SiGe microchip as an example) would cause more serious destructive effects on incumbents than a "normal" disruptive innovation that focuses on low cost but initially lower performance. However, they don't consider such an innovation to be a disruptive one, but rather make the point that an innovation can cause destructive effects on incumbents without necessarily being a disruptive innovation. These examples of microprocessors should not be confused with the low-cost, low-performance Intel Celeron one, which – according to Schmidt & Druehl – was a disruptive innovation.

In the disk drive chart, the incumbent technology lingers on for quite a while even after the introduction of a disruptive innovation, a smaller and cheaper drive. This phenomenon was support also by Gilbert (2003 p.29) in his findings of minicomputers, which according to Christensen (2000) disrupted the mainframe market. Gilbert observed that after the launch of the minicomputers, it took them nearly 20 years to lead in revenue for the first time and another 10 to sustain that lead. All this time the mainframe market grew in revenues (Ibid, 2003 p.29). Disruption is not an immediate phenomenon — it can take years and even decades before the upstart business encroaches heavily on the established market (Ibid, 2003 p.27) This is in line with Christensen & Raynor (2003 p. 69). In particular, the growth in the new value network [of a new-market disruptive innovation] does not affect demand in the mainstream market for some time – in fact, incumbents sometimes prosper for a time *because* of the disruption (Ibid, p.111).

Markides (2006) found that disruptive business model innovations will grow quickly to a certain percent of the market, but fail to completely overtake the traditional way of competing, and they aren't even expected to. However, he only refers to examples from service industries and emphasizes the differences between this and other types of disruptive innovations. His findings are nevertheless supported by Schmidt & Druehl (2008 p.350, 364) who found that while a disruptive innovation has ultimately at least some impact on an existing market, it doesn't necessarily totally displace the market. They mentioned Southwest Airlines and Intel Celeron processor as ones that proceeded only halfway. Further, Yu & Hang (2010 p. 439) addressed what they call misinterpretations of the concepts of disruptive innovations. They found that disruptive innovation does not always imply that entrants or emerging business will replace the incumbents or traditional business, and that it does not imply that disruptors are necessarily start-ups. In fact, an incumbent business with existing high-end technologies can still survive by concentrating on how to satisfy its most demanding but least price sensitive customers. (Yu & Hang 2010)

Sood & Tellis (2011) confirm that competing technologies can coexist at many points in time. Disrupted technologies may sometimes continue to survive and coexist with the new one by finding a niche, like laser printers did after the arrival of inkjets. The phenomenon is not as "fatal" or "final" as the term implies. (Sood & Tellis, 2011) To summarize Schmidt & Druehl's (2008 p.348) perception, a disruptive innovation's diffusion process is actually less disruptive initially than that of a sustaining innovation: *"Said loosely, a disruptive innovation (in that it disrupts the current market) is not necessarily a disruptive innovation (as Christensen defines it)"* (Schmidt & Druehl, (2008). Rephrased, a disruptive innovation may not yield any instant effect on the market. On the other hand, Christensen (2006) claims that the definition of disruptiveness exists independent of the outcome, in other words, an innovation can be a disruptive one even if the incumbents do not end up being disrupted by it.

Also, both Gilbert (2003 p. 29) and Christensen et al (2004 p.184) considered angioplasty operations to be a new-market disruptive innovation relative to bypass surgery. According to Gilbert's (2003 p.30) data, after 14 years of balloon angioplasty operations, the earlier bypass surgery method didn't yet show clear signs of being replaced. Gilbert's findings thus suggest that new-market disruptions may take a fairly long time to have a disruptive effect on incumbents. In contrast, Schmidt & Druehl (2008) argue that in the case of a true low-end disruptive innovation, encroachment of the incumbents' business begins immediately. They observed such an immediate effect also with sustaining innovations such as microprocessors as illustrated above. Referring to the case where mainframe computers experienced a long period of growth before minicomputers eventually caused their revenue to decline, Gilbert (2003, p.29) argues that although a disruption may not completely destroy the established business, it usually takes away all the growth.

As we have now seen, both Christensen and Schmidt & Druehl (2008) described how a new-market disruptive innovation first gains momentum in a new market segment before proceeding to disrupt the low-end of the incumbents' market. This overall view of the process is supported by Caraynnopoulos (2009), Danneels (2006 p.2) Gilbert (2003 p.28) and Sood & Tellis (2011 p.341). According to Gilbert (2003 p.28), this growth occurs in the market not traditionally served by the established players. The new customers are initially different, as is the way they use the product. Gilbert (2003 p.28) considered disruption to develop in three distinct phases: (see also Figure 8)

1) Innovation creates a new, non-competitive market independent of the established business.
2) The new market expands and slows the growth of the established business.
3) Having greatly improved over time, the disruptive innovation significantly reduces the size of the old market.

As illustrated in Figure 8, Gilbert (2003 p.27) makes an important contribution by also arguing that in every industry changed by disruption, the net effect has been total market growth. Disruption creates new net growth. Minicomputers eventually overtook the mainframe market, and personal computers eventually did the same to minicomputers, but the effect of each disruption on the industry as a whole was always positive. The author also argues that disruption can be a powerful avenue for growth through new market discovery for incumbents as well as for upstarts. (Gilbert, 2003 p.27; 32) On the other hand, this may mostly concern new-market disruptions, since Schmidt & Druehl (2008 p.351) argue that with a low-end disruption (as per Christensen & Raynor's definition) there may be little or no market expansion. This applies to the immediate low-end encroachment pattern explained above. The first sales of the new product are to customers who would have otherwise purchased the old product, as opposed to buyers in a new market segment. (Schmidt & Druehl, 2008)

On the other hand, in the fringe-market encroachment process, which can occur in a new-market disruption, Schmidt & Druehl (2008 p. 357) noticed a good degree of market expansion following the advent of the new product. The notion of overall market expansion by a disruptive innovation is also supported by Utterback & Acee (2005 p.16). Christensen and his co-authors' works haven't accounted for the phenomenon of net growth as such, as their focus has been on the adverse effects of disruption to incumbents. Then again, Christensen & Raynor (2003 p.111) argued that the growth in the new value network does not affect demand in the mainstream market for some time – in fact, incumbents sometimes even prosper for a time *because* of the disruption (italics by author). This is in line with Gilbert (2003) findings in the minicomputer/mainframe markets.

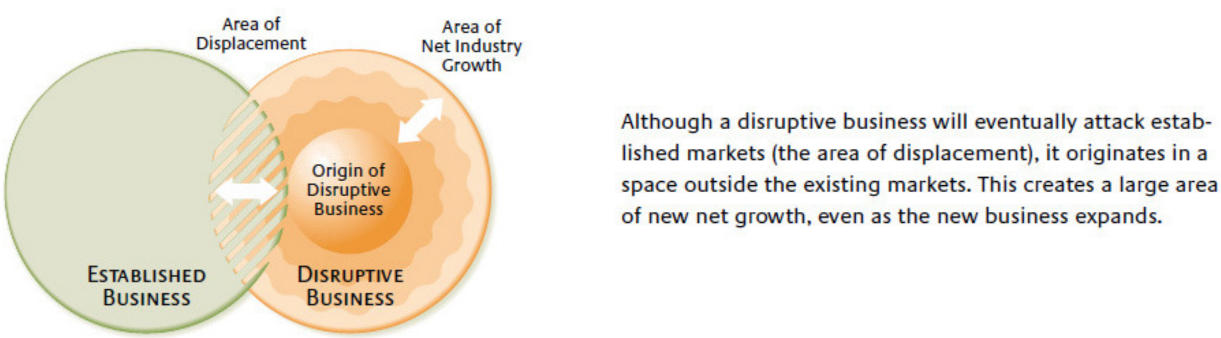


Figure 8. Disruption as an opportunity for growth. Modified from Gilbert (2003 p.28)

Perhaps Sood &Tellis' (2011 p.342) biggest contribution is recognizing the varying definitions of when disruption can be said to occur. Such milestones are, firstly, performance improvement meeting a certain level (technology disruption), a disruptor firm's market share exceeding an incumbent's market share (firm disruption) and overall market share of new technology exceeding the dominant one (demand disruption). I have seen all of these domains used in the literature to mark the "moment of disruption", if you like. In Sood & Tellis' sample, firm disruption lagged technology disruption by approximately 10 years. Demand disruption was said to generally occur with firm disruption or always follow it within a short time. (Sood & Tellis, 2011 p.345, p.348). Interestingly, Christensen (2006 p.50) also used market shares and market capitalization between the disruptors and disruptees as measures of the degree of disruption.

The general consensus seems to be that in a new-market disruption, the product opens up a new market first and only after a certain time period improves enough to encroach on the low-end of the incumbent's segments. From there the product continues to improve in an incremental fashion and eventually displaces the incumbent. However, it may take a considerable amount of time for the new-market disruption innovation to yield disruptive effects. In this scenario, the total market expands and there may thus still be room for the incumbent to survive. In the low-end disruption process, the entrant product immediately attacks the incumbent's market right from the start and there may be no such market expansion.

2.4. Characteristics of disruptor companies

There's debate in the literature about what kinds of companies typically launch disruptive innovations – are they big, small, entrants, incumbents, old firms or startups. I'll present the key findings here. In his original research of the disk drive industry, Christensen (2000 p. 24) found that despite the established firms' technological prowess in leading sustaining innovations, from the simplest to the most radical, the firms that led the industry in every instance of developing and adopting disruptive technologies were entrants to the industry, not its incumbent leaders. More specifically, the industry incumbents always led in the development of novel, performance-enhancing technological innovations such as disk drive heads, while in technologically straightforward disruptive innovations that generally packaged known technologies in a unique architecture (such as physically smaller disk drives), it was the entrants who prevailed. The development of the actual technologies was often the work of engineers at established firms. (Christensen, 2000 p. 10, 12, 13, 15, 23, 43) In other words, new entrants were the leaders in introducing new architectures using established components, while established firms led the difficult but incremental improvement of components (Utterback & Acee, 2005 p.6).

In Christensen's (2000 p.9) parlance, established firms are those that had been established in the industry prior to the advent of the technology in question, practicing the prior technology. In comparison, entrants are simply those that were new to the industry at that point of the technology change. Thus, a given firm could be considered either an entrant and or an established firm simply depending on whether it was present in the industry where a disruptive technology emerged. (Christensen, 2000 p.9) For example, Christensen & Raynor (2003 p.57) noted Canon as a company that introduced disruptive countertop photocopiers. While it was an entrant in the copier business, it was simultaneously a large, established incumbent company in the camera industry. Christensen's typology doesn't seem to differentiate whether an entrant is a startup or an old firm.

Christensen's original conclusions were questioned by Tellis (2006 p. 36) and Sood & Tellis' (2011 p. 347) who found entrants to be actually less likely to cause disruption than incumbents. As a result, Sood & Tellis (2011) considered Christensen's findings exaggerated, but did not deny the fact that entrants do disrupt, too. Tellis (2006) argued that both small and large firms and incumbents and new entrants can introduce new technologies. However, as I've mentioned, at least Sood & Tellis used very different definitions than Christensen in their study and hence the reader would perhaps be well advised to take these findings with a grain of salt.

Christensen et al (2004) admit that while many people think disruption can come only from a completely new entrant, in theory an incumbent can disrupt itself. It can also create new business ventures that disrupt others. (Christensen et al, 2004 p.66). This is in line with Yu & Hang (2010 p.439), who propose that disruptive innovation does not imply that disruptors are necessarily startups. In addition, Gilbert (2003) argues that disruption can be a powerful avenue for growth through new market discovery for both incumbents and upstarts. He nevertheless recommended that a disruptive new business should start small.

In addition, Schmidt & Druehl (2008) argue that although historically it may be the case that sustaining innovations may have more been associated with incumbents and disruptive innovations with entrants, they are not linked this way by definition. For example, Intel's Celeron microprocessor was a disruptive innovation introduced by an industry incumbent and the Apple iPod the very opposite case. (Schmidt & Druehl, 2008 p.349) Similarly, Christensen (2000 p.109-110) noted that the PC market, which was disruptive in relation to minicomputers, was created by a set of entrants such as Apple and IBM. Interestingly, these two were very different in size and age, the former being a fairly recent garage startup and the latter an established computer industry giant. Christensen (2000 p.110) attributed IBM's success in PCs by the fact that it had created an autonomous organization for PC's that had its own cost structure and metrics of success. He stated that a single organization might simply be incapable of competently pursuing disruptive technology while remaining competitive in mainstream markets.

In addition to the IBM PC, Christensen et al (2004) recognized the Intel Celeron as a disruptive innovation created by an incumbent (microprocessor) company, in addition to disruptive inkjet printers from HP, a (printer) industry incumbent. Christensen et al's (2004) explanation for the success of these products is that they were also initiated in spinoff organizations, which had their own processes and values. Thus, the authors considered a spinout – setting up a completely separate business unit free to develop its own skills and define its own metric for success – as a successful response strategy. It should be noted that Christensen et al (2004 p. 71) consider such a new spinout organization as an <u>entrant</u> in this market context. Christensen (2006 p.43) explained these anomalous instances, where the incumbent leader had succeeded in disruption and maintained its industry-leading position, by the fact that it had set up an autonomous business unit and by given it unfettered freedom to forge a very different business model appropriate to the situation.

Interestingly, many authors such as Sood & Tellis (2011), Chandy & Tellis (2000) and Tellis (2006) seem to more or less explicitly associate incumbency with large size. On the other hand, Christensen (2000) associates entrants with small company size. Christensen (2000) posits that large companies often surrender emerging growth markets because smaller, disruptive companies are actually more capable of pursuing them. While startups lack resources, it doesn't matter, since their values can embrace small markets, and their cost structures can accommodate lower margins. (Christensen 2000 s.167) An opportunity that excites a small organization simply isn't large enough to be interesting to a very large one. Because disruptive products typically promise lower gross profit dollars per unit sold and cannot be used by their best customers, disruptions are inconsistent with the leading companies' values. (Christensen & Raynor, 2003 p. 187,190) They authors argue that established companies have the resources – the engineers, money and technology – required to succeed at both sustaining and disruptive technologies, but their processes and values hinder their efforts to succeed at disruptive innovation.

Put differently, a disruptive innovation is financially unattractive for the leading incumbent to pursue, relative to its profit model and relative to other investments that are competing for the organization's resources (Christensen, 2006 p.49). Thus, a business model that can be profitable at low costs per unit is a crucial strategic asset in both new-market and low-end disruptive strategies (Christensen & Raynor 2003 p.237). Small entrant firms may even enjoy protection as they build the emerging markets for disruptive technologies since they are doing something that it simply does not make sense for the established leaders to do (Christensen, 2000 p.228) For example, minicomputer companies could profitably serve their customers at gross margins lower than those of mainframe manufacturers because their selling costs were lower, their inventory turned quicker, and their fixed costs were a lower percentage of their total business (Gilbert, 2003 p.30).

A fresh viewpoint was offered by Markides and Geroski (2005, see Markides 2006 p. 24), who described how established companies could exploit disruptive product innovations. Their thesis is that established companies should in fact not even attempt to create such innovations but should leave the task of creating these kinds of markets altogether to small start-up firms that have the requisite skills and attitudes to succeed at this game. As a result, Markides (2006) suggests that established firms should facilitate these small firms and later build a new mass-market business on the platform these feeder firms have provided.

Carayannopoulos (2009) found support that a young technology-oriented firm can actually benefit from some of its perceived disadvantages, such as low visibility and low perceived legitimacy, supporting the notion of an entrant company being in a better position to launch a disruptive innovation than an incumbent. Low visibility was found to be especially advantageous for an entrant launching an architectural disruptive innovation (such as the PC). Further, the author determined that the rigidities in the large firm may hinder its ability to respond to a disruptive innovation. (Carayannopoulos, 2009). She further argues that one should expect young firms to be successful commercializing radical and architectural innovations, but are less likely to challenge incumbents with modular and incremental disruptive innovations. This is in line with Christensen (2000 p.15, 23) who classified entrants' disruptive disk drive models as architectural innovations, and Christensen & Raynor

(2003 p.40,41) who considered entrants' chances of success with a sustaining innovation very slim indeed, although not completely absent.

Based on a review of relevant literature, Govindarajan & Kopalle (2006) sought to distinguish the type of firms that may be better able to develop disruptive innovations, relative to other firms. They argued that an "adhocracy" culture that values entrepreneurship, risk taking, experimentation, flexibility, and creativity promotes the development of disruptive innovations. Supporting Christensen, they concurred that the creation of separate organizational units will foster the development of disruptive innovations. They also mentioned a willingness to cannibalize, long-term incentive plans and orientation toward small but emerging customer segments as contributing factors. (Govindarajan & Kopalle 2006 p. 16-17) Further, Yu & Hang (2010) studied the literature for potential enabling factors for disruptive innovations. They interpreted the size of the firm and business units to be negatively correlated to disruptive innovation and attributed autonomous business units, or spin-offs, as enabling factors.

According to Christensen (2006), disruption is a business model problem, not a technology problem. He presented a case, where minicomputer manufacturer Digital Equipment Corporation (DEC) was disrupted by the makers of personal computers in the 1980s. The case is somewhat analogous to my findings about personal 3D printers. Christensen quotes Intel's chair Andy Grove: "It wasn't a technology problem. Digital's engineers could design a PC with their eyes shut. It was a business model problem, and that's what made the PC so difficult for DEC". Christensen (2006):

> *"He noted that in the early 1980s proposals to make PCs promised 40% gross margins on machines that could be sold for $2,000. What is more, none of DEC's customers could use them. These proposals were competing for resources against proposals to make more powerful computers than DEC had ever made before. These promised gross margins of 60% on machines that could sell for $500,000. It was the attractiveness of the opportunity relative to the company's business model that made the sustaining path attractive and the disruptive path unattractive."*

Disruptive entrants use business models that do not fit the ways established firms make money. Gross margin per unit sold tends to be lower but turnover or asset utilization tends to be higher… Disruptive innovations tend to be off-the shelf products, in which the customer turns either to a group of specialist or to themselves to provide postsales service. A company that has a business model based on long-term relationships and multi-year support agreements will have little interest in selling a product that obliterates those revenue streams. (Christensen & Raynor 2004 p.44)

To summarize, there are examples of disruptive innovations by both entrants and incumbents, and small and large firms. E.g. Christensen & Raynor (2003) attribute incumbents' success in disruptive innovation to spin-off organizations, which he considers as industry entrants. Due to their business models and values which appreciate (initially) small market opportunities, a small business unit or firm may be in a better position to develop disruptive innovations.

2.5. Criticism of Disruptive Innovation Theory

As prominent and widely recognized as the theory is, Yu & Hang (2010) nevertheless argue that the literature on disruptive innovation has been scattered and conflicting by nature and may pose a state of ambiguity for future research. I will address the most focal criticism in this section.

First and foremost, the original theory has been criticized for not providing a sufficiently accurate definition of a disruptive innovation (see e.g. Danneels, 2004; Tellis, 2006; Yu & Hang, 2010; Sood & Tellis, 2011). Yu & Hang (2010) claim that scholars from various disciplines of management research have generated more and more critiques, doubts and challenges concerning Disruptive Innovation Theory, particularly on the fundamental question of what the disruptive technology actually is. Danneels (2004 p.247) argues that Christensen does not establish clear-cut criteria to determine whether or not a given technology is considered a ''disruptive technology'', and calls out for exact criteria to identify their essential characteristics.

The ambiguity in the definition of disruptive technology was also addressed by Tellis (2006 p.34-35), who argued that the problem in the definition lies in the term "disruption", which is at the same time a characteristic of the innovation and its most interesting and valuable prediction. (Tellis, 2006 p.35) In other words, the major issue is the use of the same term to describe both the causative agent (disruptive technology) and the effect (disruption) (Sood &

Tellis, 2011 p.340). Also Schmidt & Druehl (2008 p.348, 349) recognized the issue and noted that the term can be easily misconstrued. A disruptive innovation may not be very disruptive initially, which they found to contribute to the confusion surrounding the term. Instead, the authors chose to use the term “encroachment” to describe the process of disruption. Anthony (2005a p.3, see Schmidt & Druehl 2008 p.348) – one of Christensen’s co-authors – admitted that the word *disruption* has become loaded with meanings and connotations at odds with the concept. This problem with the terminology was also recognized by Christensen (2006).

In addition to the definition, the scope of disruptive technology has triggered a very heated discussion as well (Yu & Hang, 2010 p.438). Utterback & Acee (2005) argue that Christensen’s model is too narrow in scope and ignores higher performing and higher priced innovations altogether. Even though Christensen and his co-authors (2003, 2004) extended the model to cover services as well, Utterback & Acee (2006 p.7) nevertheless think such generalisation stretches his model too far, or rather that services (intangibles) present mostly different dynamics than do tangible products.

Also the original empirical evidence has been subject to debate. Danneels (2004) noted that all of Christensen’s case studies are of disruptive technologies that eventually did succeed, even though – according to Danneels – there are many that actually fail. He considers this to be an analytical problem. Christensen has even been accused of cherry-picking examples to support his framework (Cohan, 2000; see Danneels, 2004 p.250) Similarly, while finding the empirical examples in Christensen’s (1997) work “quite persuasive”, Tellis (2006) considered the logic of sampling them to be missing, even hinting the sampling to be biased.

Furthermore, Sood & Tellis (2011) argue that in addition to the circular definition mentioned above, the theory of disruptive technologies suffers from inadequate empirical evidence and a lack of a predictive model. However, Christensen (2006 p.47) denies Tellis’ claims and points out how Christensen & Raynor (2003 p.69) list several anomalies that their theory cannot explain. Yet these anomalies seem to be cases where an entrant challenges incumbents with a *sustaining innovation* and succeeds despite the expectations of the theory. Christensen’s work provides little information of cases where a typical, potential disruptive innovation would’ve faltered. Then again, Christensen never does claim that all (potentially) disruptive technologies would necessarily succeed (Danneels, 2004; p. 250).

To recap, Christensen (2000 p.192) found disruptive technologies to be typically simpler, cheaper, more reliable and more convenient than established technologies. In contrast, referring to a prior study of 23 technologies across six markets, Tellis (2006) didn't find support for those product characteristics. Instead, he found that in the vast majority of cases, the secondary dimension brought by the technology was some other than price, size, convenience or simplicity. The study was based on the assumption that the new technology would be "superior" to the existing one in these secondary dimensions. However, Christensen never argued that these characteristics would be a precondition for a disruptive innovation as such. This finds support from Danneels (2004) who claims that such characteristics may be typical, but not necessary, characteristics of disruptive technology. He calls out for clarification on whether a disruptive technology always has to have a lower performance and start in the low-end segment of the market.

Many research scholars have also challenged the predictive use of Disruptive Innovation Theory (Yu & Hang, 2009 p.440). There seems to be a considerable debate around the question whether the ex-post empirical observations about disruptive innovations offer support for ex-ante predictions as well. For example, Danneels (2004) and Tellis (2006 p.35) ponder how can it be predicted ex ante which technology will be disruptive, and how can it be distinguished from other underperforming technologies? Further, Sood & Tellis (2011) argue that literature has no model whatsoever that can predict disruption. Danneels (2004) also called for clarification about the stage where a technology actually becomes disruptive – and whether it occurs only when it displaces the incumbents.

Danneels (2004) noted that Christensen's model was based only on historical data. Christensen (2006) admits this to be correct, as it was inductively derived and data existed only about the past, but denies it being a weakness of the model. Danneels (2006) and Tellis (2006) also interpreted that disruptiveness has been defined only after the fact in the theory. Christensen (2006) rebuted their claims as absolutely incorrect. He elaborates that the leader need not be dethroned or miss the technology for it to be disruptive and emphasizes that disruptiveness is not a post hoc definition. He makes an important point that the definition of disruptiveness exists independent of the outcome (Christensen & Bower, 1996; see Christensen, 2006). Thus, Christensen (2006) wants to give the term a specific meaning irrespective of the outcome.

Christensen (2000 p.143) nevertheless admits that the market *applications* (italics added) for disruptive technologies are unknown and unknowable at the time of their development. He adds that it is simply impossible to predict with any useful degree of precision how disruptive products will be used or how large their markets will be. (Christensen, 2000 p.154) Forecasting methods can fail especially badly when applied to markets or applications that do not yet exist Christensen (2000 p. 145-146). New-market disruptions, which we will address later, may thus be especially challenging in that respect. Christensen (2006) argues that while the theory of disruptive innovations can't predict the birth of individual products, it still holds predictive power in the sense that it can interpret the meaning and future potential of a phenomenon after it has been first observed. Reinforcing his claim, Christensen lists four examples of industry cases (e.g. flash memory disrupting hard disk drives) where an ex ante prediction of the disruptive potential of technologies in varying stages of maturity made based on the model turned out to be accurate. However, (Yu & Hang, 2010 p.445) claim that it remains an unexplored question whether there is any systematic way to identify new disruptive opportunities for applying existing technology or products.

Sood & Tellis (2011) did develop a predictive model of disruption, but it measures mostly company characteristics and does not address product-level indicators in any detail. In similar vein, Govindarajan and Kopalle (2006, p.12) argued that it is possible to make ex ante predictions about the type of firms likely to develop disruptive innovations. Further, based on the causes of incumbent firms' success or failure and subsequent solutions, Yu & Hang (2010 p.440 & 445) also find that disruptive innovation theory can be applied to anticipate the future of firms, supporting their study of enabling factors for disruptive innovation. Based on concepts of preference overlap and preference symmetry between market segments, Adner (2002) provides additional methods for predictive purposes by analyzing the demand conditions that may enable disruptive innovations to emerge. While the literature has been able to address the characteristics of companies that develop disruptive innovations, the criteria for recognizing a disruptive product seem inconclusive.

More recently, the theory of disruptive innovations – or Christensen's work in Innovator's Dilemma (1997) in particular – was heavily criticized by Lepore (2014) in her article for The New Yorker. She argued that disruption is a theory of change founded on panic, anxiety and shaky evidence. The cases on which the theory is based on are handpicked and notoriously weak foundation for theory, definition of company success is arbitrary, and some of the companies that were supposedly disrupted have since fared well – such as U.S. Steel, which is currently the number one operator in the U.S. Christensen's sources are often dubious and his logic questionable, the writer claims. In a recent interview for Businessweek, Christensen (2014) responded by stating that his later works have already addressed her critique. He also commented that U.S. Steel's products have nevertheless changed entirely, as it's been driven out of all lower-margin steel products to high-end sheet steel, now surviving in the top of the market. One might add that – as Christensen (2000) pointed out – industry number two, Bethlehem Steel, did falter in the face of competition from disruptive steel minimills.

Disruption is a difficult theory. When analyzing the phenomenon, it is in my opinion imperative to distinguish between disruption within an industry/market (or product class) and the possibly disruptive effects for individual incumbent companies. While many incumbents can survive and have survived, even thrived, their product lines and market shares have often transformed entirely: in July 2014, minicomputers, cable-operated excavators and 8" disk drives were in short supply. Market-level disruption seems far more sensible to observe than the (highly contingent) consequences for individual companies. Mixing these two domains has probably contributed to the confusion around the theory.

2.6. Forming a theoretical framework for the thesis

The early works on disruptive innovation argued that it will attack the incumbents and eventually displace them. However, more recent works suggest that there may be a considerable delay before the incumbents feel the effect, if they do at all. Also, it may significantly expand the market while leaving space for incumbents to survive. Some authors claim that disruption can be caused by a high-end, high-priced disruptive innovation, too. The improvements to the theory still leave ambiguity and circularity in the definition, since disruption is both an outcome and a process. Disruption as an outcome is not the same thing as a disruptive innovation; literature suggest that either can occur without the other. Also the fact that disruption can be measured in different ways adds complexity to observing a disruptive innovation.

For the purpose of this thesis, I've found the concept of new-market disruption by Christensen & Raynor (2003) and the notion of total market expansion by Gilbert (2003) most useful for the context of personal 3D printers. These concepts give the theory a broader view. Focusing on the phenomenon of net growth and market expansion helps us to put aside the problem of circular definitions and the debate on consequences for incumbents. Overall market growth becomes the emphasis.

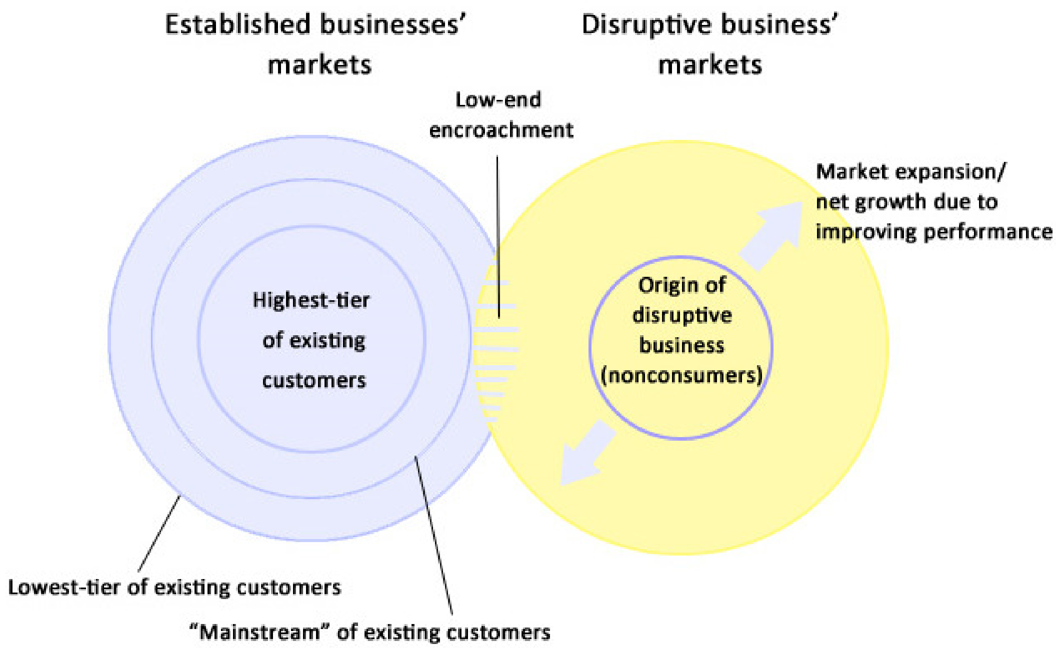


Figure 9. Theoretical framework for the thesis. Based on Christensen & Raynor (2003), Gilbert (2003) and Schmidt & Druehl (2008).

Following Gilbert (2003), this framework illustrates (see Figure 9) how a disruptive innovation has nonconsumers as its initial market, and as its performance improves, the market expands and eventually it becomes good enough to encroach on the incumbent's least-demanding, lowest-tier of customers (who, to simplify, are synonymous to low-end products' market).

To address my reseach questions, this framework provides us three fairly convenient measures for "disruption": ideally, one would have to see a noticeable amount of nonconsumers beginning to use the disruptive product, and at some point in time, falling sales for incumbents' low-end product segments. Also, observing positive performance development for the entrant innovation would support this model of disruption.

3. Methodology

3.1. Research approach and methods used

According to Yin (2009 p.36), for some topics, existing works may provide a rich theoretical framework for designing a specific case study and provide guidance even for collecting relevant data. I found the works of Clayton Christensen and his co-authors on the theory of disruptive innovations as a useful framework. Following their approach, I considered a single-case study to provide the best research approach for this thesis. As we've seen, their works were built on individual cases of different, disruptive products and technologies. As in their cases, it is of interest to track the development of personal 3D printers in time. This is in line with the case study approach, as tracing changes over time is its major strength (Yin, 2009 p.145). According to Yin (2009 p.2), case studies nevertheless focus on contemporary events over which the investigator has little control. While some of the printer data dates back to 1996, personal 3D printers are a fairly recent phenomenon and thus more appropriate for a case rather than a historical study. However, the historical context of the case study is almost always of interest (Stake, 2005 p.449) and thus I've dealt with the past developments in desktop 3D printers as well to a small extent. I would consider this thesis to have features of both explanatory and descriptive case studies – with the actual "case" being the **disruption process of personal 3D printers** and product classes (industrial/personal) as the primary **unit of analysis**.

For their cases, Christensen (et al) collected data from multiple sources: various issues of computer trade publications such as *Disk/Trend Report* (Christensen, 2000, p. 185) and *Data Sources* (Ibid, 2000, p.24), articles and interviews about electric vehicles (Ibid, 2000, p.208), interviews with company executives (Christensen & Raynor, 2003 p. 37), industry associations (2000 p.66) and product brochures (Christensen, 2000 p. 117). Considering their approach and methods, I determined that in order to study the disruptiveness of a certain technology or product, I would also need to use multiple data sources.

According to Yin (2009, p. 98), case study evidence may come from six sources: documents, archival records, interviews, direct observations, participant-observation, and physical artefacts. Also Eisenhardt (1989 p. 534-535) argued that case studies typically combine some of these data collection methods. Yin (2009) claims that a case study can and should incorporate multiple sources of evidence, as they will increase the quality of the case study substantially. Eisenhardt (1989 p.538), Yin (2009 p.114-115) and Stake (2005 p. 454) claim that multiple data collection methods make *triangulation* of the material possible (italics added).In similar vein, Eriksson & Kovalainen (2008 p. 125-127) noted that case studies are usually considered more accurate, convincing, diverse, and rich if they are based on several sources of empirical data. In addition, many authors (Eriksson & Kovalainen, 2008; Eisenhardt, 1989; Yin, 2009; Stake, 2005) note that case studies enable the combination of qualitative and quantitative data. According to Eisenhardt (1989, p. 538), quantitative data can bolster findings when it corroborates those findings from qualitative evidence.

Following this advice, I chose to gather empirical data through interviews, documents and direct observations. Similar combination of source data was employed by e.g. Gilbert (2005), who used semi-structured interviews, documents and observations as his case material, in addition to Dubois & Gadde (2002). Documents were used above all to assemble quantitative material to form printer data tables, graphs and sales figures (in the appendices). Eriksson & Kovalainen (2008 p. 125-127) note that in business research, in-depth interviews are often used as primary source of empirical data, whereas other sources (they list e.g. company documents and professional magazines) can be used as complementary. In fact, they claim that other sources are sometimes even better in terms of evidence than interviews. Hence, I've considered both the interviews and documents to be primary data.

3.2. Interviews as primary data source

Yin (2009, p.106) considered the interview to be one of the most important sources of case study information. I chose qualitative, semi-structured/thematic interviews in the expectation that they would provide rich information about the "3D printing phenomenon" and thus help guide the research into more specific areas. The semi-structured approach is supported by e.g. Rubin & Rubin (1995; see Yin, 2009 p.106) who determined that *"your actual stream of questions in a case study interview is likely to be fluid rather than rigid"*. In contrast, a quantitative survey would've typically required precise questions and a fairly large number of participants to be considered valid. This would've also been difficult to realize since the nature of the topic required fairly deep expertise from the participants, thus heavily limiting the potentially available population. I deemed an ideal interviewee to be someone with knowledge of both personal and professional-grade 3D printers and the industry in general.

The first three interviews were fairly broad in perspective and focused on the implications of 3D printing technology for manufacturing industries. Later interviews were more specific and focused on personal 3D printers, allowing me to better evaluate their significance for the 3D printing industry, their technical abilities and the meanings experts would associate with them. The interviews allowed me to form a more complete picture of personal printers' abilities, since numerical data on performance attributes can only go so far. This is in line with Eriksson & Kovalainen (2008 p.127) about combining qualitative and quantitative data in case research. They advised that qualitative data can be used at the beginning of the research project to be able to formulate and refine the focus of the study.

During the research process, eight interviews were conducted with seven people between November 2013 and February 2014. The interviews lasted between 20-60 minutes. Seven interviews took place in Espoo, Finland, at venues chosen by the interviewees, and one was conducted via Skype. One person (Partanen) was thus interviewed twice. After the 8th interview, I deemed the interview material to be sufficiently saturated. This decision was also partially influenced by the difficulty of finding more suitable interviewees. The interviews were recorded with the interviewees' permission and later transcribed. Here, I will briefly introduce the interviewees and their backgrounds:

- Chekurov. In addition to an engineering degree, he had work experience with infrastructure development at a university design lab which had a wide array of both personal and industrial 3D printers. Chekurov was an experienced operator of these machines and worked on a 3D printing-related thesis.

- Mohite had a degree in architectural design and worked in design research in the same laboratory as Chekurov, and also had hands-on experience of different printers and pushing the envelope in terms of personal printers' performance. His first experience of 3D printing dated to around 2008.

- Partanen was a newly appointed Professor in Advanced Production Methods as well as the new director of the above mentioned design lab. He had worked as a research professor in the USA and successively for a major U.S. 3D printer/AM system manufacturer for 12 years. Since 2009 he had been involved with academic research in the field of 3D printing.

- Piili had worked for 11 years as a researcher for a technological university in the field of laser technology. She first got acquainted with additive manufacturing of metals in 2009 and helped pioneer the research in this field in her home university.

- Tuomi was the Research Director of a prominent technological university and the President of Finnish Rapid Prototyping Association (FIRPA). He had been involved with 3D modeling research already in late 1980s and first introduced to 3D printing in early 1990s at the Fraunhofer Institute. Subsequently, he helped found research projects in Rapid Prototyping technology in Finland.

- Väistö was a doctoral student in the same university as Piili. He had worked for its laboratory of laser processing and in this way gotten familiar with 3D printing technology in 2010-2011. He had performed research on the costs of 3D printing.

- Mäkelä worked as the CEO of a Finnish software company that developed e.g. data processing software packages for additive manufacturing, supplying some of the leading industrial 3D printer manufacturers. He had also worked as a researcher and in this way became involved with additive manufacturing software already in the early 1990s.

To summarize, all interviewees had extensive, expert-level experience of additive manufacturing and several of them had been involved with 3D printing technology already from the early 1990s. At the time of the interviews, the majority of them were working for Finnish universities or related organizations. Several interviewees were found by a snowballing-method, whereby interviewees were asked to recommend other knowledgeable people to interview. I met three interviewees as they were hosting two separate 3D printing events that I attended in Fall 2013. One interviewee was found through my thesis supervisor's suggestion. Seven of the interviews were conducted in Finnish and one in English. As the interviewees represented different kinds of experience with different 3D printing technologies, I considered it best to heavily modify the research questions according to each interviewee, while retaining a few key themes to provide some degree of benchmarking among them.

3.3. Documents as secondary data

According to Yin (2009, p. 103, p.109), documents play an explicit role in any data collection in doing case studies because of their overall value. He argued that for case studies, the most important use of documents is to corroborate and augment evidence from other sources, such as interviews. Furthermore, as per Christensen's (2000) recommendation, in order to examine the disruptiveness of a given technology, one should graph the trajectories of performance demanded and offered. For this purpose, I collected an extensive amount of technical data about personal 3D printers and entry-level industrial printers from document sources. Based on Adner's (2002) suggestion, also price data was collected, along with dates for first introductions and price changes.

These sets of data were acquired from physical copies of several editions of *Wohlers Report (*a prominent, annual industry publication about 3D printers with a focus on professional systems), manufacturers' press releases, annual reports, journal articles, company blog entries and product websites, sales brochures, specialist websites, user manuals as well as the odd doctoral thesis. These sources were so numerous that I deemed it best to collect them in the appendices (see Appendices D & E). This data was ultimately used for creating the performance trajectory charts (see appendices) to allow for a comparison between personal and entry-level industrial 3D printers performance and price developments.

Data was collected for 37 personal 3D printer models of 13 manufacturers, along with 30 entry-level industrial printers from seven manufacturers. The personal printers were chosen partly on the basis of the list of 26 "most popular" models from 17 manufacturers as presented in the industry publication Wohlers Report (2013a) and to a lesser extent a special issue of MAKE magazine which listed 24 novelties. One criterion for a manufacturer to be included was the availability of sufficient technical data about their current and past models. In addition, there had to be evidence of actual sales and not just a recent prototype model.

The chosen entry-level industrial printers represented incumbent companies' products in this study, as this product class has been and is dominated by incumbents. I selected the lowest-priced printer from the major manufacturers' product lines for any given time. This is because I considered them to be at the largest risk of disruption (as they form the low end of the incumbents' product lines). The higher-end additive manufacturing systems which can cost up to hundreds of thousands of dollars (see e.g. Wohlers Report, 2013) were thus omitted. The selected manufacturers were the ones with the largest market shares over the years as illustrated in several editions of Wohlers Reports, e.g. 2011a and 2013a. Note that due to strong industry consolidation, several of these companies have merged. As a result, incumbents 3DSystems, Inc. and Stratasys, Inc. have become by far the dominant producers of professional-grade 3D printers and AM systems.

3.4. Observations and documents for purpose of corroboration

Secondary data was also collected from magazines, websites, industry reports, press releases, research articles, and thesis related to 3D printing. These sources were used above all to compare, triangulate and corroborate the findings from the empirical sources (interviews and collected printer data). Some examples were a 3D printing theme issue of MAKE magazine, a master's thesis on innovation in the RepRap project by Ultimaker's co-founder and a few research articles on performance comparisons between personal and entry-level industrial printers. In addition, two books on maker communities (Gershenfeld, 2005 & Anderson, 2012) were used to evaluate the social context of this study. It should be noted that some of the same sources were also used as documents for the data tables and graphs.

If a case study is about e.g. a new technology, observation of the technology at work is invaluable aid for understanding the actual uses of the technology (Yin, 2009 p.110). With this in mind, I set off to make several field visits to Aalto University's FabLab and ADDLAB and participated in two 3D printing theme events in Helsinki and Tampere. In these venues, I was fortunate enough to be introduced to many different printer models and even observe some of them in operation. In addition, some of my interviewees were friendly enough to present me with physical artifacts in the form of different 3D printed objects. Some were made using industrial-grade printers and some with personal printers, some were samples ordered from manufacturers and some were printed on location. Although I did not make much systematic notes, these visits and tours helped me to familiarize myself with different 3D printers' uses and abilities.

3.5. Analysis of data

From the interview material, I looked for certain themes. Firstly, how the interviewees' backgrounds and prior experience with 3D printers may have affected their perceptions of personal 3D printers was of interest. Second theme was their perceptions of how the personal 3D printer category was originally born. Third, I analyzed how they perceived personal 3D printers in relation to industrial ones: were they considered to be better, inferior or just as good and in what aspects. Fourth theme was their perceptions on the potential uses of personal printers. Fifth, I tried to gather if they believed that personal printers had the potential to encroach on industrial printers' market share.

Furthermore, I also wanted to grasp the incumbent companies' point-of-view: to help choose appropriate attributes of performance for the data charts, I relied on the interviewees' perceptions of the most important product performance attributes of incumbent manufacturers' development work. Key theme was also whether the market was attractive for them to begin with, how did they react, why the late entry to the personal printer market and if they would've in theory had the ability to develop a sub-$5000 printer at the same time as the entrants. One interviewee had worked for one of the major incumbent manufacturers, so his insights about this aspect were invaluable. Finally, two interviewees were consulted on their perceptions of "good enough" performance for a 3D printer.

In terms of the document sources, the collected quantitative data was refined into scatter plots that track development of prices, layer thicknesses and build volumes over time. These were formed for both printer categories. Based on these scatter plots, I simply formed linear trend lines which I finally merged in the same chart for visual comparison. These trend lines roughly estimate the development of average/median prices and performance measures in time. The idea was to adapt Christensen's (2000, 2003) method of charting performance trajectories: in e.g. the disk drive case, he calculated median values for product attributes based on a census of data for each year. From these charts, the purpose was to address the following theory-based aspects:

- if personal 3D printers have started at a lower level of performance than incumbent's products
- if there indeed is an ascending trend in performance for both incumbents' and entrants' products

- whether personal 3D printers are lower-priced than incumbents' ones, as the theory would suggest for disruptive products
- whether personal printers' performance is improving at a rate that will eventually meet with the mainstream market's demand
- whether there are signs of performance oversupply in incumbents' products.

Also, I resorted to secondary data sources to corroborate and triangulate the primary data – mainly in terms of the contributing factors to the birth of personal 3D printer market and the performance and technical characteristics of the machines themselves. Two research articles performed comprehensive tests for 3D printers of both categories with the help of a printed, standard test object. They helped complement my empirical findings with objective test results. Secondary data also provided accurate information on the actual running costs of different 3D printers. In addition, sales figures and forecasts from research firms and trade publications greatly complemented my findings, adding to the robustness of the case. For the sake of clarity, all of the data sources for this thesis were aimed at corroborating the same phenomenon – the disruptiveness of personal 3D printers.

3.6. Validity and limitations

The first three interviews were fairly wide in scope, focusing on 3D printing as replacing traditional manufacturing. Although they helped narrow the scope, the questions for the interviewees could have been more specific. Also, personal 3D printer manufacturers could've perhaps made a good contribution. Four manufacturers of personal 3D printers – three foreign and one domestic – were approached with an interview request but despite their initial signs of interest, I was unable to get them to participate.

Deciding which personal 3D printers to include and which ones to omit was a cause for concern. According to Wohlers Associates (2013a, p.112), there are over 100 manufacturers of personal 3D printers, or even several hundred (Tuomi, 2014), so there is an overwhelming amount of models available. It was thus not feasible to attempt to gather comprehensive census-type of data for every model in the world from every consecutive year and calculate averages or medians on that basis, like Christensen (2000) did in the disk drive cases. For the personal 3D printers in particular, reliable aggregate data is in short supply. In addition, during the research process there seemed to be new 3D printer models and manufacturers born almost on a weekly basis.

Certain models were omitted if sufficient technical data was not available or if they appeared to be in a prototype stage. Also omitted were many less prominent also-rans that are technically very similar to the included ones and would not have made a difference to the overall results. All in all, I believe the selected 37 personal 3D printer models form a sufficient amount of data to illustrate performance development over time in this product category.

In addition, a few printer models were difficult to categorize in either group. E.g. Leapfrog Xeed, Makerbot Replicator Z18, re:3D Gigabot and Deltatower were introduced by entrant companies, yet priced well over 5000 USD and thus too expensive to be classified as personal printers (as defined by Wohlers Associates, 2013a). If included in the entry-level industrial group, the resulting data would no longer work as a depiction of incumbent companies' products. As a result, they were omitted from the data altogether. On the other hand, despite a price lower than 5000 USD, the 3DSystems Projet 1200 was included as an industrial printer due to its highly specialized, business-application nature. Asiga Pico was included for the same reason despite being an entrant. Thus, the 5000 USD quasi-boundary between personal and industrial machines is diluting. In addition, acquisitions have obscured the boundary between entrants and incumbents.

In order to estimate the level of performance demanded by printer users (using layer thicknesses as a factor of printing accuracy), only two interviewees were consulted. Admittedly, more interviewees should have been involved, but the relevance of the question only dawned on me in the last round of interviews. However, the two interviewees that were consulted were more than capable of providing educated estimates. The average of these two estimates was calculated (125 microns) and marked in the graphs with a dotted line (see Appendix G). This flat trajectory for performance demanded was assumed to be flat, as per Christensen & Raynor's (2003, see page 36 of this thesis) perception on the stable nature of demand, and for the sake of simplicity. Similar measure should have been formed of build volume, but only one interviewee was consulted. Thus I deemed it best to leave the demand-line out of the build volume graphs altogether and address it in the text instead.

4. Empirical findings

4.1. Contributing factors to the advent of personal 3D printers

4.1.1. Expiring patents of 3D printing technology

> *"From the beginning, we could only do what we did because the original patent expired… we spent a lot of time at MakerBot routing around the intellectual property of the big companies. There are probably around eight patents that we couldn't have that we had to work really hard to route around to be able to have our products."*

-Bre Pettis, co-founder of MakerBot (MAKE magazine, 2013)

Similarly, most interviewees (Mäkelä, Väistö, Mohite, Piili, Partanen and Tuomi) recognized the expiry of certain 3D printing patents as a contributing factor to the recent proliferation in 3D printing and personal 3D printers. Mohite (2013), Tuomi (2014) and Mäkelä (2014) specified that it is about the expiry of Fused Deposition Modeling (FDM) patents, which have been held by Stratasys, Inc. Stratasys still holds several patents on FDM technology (see. e.g. Google Patents, 2014). The great majority of personal 3D printers, including the RepRap project, are based on FDM technology – the sole exception in this thesis' data being the Formlabs Form1, which is based on stereolithography.

According to Piili (2013), consumer 3D printers have come to the market purely due to the fact that the patents of the first plastic 3D printers expired about four years ago. Tuomi (2014) elaborated that the expiry of patents wasn't the kickoff for the personal 3D printers, but building them for research use and consequently people building them in their garages. Originally it may have been that Stratasys' most essential patents were still in force when this university laboratories' research ventures commenced, since patents don't matter for research purposes; also private individuals, can build devices for their own use irrespective of whether someone holds a patent for it. However, he argued that the expiry of patents has enabled the commercial use and serial production of these printers. (Tuomi) In contrast, Mohite (2013) sees the patent expiry as the driver of RepRap project:

Mostly, I think, it's because FDM technology, the trademarks were old, like the patent was old, and that was the whole… it drove the whole RepRap project… what the RepRap project is like. Because Stratasys, the company which invented the FDM technology, which melts plastic, and then they also like… the patent period was over, and then suddenly the designs was available to everybody.

However, Partanen (2013) – who has filed 50 patents for 3DSystems – claims that in 3D printers it is a not a question of just one patent, but a huge amount of patents. And even if patents of some of the basic aspects of a technology have expired, some auxiliary patents may not have. And if they cannot be used, the product may not necessarily be much good. (Partanen, 2013) One such aspect seems to be the heated build chamber for FDM printers, the patent of which is still in force and held by Stratasys. According to Chekurov (2014), the lack of a heated build chamber greatly affects the printing quality and reliability of personal 3D printers, since the temperature doesn't remain stable. Due to the patent, they have so far not been employed in personal 3D printers. (Chekurov) Also Mäkelä (2014) considered the lack of a temperature-controlled enclosed build chamber to have an adverse effect on the printing quality of personal printers, compared to industrial ones. Thus, an existing patent still hinders the performance development of FDM-based personal printers.

In their article about the development of RepRap, Jones et al (2011) refer to a Stratasys FDM patent *"Apparatus and Method for Creating Three-Dimensional Objects"*, patent number US 5121329, which is apparently one of those expired patents (see e.g. Patentbuddy, 2014a). Also Roberson et al (2013) mention the very same patent as one of original FDM patents that has opened the material extrusion technology market. Further, the patent still in force for a heated build chamber as mentioned by Chekurov appears to be US 6722872 *"High Temperature Modeling Apparatus"* (see e.g. Patentbuddy, 2014b).

Further, Mäkelä (2014) believed that most of the original 3D printing patents have now expired or are about to expire, including stereolithography (SLA) patents. Also Partanen (2013) estimated that the primary stereolithography patent has expired. According to Wohlers Associates (2011b), it was filed in 1986 and titled *"Apparatus for Production of Three-Dimensional Objects by Stereolithography"*. This patent (US 4575330 A) seems to have indeed expired in 2004 (Patentbuddy, 2014c). In addition, according to MAKE magazine (2013), another 3DSystems stereolithography patent "Method and Apparatus for Production of Three-Dimensional Objects by Stereolithography" (US 5554336 A, filed in 1986) is also expiring soon. As a result, also personal 3D printers are now beginning to employ stereolithography technology. The industry entrant Formlabs has apparently been the first company to introduce a stereolithography-based 3D printer in the sub-$5000 price class. The Form1 came to the market in May 2013 at a price of $3299 (Formlabs, 2013). In June 2014, there were at least a half a dozen SLA-based personal 3D printers on the market or in the development phase (see e.g. Kickstarter, 2014; Indiegogo, 2014).

Stereolithography (SLA) is a very accurate method and it has been referred to as the "gold standard" of the industry (3DSystems 3.12.2013 & Formlabs, 2014). MAKE magazine (2013) claims that printers using SLA technology can produce parts with resolution four times greater than those from FDM-type machines. Thus, the growing number of low-cost SLA printers on the market is no wonder. Also Tuomi (2014), Partanen (2014) and Chekurov (2014) considered stereolithography a more promising technology than FDM. It may thus spur personal 3D printers to become even more serious contenders to industrial printers. In addition, albeit a more expensive system in general, several SLA-based personal printers can be operated with a common household DLP projector instead of laser as in most incumbents' SLA printers. This contributes to a simpler, more affordable and more modularized construction.

To summarize, when a key FDM patent expired, inexpensive equipment in the form of kits and fully assembled machines based on the RepRap open-source project became available. Since their introduction, these low-cost "personal" systems have experienced very strong growth. When critical stereolithography and laser sintering technology patents expire, individuals and organizations can be expected to take advantage of similar opportunities with these processes. (Wohlers Associates, 2013b) Anderson (2012) describes how countless of small entrants will pour in when industry barriers are lowered. In the case of personal 3D printers, the expiring FDM and SLA patents seem to have lowered the industry entry barriers significantly.

4.1.1. The RepRap project

When I asked which factors have driven the strong growth of 3D printing during the last few years, Väistö, Partanen and Mohite specifically named the RepRap project as a contributing factor. In addition, Tuomi considered the research ventures of university laboratories as the start for personal 3D printer production – apparently also referring to the RepRap project. The RepRap, which stands for *Replicating Rapid Prototyper*, was the world's first open-source 3D printer (de Bruijn, 2010; Anderson, 2012) and it may thus be considered the very first step on the development path that has led to the personal 3D printer market of today. Most personal 3D printers copy the RepRap reference design and improve upon it (Wohlers Associates, 2013a p.112). According to Mohite (2013), the whole RepRap project was driven by the fact that the FDM patents had expired. He explains:

> *"…the patent period was over, and then suddenly the designs were available to everybody… and then that's when the RepRap project… and then people started making them in their backyards, and try to start selling parts so people could just, like, laser cut it and a build it themselves in their backyard. So that drove the 3D printing, I think, a lot".*

In similar vein, Väistö (2013) estimated that when the first RepRaps and other home printers started coming, the patents had already practically expired. Jones et al (2011) describe the RepRap printer as an *open-source self-replicating rapid prototyping machine* (italics added) – in other words, a royalty-free 3D printer that is designed to be able to print most of its own parts. The primary motivation was to allow the machine to spread as effectively as possible. This priority on reproductive ability has fueled its strong proliferation and provided a breeding ground for promising startups that wanted to take the idea further.

The RepRap project was originally conceived by Dr. Adrian Bowyer from the University of Bath in the UK (e.g. Pearce et al, 2010), with the first unit – called the RepRap Darwin – built in May, 2007 (Jones at al, 2011), heralding the first time a low-cost 3D printer – or at least its blueprints – was made available to the public. This was followed by a second generation of the printer called the Mendel in October 2009 (Jones et al, 2011), and concurrently the third generation in 2010, called the Huxley (RepRap, 2010). According to Wohlers Associates (2011a), the open-source RepRap project developed quickly, and became surprisingly popular. In early 2008, there were a total of four RepRap printers in existence. In October 2010, the total unit population was conservatively estimated to be 4500, spread in many parts of the world. (Jones et al, 2011).

The first generation machine “Darwin”, could make 48% of its own parts excluding fasteners such as nut, bolts and washers. The printer was designed in such a fashion that virtually all of the parts that the machine cannot make for itself – other than the electronics and the motors – are standard engineering materials that can be obtained cheaply worldwide, from an ordinary high-street hardware shop. This was done to maximize the ease – and hence probability – of reproduction. For the same reason, the RepRap was designed to be easy for any technically competent person to construct and to run the machine at home. (Jones et al, 2011) See Appendix B for a picture of the RepRap Darwin.

Further, asking for payment for a copy of the design was considered to be detrimental to its reproductive fitness. Therefore, every piece of information required to build a RepRap was distributed for free under a software libre licence. For the actual 3D printing technology, Fused Filament Fabrication (FFF) – also known as Fused Deposition Modeling (FDM) – was chosen due to several considerations: (Jones et al, 2011)

> *“FFF offered the possibility of being able to build with multiple different materials. This in turn offered the significant advantage in the future of being able to have the machine make a larger proportion of its own components than could be created out of just one material. This, combined with the fact that it was conjectured that fused-filament fabrication could be implemented using low-cost garden-shed methods, led that to be chosen for RepRap.”*

This is supported by Tuomi (2014), who considered FDM technology to be the most suitable of 3D printing technologies to realize very cheaply, and for which very affordable components are available. Also Mäkelä (2014) considered FDM as a researched technology that is easy to copy. After a series of experiments, polylactic acid (PLA) plastic was found to be the most suitable printing material for the RepRap and as such an almost perfect material for the fused-filament fabrication process (Jones et al, 2011). Interestingly, according to data from Wohlers Associates (2011a), none of the incumbent companies’ industrial 3D printers or additive manufacturing systems seemed to offer PLA as a choice of material, making the RepRap a frontrunner in that respect. For example, Stratasys’ entry-level FDM machines only used ABSplus (Wohlers Associates, 2011a). Currently, PLA seems to be, in addition to ABS, by far the most common extrusion material of personal 3D printers – an innovation which can be traced back to the RepRap project.

In addition to the RepRap project, Fab@Home was another open-source development 3D printer project, with the technical difference that it employed a syringe instead of a filament on a spool (Wohlers Associates, 2011a). According to Jones et al (2011), the Fab@Home project originated from the Cornell University and it was inspired by the RepRap project. The Fab@Home was nevertheless not a RepRap derivative (de Bruijn, 2010), although its development bears many similarities to the latter. Between 2007 and 2010, 165 Fab@Home units had been built (Wohlers Associates, 2011a). However, the project seems to have been discontinued.

As was the case with Linux open-source operating system, commercial and quasi-commercial activity has spun off the RepRap project (Wohlers Associates, 2011a). Two companies, Makerbot in the USA and Bits From Bytes in the UK, were subsequently formed to make and sell RepRap-based printers using lasercut parts instead of 3D printed ones (Jones et al, 2011). According to de Bruijn (2010), Bits From Bytes started out by selling moulded parts for the early RepRap Darwin designs, later moving to sell full kits initially based on the RepRap Darwin model. In a similar fashion, Makerbot's first machines even employed standard RepRap electronics and control boards (Wohlers Associates, 2011a). As a result, apparently the very first commercialized RepRap-based 3D printers were introduced in April 2009 – namely the RapMan by Bits From Bytes and the Cupcake CNC by Makerbot. Both were sold in kit forms for prices of 750 £ and 750 $, respectively. (Wohlers Associates, 2013b) In comparison, the total cost of building a RepRap was initially about 500 € (Jones et al, 2011; de Bruijn, 2010), which was less than 5 % of the price of the lowest-priced commercial printer at the time.

According to Wohlers Associates (2011a), the personal 3D printer category was largely spawned by the RepRap open-source project. The amount of derivatives and variations of the RepRap printers has experienced explosive growth, with the RepRap Family Tree (RepRap, 2014b) containing ca. 400 variants developed between 2006-2012. In fact, the majority of personal 3D printer manufacturers, such as Makerbot, Ultimaker, Printrbot, Bits From Bytes, Deezmaker, Botmill, Lulzbot, Magicfirm (mBot), Solidoodle, Leapfrog and Delta Micro Factory Corp (DMFC) had their roots in the RepRap project (see e.g. Reprap, 2014b; Roberson et al, 2013; Perez et al, 2013; Wohlers Associates, 2011a+b; Wohlers Associates, 2013a+b; De Bruijn, 2010; De Jong & De Bruijn, 2013 & MAKE, 2013).

In a recent edition of Make magazine (2013), the founders of many of these companies, such as Makerbot, Ultimaker, SeeMeCNC, Printrbot and Deezmaker/Bukobot explicitly expressed their desire to improve on the RepRap as the impetus to create their own printer model or having at least become familiar with 3D printing through their experience with RepRaps. Ultimaker's co-founder Erik de Bruijn states that the company's aim was to make the RepRap easier to build (de Bruijn, 2010). At least according to MAKE magazine (2013) Makerbot had the very same goal, as the founders were allegedly frustrated with the process of building a RepRap.

De Bruijn (2010) found out that "increased ease of assembly and use", or convenience, was one of the most common domains of innovation in the RepRap community. He named derivative designs such as RepRap Mendel, Makerbot and Ultimaker as examples of such convenience-improving innovations. Currently, manufacturers such as Ultimaker and Makerbot seem to be moving away from kit versions altogether, selling only fully assembled 3D printers (see Appendix D).

To summarize, the emphasis on self-reproduction and dissemination drove the proliferation of the RepRaps worldwide. Its plastic components could be printed with another RepRap while the remaining parts were mostly standard-issue rods, nuts and bolts. Also the chosen FDM technology was the most suitable technology for low-cost applications due to its simple structure and cheap components. The RepRap project contributed heavily to the birth of a number of startups, the motive of which was to improve the RepRap. Some of them have since become major players in the personal 3D printer industry. While the RepRap project seems to have since ceded to a minor role, its legacy lives on in many personal 3D printer manufacturers of today. Next, I will discuss the role of open-source development work in the RepRap and its commercial successors.

4.1.3. Open-source technology

Partanen (2013) recognized the open-source community as an extremely important factor in the development of the RepRap and its software. Also Mäkelä (2014) considered the RepRap to be in a way a model for all personal 3D printers, and in this way the open-source approach to be a significant factor in their development. According to De Bruijn (2010), the term "open source" is usually referred to as a development methodology often practiced by communities of autonomous individuals who are geographically dispersed. The Open Source Hardware Association (2013) defines open-source *hardware* the following way:

> *"Open source hardware is hardware whose design is made publicly available so that anyone can study, modify, distribute, make, and sell the design or hardware based on that design. The hardware's source, the design from which it is made, is available in the preferred format for making modifications to it. Ideally, open source hardware uses readily-available components and materials, standard processes, open infrastructure, unrestricted content, and open-source design tools to maximize the ability of individuals to make and use hardware. Open source hardware gives people the freedom to control their technology while sharing knowledge and encouraging commerce through the open exchange of designs."*

Open-source development work has predominantly taken place in software projects, such as the Linux computer operating system and the Firefox web browser (Anderson, 2012; de Bruijn, 2010). Anderson (2012) argues that "open hardware" is now doing the same for physical goods what open source did to software. Thus, the approach can be applied to hardware projects, too, such as the RepRap printer. To clarify, in the RepRap project, the open-source development effort includes both software as well as hardware (De Bruijn, 2010). He also offered evidence that the open-source approach works in a fairly similar way with both software and hardware projects. Further, Wohlers Associates (2011a) found that the RepRap most closely resembles the Linux open-source operating system development in terms of spinoff commercial activity.

De Bruijn (2010) studied the open-source development approach in the context of the RepRap project and found that *"…with its tools, infrastructure and incentives, the RepRap community uses the open source development methodology for the design of physical objects in a highly successful and democratizing way"*. Essentially, what this open-source hardware – or open design – means is that information about hardware, such as schematics, bills of materials and assembly instructions are freely revealed (De Bruijn, 2010). In the case of the RepRap, the software, documentation, electronics and mechanics of the RepRap were done by the collective and distributed online using wikis, blogs and Sourceforge (RepRap, 2009). At the time of this writing, all the component blueprints and software needed to build different

RepRap models were available at RepRap wiki pages (reprap.org) and the open source project repository GitHub (github.com/reprap).

Collaboration in an open source community is facilitated in several ways, one of which is through a license that is used to provide freedoms rather than imposing restrictions on usage. It e.g. enables reuse and improvement of the open-source product without need to ask for permission (De Bruijn, 2010). The RepRap belongs under a GNU General Public License, which obliges people who improve the machine to make public their improvements as well under a similar free license (Jones et al, 2011). In other words, the General Public License requires that all derivative and downstream modifications of the hardware project are released under the same license and may be distributed freely (de Bruijn, 2010). What this means is that also the RepRap derivative 3D printers' designs are being distributed free and open-source, as required by the license (Jones et al, 2011).

The open-source approach has indeed been very pervasive especially in the early personal 3D printers. While based on the RepRap printer, the early Makerbot printers were also based on other previous open-source projects, such as the Arduino microprocessor and a series of software packages. In the early Makerbots, *open source* (italics by author) meant open everything: electronics, software, physical design, documentation, even the logo. Practically everything about the MakerBot was either developed by a community or given to one to do with as they please. (Anderson, 2012) Also the Dutch RepRap-based Ultimaker printers started out as open-source (De Bruijn, 2010). According to an interview of the company founder,*"Ultimaker turned out even more successful than we imagined, to a large part thanks to the great open-source community."* (de Bruijn, 2013; see MAKE, 2013). Ultimaker shares the bill-of-material (basically, parts lists), component blueprints, assembly instructions and firmware of its printers online under a Creative Commons license (Ultimaker, 2014b). Thus, at least in theory, one would be able to procure or make the parts separately and build a copy of the printer his/herself. This reflects another core aspect of open-source hardware: users can make the products themselves, if they want – without needing to pay [for the designs] (Anderson, 2012). It should be noted that the open-source approach also means that a printer's software and hardware are open for users to modify and tweak. This makes it possible for the users to tune the 3D printer to suit special printing purposes (Chekurov, 2014).

Further, MAKE magazine (2013) recently tested 18 personal 3D printer novelties – eight of them were said to be open-source both in hardware and software (e.g. Ultimaker, Printrbot, Deezmaker, Lulzbot) six were closed-source in both aspects (e.g. Formlabs Form1, Makerbot Replicator 2, 3DSystems Cube 2) while the rest were partially open-source. So while open-source technology has been an essential part of the development of personal 3D printers, fully closed-source printers exist too. Also, some printer manufacturers such as Bits from Bytes and Makerbot started out with open-source design but moved away from it in their later printer versions (see e.g. De Bruijn, 2010; Pettis, 2012). Makerbot's co-founder Bre Pettis justified the move with the fear of "carbon-copy clones" and "competition from below and above" as well as a transition in focus from hacker-friendly machines to user-friendly ones (Pettis, 2012). Concurrently, both of these companies were acquired by the industry incumbents.

In his book "Makers", Anderson (2012) points out how an open-source approach can be a very powerful method in developing software and hardware. He argues that open source creates a virtuous cycle that accelerates the innovation process far faster than conventional development can. The logic behind it is simple. Inventors increasingly share their innovations publicly because they believe that they get back more in return than they give away – free help in developing their inventions (Anderson, 2012). The author elaborates:

> *"What that means is cheaper, faster and better research and development, which in turn can create unbeatable economics for companies whose products are developed this way. And it's not just R&D. Product documentation, marketing, and support are often done the same way, by a community of volunteers within a community. Some of the most costly functions of traditional companies can be done for free, so long as the social incentives are tuned right."*

Jones et al (2011) claim that many design variations developed by the RepRap user community would not have been possible if the project had not been open-source. De Bruijn (2010) considered the levels of innovation of the open-source approach in the RepRap project to be similar to large players in the incumbent industry, while exhibiting radically higher growth rates. He also found it feasible that its adoption and levels of innovation would exceed that of the incumbent industry.

Anderson (2012) stresses the point how open-source product development is faster, cheaper and better than traditional closed R&D, even that of some of world's biggest companies. Then again, De Bruijn (2010) estimated the incurred expenditure for RepRap users' innovation efforts alone to total roughly between 382 000 and 478 000 USD by October, 2010. This is in contrast to Anderson (2012) who considered an open-source approach to yield virtually free R&D activity even in hardware projects. That, in my opinion, applies to companies that wish to commercialize an existing open-source design, the incurred development costs of which have already been borne by the open-source community. De Bruijn (2010) nevertheless claims that together, users can in many cases innovate at a low cost. These findings are supported by Partanen (2014), who considered hobbyism to be a strong component in the RepRap project. He felt that if one would've had to pay salaries for all of its development work, such activity might not have emerged so easily. Thus, he believed that an incumbent company would hardly have made any margin at all to cover the (in-house) development costs of a printer similar to a RepRap.

Using an example of an open-source garden water sprinkler, Anderson (2012) estimated that it could be made and sold at a modest profit for something between one-third and one-fifth of the price of an equivalent commercial sprinkler. He adds that the essentially free open-source R&D for the water sprinkler would've cost hundreds of thousands of dollars if it had been a closed-source endeavor. You see, in the open-source version, there is no charge for intellectual property by the manufacturer. (Anderson, 2012) In comparison, the initial material costs for a RepRap kit were approximately 500 € (de Bruijn, 2010; Jones et al, 2011) which translates to something between 5 and 7 percent of the cheapest industrial 3D printers' prices at the time, depending on the year the comparison was made (see Appendix E & Jones et al, 2011). Moreover, the first commercially sold RepRap-derivative printer kits were closer to 10 percent of the incumbents' lowest-priced machines (see Appendices D and E). Also Pearce et al (2010) found that while commercial printers excelled at rapidly producing high-tolerance representations of complex parts, they were far more expensive ($5000-$200,000) than the ~$1,000 open source rapid prototypers. Thus, when your R&D is free – thanks to the open-source community – and you don't charge for intellectual property, it's not hard to undercut proprietary alternatives, even at a lower volume (Anderson, 2012). In contrast, Partanen (2013) explains the incumbent companies' higher prices by the fact that they had incurred investments in R&D and wanted to get a return for such investments.

To summarize, the RepRap project is existing proof that the open source development methodology also works for the design of physical objects (De Bruijn, 2010). The RepRap offspring 3D printer manufacturers have been able to tap into a pool of virtually free R&D thanks to RepRap's open-source technology and incumbents' expired patents. This means that they didn't initially have accumulated R&D expenditures to cover when selling their products, helping keep the prices at a very low level. Also many of the designs have been distributed completely free of charge, allowing users to build their own machines at the cost of mere components.

4.1.4. Development work by user communities

According to Anderson (2012), one has to build a community and manage it in order for the open-source model to succeed. Thus, user communities and open-source approach in either software or hardware are in many ways inseparable. The contribution of these communities in the development of RepRap was recognized by Partanen (2013) and Väistö (2013). In his study of the RepRap project, de Bruijn (2010) distinguished a core community as well as a peripheral community with regard to involvement in the project. In 2009, there were 16 people working in the core team from all over the world (RepRap A, 2009), while de Bruijn (2010) mathematically estimated the entire community to consist of something between 3872 and 4840 people as of October, 2010. He further estimated the aggregate R&D effort of the RepRap community to equal something between 145 and 182 full-time employees, assuming 40 hours of work per week. (de Bruijn, 2010) He also found that like many larger open source software communities – but unlike most hardware based projects – the RepRap community has been geographically distributed (de Bruijn, 2010).

According to Jones et al (2011), the worldwide RepRap community provided lots of improvements and suggestions for the "Mendel" version, posted online in the project's website. These were then included in the design. The authors also acknowledge that without the continuous volunteering of the worldwide RepRap community, the project *"…would be but a shadow of what it has become through their unflagging input and support."* (Jones et al, 2011) Not only did the entrant printer manufacturers benefit from existing communities, like the RepRap one, but they also subsequently built their own ones. The great majority of the personal printer manufactures seem to have at least an online discussion and support forum on their websites. In relation to RepRap derivative businesses in general, De Bruijn (2010) argues that such *“community-centric businesses also greatly benefit from the community, since it provides a stream of updates and modifications to the machines that they sell”*. He makes a reference to Makerbot, claiming that *“…in the case of Makerbot, these modifications are contributed at a rate beyond what would be feasible for in-house development by any single firm in the industry”* (De Bruijn, 2010). According to De Jong & De Bruijn (2013), incorporating community innovations is an almost routine practice in 3D printing. At the time, they argued that user-founded businesses like Makerbot and Ultimaker were intensively collaborating with the communities from which they emerged, regularly incorporating community innovations in their newest releases.

More recently, crowdfunding websites Kickstarter and Indiegogo seem to have emerged as significant communities around personal 3D printers. According to Wohlers Associates (2013a p.114), Kickstarter has been instrumental in launching many 3D printer startups and projects. On July 16th, 2014, I counted a total of 40 successfully funded 3D printer projects on Kickstarter, some of the most successful being the Formlabs Form1, Deezmaker Bukobot and Printrbot.

Also, a wider phenomenon known as the Maker Movement adds to the social context of this case. An early account by Gershenfeld (2005) addressed a rising phenomenon of “personal fabrication”, whereby individual people are increasingly able to design and produce their own products, in their own homes, with the help of machines that combine consumer electronics and industrial tools. Later authors such as Anderson (2012) refined this phenomenon, labeling it the Maker Movement and associating personal 3D printers as an integral part of it. He considered the Maker Movement phenomenon to be “less than seven years old”, thus dating it to roughly the same time the RepRep project was initiated. He also considered the RepRap printer as *“another key milestone of the Maker Movement”*. (Anderson, 2012)

Summarizing Anderson, the phenomenon is about people using digital tools, designing onscreen and outputting to desktop fabrication machines, instinctively sharing their creations online. Essentially, one of its key principles is that the technology to create and design new products is available to anyone today. (Anderson, 2012) Thus, Anderson also sees open hardware – as discussed in the previous part – as a part of the Maker Movement. To summarize, Maker Movement is DIY culture connected with advanced fabrication machines and online communities. According to Wohlers Associates (2011a), the open-source 3D printer systems and kits have been the "catalyst" for the maker movement. Many of the machines are being sold to hobbyists, do-it-yourselfers, young engineers, and engineering students (Wohlers Associates, 2013a p. 135). As a result, one can assume that the maker movement phenomenon has occurred hand-in-hand with the development of personal 3D printers. and contributed to their demand.

Another part of the Maker Movement are FabLabs (Gershenfeld, 2012). A FabLab stands for "a lab for fabrication" (Gershenfeld, 2005) and they typically offer at least a minimal set of digital fabrication tools such as a laser cutter, a CNC machine and a 3D printer (Anderson, 2012). These physical maker communities – also known as makerspaces or hackerspaces– seem to have contributed to the founding of many personal 3D printer manufacturers. According to interviews with the founders, companies like Type A, Deezmaker and Printrbot originated from hackerspaces and 3D printer meetup groups, each founded between 2011-2012 (MAKE, 2013). MakerBot was founded in 2009 as a project among friends in a makerspace in New York (Makerbot, 2014; MAKE, 2013) while Ultimaker originated in 2011 out of a RepRap workshop at a Dutch FabLab (de Bruijn, 2010; Ultimaker, 2014a). Many other manufacturers, such as SeeMeCNC, Formlabs and MakerGear were launched between 2009-2012 as well (MAKE, 2013). These observations suggest a considerable amount of entrants to the personal 3D printer market have predominantly been fairly young and small community-based startups. As a anecdotal analogy, Anderson (2012) sees a similarity in the birth histories of the first Makerbot 3D printers and the first Apple personal computers, as both originated from maker/user communities.

With reference to the theoretical framework of this thesis – disruptive innovations – De Bruijn (2010) commented on the interplay between an open-source community and incumbent industry. In his case study of the RepRap, he found that an open source community of user innovators can be a source of disruptive technology in the presence of a pre-existing industry, in this case the 3D printer industry. He states that *"Players in this industry have been unable or unwilling to address the needs of the segment of user-innovators who are now increasingly able to address their own needs."*

4.2. Potentially disruptive aspects of personal 3D printers

During the first three interviews, I tried to find out more about the disruptive potential of 3D printing technology in relation to traditional manufacturing methods. This was based on claims in many articles and publications which emphasized how 3D printing will displace traditional manufacturing (see e.g. The Economist, 2012; CSC, 2012). However, it soon became painfully clear that not only was such an approach too broad and vague for a thesis, but the interviewees didn't seem to find the topic very sensible. In fact, they were quick to point out that 3D printing will not widely displace subtractive manufacturing methods, except in certain individual applications (Piili, Väistö).

In addition, the theory of disruptive innovations suggested that disruption always takes place relative to some other, much more specific technology or industry. However, it was difficult to pinpoint an ideal case of a technology, product or method that 3D printing as a technology would actually displace. Also, 3D printing as a technology was too vague a concept in itself. Therefore, the research questions as well as the interview themes had to be reconstructed. The first interviewees identified the RepRap project as an important driver of 3D printing, which lead me to discover the ideal viewpoint for the theory of disruptive innovations: the novel, low-priced personal 3D printers in relation to the fairly expensive industrial ones. This became the focus for the remaining interviews. Several interviewees (Piili, Väistö, Tuomi) thought that personal 3D printers have contributed to a 3D-printing *hype* or *bubble* (Mohite) to emerge – perhaps best translated as inflated expectations regarding the technology. Also the research company Gartner placed consumer 3D printing at the very top of their concept of a "hype cycle" (Gartner, 2013c).

4.2.1. Perceptions of personal 3D printers' abilities

As I pointed out in the literature review, Christensen and his co-authors (2000, 2003, 2004) determined disruptive innovations to be typically simpler (and simpler to use), smaller, more convenient and more reliable yet initially inferior in the primary performance attributes that matter most in the mainstream market. Customization and affordability are also some of their typical benefits (Christensen et al, 2004 p.41).

This begs the question how closely do these characteristics match personal 3D printers? While addressing Christensen's performance trajectory models with quantitative, more objective data of 3D printers in the form of graphs and tables (see appendices), I will address these more subjective, qualitative characteristics of disruptive innovations here with the help of my interview material. Further, I will add depth to the analysis of interviewees' perceptions of personal 3D printers' performance and abilities by drawing on secondary sources, such as articles by Perez et al (2013) and Roberson et al (2013) who tested different printers in a more objective manner.

Tuomi (2014) had experience of both personal and industrial 3D printers – dating back to the early 1990s – and worked on the technology in a university at the time of the interview. He is also the chairman of the Finnish Rapid Prototyping Association (FIRPA). He had perhaps the most skeptical perception of the personal 3D printers. According to Tuomi, *cheapo printers* – as he called them, in addition to *home printers* – produce very poor quality from a manufacturing point of view. Therefore, he claimed that doing service business by selling the printed objects to customers would be out of the question. Thus, he didn't consider these printers to be that interesting for people and companies that make something professionally. He elaborated that their components are very cheap, surface finish of printed objects and dimensional accuracy are very weak, and the array of materials is inadequate.

Further, Tuomi considered the difference between a 3D printed technical product – printed for the purpose of resale with a professional device – and one made with a personal printer to be "enormous". He deduced that in order to print items for resale purposes, one must still invest in professional-grade machines. Tuomi considered personal 3D printers to be above all "experience" machines, where it is the experience that a user gets from printing something on their own that counts, printing objects for no particular use. Also, he noted that their university lab had certain kit-based printers that had never been able to print an object successfully. Essentially, Tuomi considered even the newest personal 3D printers to be unable to print in such a quality that would allow selling the printed items to customers.

Chekurov (2014) had work experience from a university design lab which was equipped with several different 3D printers, both personal and entry-level professional ones. Based on his experiences with these machines, he also supported the view that personal printers – simply referring to them as *the cheaper devices* – don't produce nearly as good quality as the professional ones. In the lab, the personal ones were used by students as learning tools, for their own projects as well as by the design team for certain special purposes. He stated that personal printers are not even considered for company projects such as prototyping purposes due to their inferior printing quality. When I asked him if the ways personal and industrial printers are used differ from each other in the university lab, he replied:

> *"Yes, like night and day when the actual professional stuff is done. That is, when research is being done and enterprises are involved in the research, then the use of cheap devices is not even considered."*

He also considered printing speed (in association with printing quality) to be better in industrial ones; while personal printers can in fact be faster, it comes at a great expense in quality. He nevertheless estimated printing speed between the latest personal printers and the entry-level industrial ones to be on par. He considered the reliability of the printing process to be an important thing for him and argued that industrial printers fare well in that respect, whereas personal machines require constant monitoring. (Chekurov) Chekurov accepted the generalization that the build quality and thus printing quality of personal printers are weaker than in industrial entry-level machines. He nevertheless admitted that new FDM-type personal printers can achieve "okay" quality, if one doesn't demand much and has the ability to tweak the design, but working with them takes more time.

> *"What I've gathered, the time that a person uses in half a year to struggle with the small device, could have afforded the purchase of the more expensive one straight away."*

As a result, he found there to be a large difference in the ease of use between the personal and entry-level industrial ones – the latter being designed for people who aren't experienced in using them and thus have a straightforward operating procedure. In comparison, he felt that personal printers require quite a bit of small adjustments. Hence, a professional printer is much easier to use, while a personal one suits teaching purposes well. (Chekurov) Then again, depending on the technology employed, certain entry-level industrial printers have at least previously required elaborate post-processing procedures for the printed parts (TA Grimm report p.46) which are uncommon among (predominantly FDM-based) personal printers. Furthermore, according to Piili (2013), the biggest problem and challenge with consumer 3D printers is making the three-dimensional images. She argued that it takes quite a lot of hobby-orientation for an average consumer to learn how to use a 3D modeling program.

Chekurov's findings are supported by the industry research firm Wohlers Associates (2013a p.113), who argue that personal 3D printers are currently [May, 2013] among the least reliable devices that a consumer can buy for home use. They claim that many vendors overstate their machine's reliability and ease of use, while downplaying technical issues. However, they also claimed that *"Customers may soon expect personal 3D printers to have reliability similar to that of popular consumer electronics"*. (Wohlers Associates, 2013a) Personal printers nevertheless allow the access to a greater amount of parameters, emphasizing that these low-cost printers are thus a better alternative – and perhaps the only one – for special printing purposes, since both software and hardware can be tweaked. (Chekurov) Such tweaking is enabled by the printers' open-source structure. Most of the 37 personal 3D printer models listed in Appendix D are open-source at least in software or hardware; some in both. Then again, Tuomi (2014) noted that not all professional printers are closed systems either; certain manufacturers do allow the user to manipulate the process, which he considered to be one competitive advantage as well.

As for other advantages of personal printers, Chekurov mentioned smaller material costs and an open material library, allowing for more alternatives in materials than entry-level industrial printers, which often only employ ABS plastic. When asked if it would be possible for personal 3D printers to replace the entry-level industrial ones currently in the university design lab, Chekurov considered the biggest precondition to be an improvement in printing reliability of the personal printers. Expiry of a Stratasys patent regarding the heated build chamber would in his opinion be a big thing and help overcome these hurdles in personal printers' reliability. He considered the Formlabs Form1 3D printer to be promising in possibly replacing some industrial printers in the lab.

Partanen (2013, 2014) had long first-hand experience in the actual development work of industrial AM systems for one of the leading manufacturers, and conducted research on the technology in a university at the time of the interview. He considered material attributes, along with printing accuracy, to be biggest development priority for professional-grade printer manufacturers, with the aim of finding materials that suit as many applications as possible. He explained that expensive [industrial] printers are assembled very carefully, tested to a great extent and given some guarantee that they work relatively well. As for the cheap printers, he implies that the buyer is responsible for getting the device to work. (Partanen) In line with Chekurov's perception, Partanen considered the reliability of the printing process and the printing quality to yield the biggest differences between the personal and industrial printers. The printed objects (of personal printers) are of inferior quality and material attributes may not be on par either. (Partanen) When asked if his findings can be generalized, Partanen concurred:

> *"Surely, better objects can be made with the cheapest professional-grade printer, and their printing reliability is perhaps better."*

He also added that the material properties may not have been studied so extensively in the low-end machines than professional-grade machines, repeating the point that in the cheap printers, the printing results are up to the buyer. However, Partanen – as well as Chekurov – considered the first stereolithography-type personal 3D printer, the Formlabs Form1, to already be competitive in quality to some extent with the more expensive professional printers.

Mohite (2013) worked in design research in the same design lab as Chekurov. He said that they are basically more focused on cheaper 3D printing technology, one reason being the lower-cost material compared to their industrial printers in which it can cost ten times more. Also, the cheaper printers are used to explore the boundaries of the technology in terms of what is possible be print. (Mohite) Also Chekurov recognized the lower material costs of the personal printers as one reason why he might choose to use a personal printer instead of an industrial one in their lab. Mohite compared his first experience in 3D printing with German Envisiontec stereolithography printer from the last decade to the modern Formlabs Form-1, the first SLA machine to break the $5000 barrier. He claimed, that the Form1 "does exactly the same", with the "same technology and the same build volume", with a price of $3000 compared to the original price of 300 000 € for the old Envisiontec one. He pointed out that the same goes for FDM printers, with a 800 € device "doing the same thing, most of the time" as an 16000 € Stratasys machine (apparently referring to a uPrint SE Plus in his lab) with the same technology. (Mohite, 2013)

When I asked whether he thought 3D printers (the context of the conversation being the personal ones) generally consist of novel technologies, or if are they mere adaptations, Mohite replied:

"Most of them [3D printers] *are just adaptations of older technologies. It is… in terms of innovation, there is very little being done at this point. This is what I feel. Because, most of the technologies – like this powder printer – that I know, existed like 20 years ago. FDM existed 20 years ago. Stereolithography had, like, is been for 20 years, and now all the new machines which are coming are using the same technology".*

Also Tuomi claimed that personal 3D printers do not contain any novel technology; they are in fact very easy to make, and virtually all the biggest manufacturers in the world such as Stratasys would be able to produce one. This view was shared by Partanen, who concurred that incumbent printer manufacturers would've had the ability to make a 3D printer in the sub-$5000 price class already when the RepRap project started. Also Mäkelä (2014) presumed that the incumbents would've been able to make such a printer at that time, but he didn't really see why they would have, as the margins from business-to-business-type of machines were a lot higher. Personal 3D printers are predominantly based on FDM-technology; Tuomi gathered that this is because it is the most appropriate technology to produce very cheaply, and that extremely inexpensive components are available for it.

Of all types of additive manufacturing technologies, Mohite considered cheap FDM printers for the consumer market to have the biggest market potential, and drive the whole market in a bigger sense because all other machines are so out of reach of the consumers. On the other hand, Piili (2013) considered the biggest market potential in 3D printers to come from reasonably low-priced (15 000 €) industrial plastic printers which produce good quality.

To benchmark the interviewees' findings, I'll here summarize the findings of Roberson et al (2013) and Perez et al (2013), who constructed models to allow for a mostly quantitative comparison between different 3D printers. The first study consisted of two personal printers and three entry-level industrial ones, while the latter study had just two personal and two industrial printers. With the help of printing standard test parts, both studies were able to evaluate product aspects that consumers would value, e.g. printing quality, build time, unit cost and material cost. Biased evaluations such as the user-friendliness of the system were removed (Perez et al, 2013).

Contributing to portability, both personal 3D printers tested could be operated from an SD card (and thus a PC wasn't required to use them), whereas all of the industrial printers needed to be connected to a computer and the 3DSystems' V-Flash even required an internet connection. In addition, the (personal) Makerbot Replicator weighed only 16 kg (and the later Replicator 2X 12,6 kg in Perez et al), while the industrial-level Stratasys uPrint Plus and 3DSystems V-Flash weighed 76 and 66 kg, respectively. As a result, Roberson et al found the Makerbot Replicator to be the most portable machine in their study. For these reasons, Perez et al considered these machines to be well-suited for remote location and in-home use. Their open structure also rendered them suitable as educational tools (Roberson et al, 2013). The benefit of educational use of personal printers was also brought up by Mohite, Tuomi and Chekurov.

In addition to portability, the Makerbot printer was very competitive in terms of printing speed, unit cost and material cost in Roberson et al's (2013) data. However, they found both personal printers to produce the roughest parts in terms of surface quality, while the industrial printers SD300Pro and 3DSystems' V-Flash produced the smoothest ones. It should be noted that the Makerbot Replicator cost $2072, as opposed to $20900 for the Stratasys and $9900 for the 3DSystems' printer. (Roberson et al, 2013)

Perez et al (2013) found the newer version of the Makerbot Replicator, the 2X, to yield even better results. Its surface finish actually surpassed both Stratasys uPrint Plus and the Solido SD300 Pro. On the other hand, both Perez et al and Roberson et al found the Stratasys' uPrint Plus to have the best dimensional accuracy and by far the shortest build time. After accounting for unit price and material costs, both articles gave the Makerbot Replicator (Perez et al tested the newer model "2X") the best score. It should be noted that both tests found the other personal printer, the 3DTouch (which was introduced in 2011), to be significantly weaker in most aspects, yet still somewhat competitive to the chosen industrial ones. Both articles found very significant differences in printing material costs for the benefit of the personal printers. The findings suggest that there can be considerable differences in different personal 3D printers' performance. Their prices also vary significantly; from $449 to $3299 in my data (see Appendix D).

The findings nevertheless match most of disruptive innovations' typical traits as defined by Christensen and his co-authors. Personal 3D printers were considered by the interviewees to be inferior in build quality as well as printing quality – perhaps the primary performance attribute of incumbents' products. On the other hand, many of them allow users to customize the device by tweaking the printing process. They are more affordable, most have a simple FDM-based structure, and they make it possible to be placed near the users (such as students), thus contributing to convenience. In terms of printing reliability and ease-of-use, however, personal 3D printers may be inferior to industrial ones. Theory also suggests that disruptive innovations contain no novel technologies, and personal 3D printers are indeed based on established technologies such as FDM and stereolithography printing.

Generally, the interviewees seemed to have somewhat skeptical and pessimistic views of personal 3D printers. They were commonly referred to as “toys” and “cheapo printers”, and their proliferation as a “hype”. This may be explained by the interviewees’ backgrounds: their first experiences were usually of industrial printers and they seemed to be more familiar and experienced with them. An interviewee with high involvement in personal printers, and no previous experience of industrial machines, might have had more favorable perceptions. Also, the interviewees’ first-hand experiences of personal 3D printers may have been predominantly based on earlier, less advanced models, such as those in the university design laboratory. This could also help us understand where the interviewees were coming from. In his 2012 book, Anderson claimed that consumer-grade 3D printers’ are still in an early development phase similar to the earliest document printer technology, the dot-matrix printer: great for drafts and prototypes, but you’ll still want to use a professional [3D] printing service for the final version. 3-D printing is still a bit expensive and hard to use; it’s not yet for everyone. (Anderson, 2012 p.58, 234) More recently, Wohlers Associates (2013a p.112) nevertheless stated that print quality and machine reliability of personal 3D printers have increased considerably over the past couple years.

4.2.2 Incumbent companies’ reactions

Even though the open-source RepRap project developed the first open-source printer blueprints already in 2007, the leading incumbent 3D printer manufacturers 3DSystems and Stratasys only expanded to the low-end market segment several years later. This occurred in the first phase through acquisitions of entrant personal 3D printer manufacturers. In Christensen’s (2000) examples, such a delay may prove to be fatal for a company even if they eventually manage to introduce a competitive product. In contrast, Partanen (2013) did not see that the incumbents would’ve made a mistake by entering the personal printer market only later. Christensen (2006 p.50) and Markides (2006 p.21-22) debate on whether inaction of incumbents in the face of a disruptive innovation is sensible. Christensen claims that survival is possible even with inaction; Markides finds that the appropriate action is context-specific.

Christensen et al (2004 p.42) deduce that when facing a threat from a disruptor, the best that an incumbent can typically do is to belatedly acquire the winning firm and avoid ultimate destruction. Furthermore, Gans (2014) suggests that incumbents' should "wait and see" – continue to monitor potentially disruptive technologies to see what happens. The logic is that the incumbent can then move to acquire the technology that turns out to be successful. He concludes that disruptive technologies (when identified after the fact), are associated with startups competing and then being acquired as much as they are associated with those startups growing as independent firms. (Gans, 2014) This seems to depict incumbents' logic in this case fairly accurately.

In their article about open-source 3D printing movement, De Jong & de Bruijn (2013) recognized five strategies how incumbents can respond to community-based open-source initiatives such as personal 3D printers: *monitor, attack, adopt, acquire* and *facilitate*. They argue that existing companies may acquire startups founded by community members in order to get a foothold in an emerging market. This makes sense especially when user communities develop innovations that could compete with a company's products. The authors point out that in 3-D printing, some existing system manufacturers – such as 3DSystems – have indeed engaged in quite proactive acquisition behaviors. (de Jong & de Bruijn, 2013)

In October 2010, 3DSystems acquired the low-end market-leading 3D printer manufacturer Bits From Bytes, situated in Bristol, England. This marked the first time a commercial spinoff from the RepRap project was acquired by a major industrial player. This way 3DSystems was able to expand its product line as low as $1300 for the RapMan kit and $3200 for the BfB kit, far below the $9900 for its own entry-level printer. (Wohler's Report, 2011 p.59) In August 2011, 3DSystems acquired RepRap-based printer manufacturer Botmill from Florida, US (Fabbaloo, 2011). Following these events, 3DSystems launched its own version of personal 3D printer, the Cube, in January 2012 (3DSystems, 2012). Stratasys, on the other hand, acquired the leading personal 3D printer manufacturer Makerbot in June 2013 (Stratasys, 2013b).

As mentioned earlier, Christensen et al (2004) considered a spinout – setting up a completely separate business unit free to develop its own skills and define its own metric for success – as a successful response strategy for an incumbent company. The authors attribute Intel's success with the Celeron microprocessor to setting up an independent organization, and for the same reason IBM's success in personal computers as well as HP's success in entry to disruptive inkjet printer business. Christensen (2006 p.43) explained anomalous instances, where the incumbent leader had succeeded in disruption and maintained its industry-leading position, by the fact that it had set up an autonomous business unit and by given it unfettered freedom to forge a very different business model appropriate to the situation. The incumbents' reactions seem to follow these recommendations. Stratasys has preserved Makerbot as a separate subsidiary (Stratasys, 2013b) and this is also the case with 3D Systems' Bits From Bytes, which is a subsidiary of the company (3DSystems, 2014).

4.2.3. Differences in business models

Christensen's view of disruption as a business model problem finds strong support in the case of 3D printing entrants and incumbents, the business models of which seem to differ significantly. Theory would suggest that incumbents should be capable of conceiving the disruptive innovations (Christensen & Raynor 2003 p. 190). Tuomi and Partanen argued that incumbent printer manufacturers would've had the ability to develop a personal 3D printer on their own already before the first entrants, but the margins would've been unattractive and thus unsuitable for the incumbents' business models. In fact, Tuomi argued that the 20 largest manufacturers could at any time make a personal printer, as they are very easy to make, but profitability is the issue. His view was that 3DSystems is not selling their personal printers very profitably compared to their other machines, which have high margins. Quoting Partanen (2013):

> [Before the RepRap project] *"None of these commercial actors wanted to make cheap machines. The reason was that, even though the machine can be pretty cheap as such, there is quite a lot of R&D in the background, and their purpose was of course to get that R&D back in some way, the investment, with higher prices on machines. At the time, nobody was able to see that these cheap ones would sell so much more, that the same business could be conducted with them, and that is why no-one had made cheaper machines."*

Partanen also noted that while the industrial machines are sold a lot less, their business is 10 to 20 times larger in monetary terms. As a result, the market for personal printers hasn't appeared to be very strong for the big manufacturers (Partanen). He also ponders the margins in the cheap products may be lower than those of the expensive ones, they need to be sold more, and thus the business model in the cheap printers can be more difficult.

> *"Selling this kind of an expensive machine is largely based on selling over and over again better, newer machines to the same customer, in addition to services and materials, and there is quite a large amount of euros involved."* (Partanen)

Partanen notes that the cheap printers are a small business and not necessarily very profitable one. The main business [of the incumbents] is the profit from the expensive machines, and strategically it may be of bigger concern to make sure that the large profits and high prices are gained from the large ones [printers] (Partanen). Partanen doesn't consider the personal 3D printer market to be significant from the incumbent's point of view, since it only makes up for 6,5% of industry revenues (see page 86). Partanen sees that the manufacturers of expensive machines may not be the most natural players in the business for cheap printers, and that some other organizations – that are more used to lower margins – may be better suited to it.

> *"If they are used to getting 500 000 for one sale, it's a fairly different business model than selling products to a thousand different people and getting the 500 from each of them."*

In a second interview, Partanen (2014) determined that margins would've been non-existent had the incumbents developed a sub-$5000 printer at the same time as the RepRap project. This is supported by Tuomi (2014), who claimed that the sales margins of the personal 3D printers are really weak, competition is extremely tough and thus doing business with them profitably is challenging. He also suggested that there would have been a risk of *badwill.* Also Mäkelä (2014) referred to the low margins of personal printers as one explanation why incumbents didn't initially enter the market. He argued that they get a lot higher margins from the business-to-business type of machines. While the entrants' gross margins are unknown, Stratasys has recently earned gross margins of over 60% in machine sales (Stratasys, 2013c). Interestingly, Stratasys (2014) stated in its latest annual report that

> *"our high-end commercial systems and related consumables yield a greater gross margin than our entry-level commercial systems. Furthermore, our desktop 3D printers and related consumables* [meaning Makerbots] *yield a lower gross margin than our entry-level commercial systems."*

The personal printer manufacturers' business models differ from the incumbents in earning logic: they do not offer service contracts, nor do they employ proprietary printing materials. The printing material in industrial printers, such as the filament reels in FDM machines, and powders, are often proprietary to the machine manufacturer and equipped with a microchip, essentially forcing the user to purchase the material from the manufacturer (Mohite, 2013). He further compares this strategy to the one in paper printers, where a customer has to purchase a proprietary ink cartridge for 80€ to a printer that costs 100 € and concludes that *"that is how they* [the incumbents] *make most of their money"*. (Mohite (2013)

According to Wohlers Associates (2011a), most (industrial) AM plastic materials are priced at $175-225 per kg. In comparison, many personal printer manufacturers sell PLA and ABS plastic filament spools for less than $60 per kg (Ultimaker, 2014a; Leapfrog, 2014), and some third party suppliers even under $20 per kg (3ders.org, 2014). Most of these printers allow to user to procure the material from any source. Perez et al (2013) found that their standard test part cost $1,41 in materials when printed with a Makerbot Replicator 2X, as opposed to $11,59 and $33,25 for the entry-level industrial machines.

In addition, industrial 3D printers are almost always sold with a maintenance contract (Tuomi), which adds to the cost of the initial investment. According to Wohlers Associates (2011a), the annual maintenance costs of 3DSystems' machines ranged from $1000 to over $20 000, with Stratasys' models – which employ FDM technology similar to most low-end printers – starting from $1950 per year. With the exception of now Stratasys-owned Makerbot, personal printer manufacturers do not offer service contracts. In comparison, the annual service cost of the RepRap Mendel open-source printer is said to be limited to *"Occasional oiling = $8"*. It can also print its own replacement printed parts at material cost. (RepRap, 2014a) However, personal 3D printers' warranties are either non-existent or very limited. For example, the Dutch Ultimaker's printers' have a very limited warranty with duration of only three months (Ultimaker, 2014a).

Based on these findings, the business models of the incumbents and the entrants seem very different, with the incumbents selling high-margin products, earning on services and proprietary materials as well and the entrants selling merely a low-priced machine and non-proprietary material. Accounting for purchase price, material costs and maintenance, actual printing costs seem to be considerably higher with industrial printers.

4.2.4. Sales and price developments

Based on the literature on disruptive innovations, unit prices, price trajectories, unit sales and market shares can be used to interpret whether disruption is taking place (see e.g. Adner, 2002 p670, Christensen, 2006, Sood & Tellis, 2011). Hence, I've collected price and sales data on both classes of 3D printers and charted their price trajectories (see Appendix D, E and F). The price graphs do not account for inflation, but I consider them to be accurate enough for the purposes of this thesis.

The prices of low end of the biggest industrial 3D printer manufacturers model spectrum has seen a fairly clear downward trend during the period 1996-2013, although the absolute prices have still remained relatively high. Since the introduction of the first desktop-grade 3D printers by the incumbent manufacturers, the prices of these entry-level industrial printers have fallen steadily with successive lower-end product generations (see Appendices E & F). Starting at over $50,000 in 1996-1997, the prices have went down with virtually every new model and currently sell for around 10,000-15,000 USD, with a few special-purpose machines even less (see Appendix E).

	Personal	All Industrial
2012	1124	79480
2011	1030	73220
2010	N/A	62570
2005	N/A	68004
2004	N/A	87109
2001	N/A	116488

Table 1. Average Selling Prices of 3D printers and AM systems, USD. Source: Wohlers Associates, 2006 & 2013a.

While the average prices of all industrial printers and AM systems sold have fallen in the long-term, there is an even greater difference to personal ones: the average selling price of personal printers was $1124 in 2012 and $79480 for all industrial ones (see Table 1). Interestingly, research firm Gartner expects the average selling prices of enterprise-class 3D printers to be available for under $2000 by 2016 (Gartner, 2013b). I do not know how on what basis this noticeably optimistic forecast has been made, but Partanen (2013) did also consider it likely that the prices of current industrial printers would come down in the future, migrating to lower price segments, in particular if their unit sales keep growing.

In Appendix F, I've charted the price trajectories of personal and entry-level industrial machines. In addition to the falling prices of the industrial ones, the personal printers also signal a moderately rising trend in prices, supported by the average selling prices above. This may be due to growing build volumes. The trajectories nevertheless indicate that personal printers have been and continue to be drastically cheaper than industrial ones. According to Jones et al (2011), the first iteration of the RepRap, the Darwin, cost 500 € in individually purchases materials to build, while the materials for the second iteration, the "Mendel", cost significantly less at 350 €. The authors point out that the lowest-cost commercial 3D printer – Solido SD-300 – cost 12 000 € at the time. Currently, a personal 3D printer can be had for under $500 (see Appendix D).

In 2007 – the first year sales in the personal printer category were documented – a total of 5004 (66 personal + 4938 industrial) 3D printers and AM systems were sold worldwide (Wohlers Associates, 2013a). In 2012, personal printers had exponentially risen to over 35 000 units, with Stratasys forecasting sales to double in 2013 (see Appendix B for full data). During the same time, all industrial 3D printers and AM systems have also seen fairly steady growth, selling 7771 units in 2012 and expecting to sell 11000 units in 2014 (Wohlers Associates, 2013a). Furthermore, research firm Gartner estimated all sub-$100,000 printer (industrial and personal) sales to reach 98,065 units in 2014, which is again expected to nearly double in 2015. (Gartner, 2013a) Since the over $100 000 machines are evidently sold in very small numbers, we may estimate from these findings that personal printers sales in 2014 would be approximately 87,000 units. Gartner further forecasted the combined total shipments of sub-$100,000 printers to exceed one million units in 2017, with a significant amount of the growth coming from personal printers (Gartner, 2013d & 2014). In contrast, Juniper Research forecasted consumer 3D printer sales to pick up from an estimated 44,000 this year and exceed one million units by 2018 (Juniper, 2014).

However, personal 3D printers' share of total (machine) sales revenue is less impressive. In 2012, personal printers represented just $39,9 million (6,5%) of the total market revenue of $617,5 million for AM systems sales, thus leaving 93,5% for industrial printers (Wohlers Associates, 2013a, 136). Table 2 offers more detailed data on incumbents' unit sales. Only those manufacturers that have entry-level, "desktop" –type of industrial printers in their model ranges were chosen for this table, ruling out manufacturers that only offer high-end systems. This was done to get a better grasp of sales at the low-end of the market, albeit the numbers also include their high-end products as well. The first five were the market leaders and Solido was chosen as its model range consists of only one (entry-level) printer, which has nevertheless sold fairly well.

	2007	**2008**	**2009**	**2010**	**2011**	**2012**
Stratasys	2169	2184	1918	2555	2428	3026
3DSystems	194	146	118	396	733	1359
Objet	402	433	388	594	929	1130
Z Corp	1022	950	623	709	722	-
Envisiontec	238	356	376	435	540	880
Solidscape	464	384	230	302	269	312
Solido	22	18	289	450	-	-
TOTAL	**4511**	**4471**	**3942**	**5441**	**5621**	**6707**

Table 2. Leading incumbents' unit sales. Source: Wohlers Associates, 2013a.

Based on this data, incumbents' unit sales (of all models combined) do not seem to have suffered from the advent of personal 3D printers, unless one counts Solido going out of business in January 2011 (see Wohlers Associates, 2013b). Interestingly, Stratasys (2014) does nevertheless recognize such a displacement as a business-related risk in its annual report:

> *"As we continue to ship entry-level commercial systems and, to a greater extent, desktop 3D printers, including as a result of our MakerBot transaction, our sales of those systems have grown, and we expect them to continue to account for a growing percentage of total systems that we sell. Furthermore, some of those sales may displace sales of our other* [higher-margin] *systems."*

4.2.5. Performance development

As Christensen (2000) suggested, graphing the trajectories of performance improvement demanded and offered on the market can help identify a disruptive innovation. The diagrams he used charted both the incumbent and the entrant companies performance developments in the primary performance attribute over time. Also, in the case of a new-market disruption, the entrant introduced new (secondary) performance attributes. Firstly, one would have to determine what these attributes actually are.

Danneels (2004 p. 249) observed from Christensen's cases that often only one or two performance dimensions dominate the customer's choice criteria, such as disk drives' capacity and size. Danneels argued that in many cases, such as cars, the number of performance dimensions is actually much higher, and that customers trade them off against each other, making the set of variables complex and recursive. Thus, the multitude of these dimensions and their interrelationships may in his view make the use of trajectory diagrams challenging. (Danneels, 2004) Also Schmidt & Druehl (2008 p. 354) admit that real-life problems may be more complex (than their case of disk drives' diffusion patterns), possibly including more than two key performance attributes.

Similarly, the performance attributes of 3D printers from the customers' point of view can range from e.g. printing reliability, printing quality, printing speed, build volume, portability, customization, material selection and affordability. A customer may choose a model based on any combination of these. In line with Danneels' view, I find some of these dimensions – as important as they might be – to be overwhelmingly difficult to translate into trajectory diagrams. For example, comprehensive, comparable data about printing speeds does not exist.

Printing quality seemed to matter a lot for several of the interviewees; they considered incumbent products to lead in that respect and they seemed to consider it the primary handicap of the personal 3D printers. Tuomi (2014) considered printing quality (consisting of printing accuracy, material attributes and surface quality), build volume and *volume produced per time unit* to be the priorities in industrial 3D printers' development work, and as a typical set of requirements for a company buying a printer. Thus, I considered printing quality as the primary performance attribute. At the end of the day, only a test print on a standard part (as per Perez et al, 2013 & Roberson et al, 2013) will yield reliable differences in the actual print quality.

However, *layer thickness* is an important feature because it affects the surface finish of a part. Typically, the thinner the layers, the less surface roughness present. (Perez et al, 2013, italics added) While it cannot account for the quality of the printed object alone, it contributes to it and such data is widely available for most models. To elaborate, thinner layers can lead to better print quality –100 microns is a typical number for current personal printers and translates to 0,1 millimeters. Chekurov (2014) considered X-Y-accuracy to contribute more to printing accuracy than layer thickness, but manufacturers seldom disclose that data. All but one personal printer in Appendix D are FDM-based. Of the industrial printers, only Stratasys ones are FDM's, so I've marked them with triangles in Appendix G to allow for a comparison with the same type of technology employed in personal printers.

Another attribute with fairly easily collectable data was the *build volume*, which simply refers to how large an object a printer can make. Chekurov (2014) argued that there is a great demand for large printed objects in industrial use. This was supported by Piili (2013), who recognized the desire to print larger objects as a trend in the industrial context. Thus, I assumed that a larger volume would make a printer more attractive for business users, and contribute to the threat of disruption by the personal printers.

In order to define the level of performance demanded by the market, I consulted two of my interviewees. Both Chekurov and Partanen shared a surprisingly similar view of "good enough" layer thickness. Partanen commented that while heavily application dependent, 150 microns can be perceived as a good enough layer thickness "for most purposes". For the purposes of a university design laboratory, Chekurov (2014) estimated 100 microns to be sufficient. As a compromise, I've charted 125 microns to depict the performance demanded in Appendix G. Based on these insights, I would very cautiously assume that as far as print layer thickness as a performance attribute goes, the personal 3D printers have developed to a level demanded by the core of the mainstream market.. Appendix G demonstrates the personal 3D printers were initially inferior in performance (layer thickness) than the incumbents' printers. However, they have improved continuously and currently the majority of them on the market can produce layers of 100 microns, many even better. The results in Appendix G indicate that personal printers have by now generally reached the level of performance of the entry-level industrials in terms of layer thickness, which is one aspect of print quality.

Regarding build volumes, Chekurov (2014) estimated that 90% of the objects he has printed while working in the university design laboratory would fit in a 200x200x200 mm (8000 cm^3) cube. These contexts of use are design projects for companies as well as in-house design works and students' own projects (Chekurov). A great deal of current personal 3D printers can offer this build volume. However, I considered this need of build volumes to be highly subjective and didn't illustrate the level of performance demanded in the build volume charts. It should be noted that the build volume development trajectory of personal printers has actually crossed the entry-level industrial printers' one: many personal printers now offer tremendously higher build volume than what is available in the entry-level industrials. In fact, some of them are on par even with the high-end AM systems in terms of build volume, for a fraction of the price. Anyone seeking a build volume in excess of 10 000 cm^3 can find several suitable personal 3D printers on the market. Alternatively, he/she will have to turn to prohibitively expensive high-end AM systems, as the current entry-level professional printers cannot cater for such volumes.

Interestingly, while I found a considerable variety in personal 3D printers' build volumes (see Appendix H), I discovered a certain amount of correlation between build volumes and unit prices in both entry–level industrial and personal printers (see Appendices F & H). Correlation charts are not included here, but they are available in the case database. Thus, build volume seems to be more or less a tradeoff of price and perhaps partly explains the rising trend in personal printers' prices as well as the falling trend in entry-level industrial ones. The development of build volumes may simply be a case of choices made in product architecture.

Christensen and his co-authors' method for recognizing disruptive products by charting performance demanded and supplied seems to be most appropriate when a product's performance can be measured with only a few easily definable metrics, as was the case with disk drives. If the product is complex and its performance can be measured in a multitude of ways, which is the case in 3D printers, such charts become increasingly difficult to compose. Contrary to Christensen and his co-authors' premises, the charts I've developed of 3D printers show intersecting performance trajectories between the incumbent and entrant technologies in the chosen attributes. However, they do illustrate reasonably well that personal 3D printers have been inferior in relation to incumbents in a few key attributes upon their introduction, yet developed over time to meet the performance demands of many purposes.

4.3. Positioning personal 3D printers as a disruptive innovation

In this section, I will address my primary research question – whether personal 3D printers can be defined as a disruptive innovation – by synthesizing the empirical findings with the theoretical framework and literature. In terms of Markides' (2006) concept of new-to-the-world-innovations, I would argue that 3D printing – or additive manufacturing – technologies, when they were first invented, fit the bill of a new-to-the-world category in the sense that they didn't seem to have any kind of a clear predecessor. We could also think of the early 3D printing technology of the late 1980s to challenge both modular and architectural dimensions, thus making them a radical disruptive innovation in Carayannopoulos' (2009) model. Upon an email enquiry for the purposes of this thesis, Carayannopoulos (2013) confirmed that 3D printing could indeed be classified as a radical disruptive innovation at least from the perspective of manufacturing industry. In contrast, personal 3D printers are anything but new-to-the-world, as they are merely novel architectural or design reconfigurations based on existing technologies (as per Carayannopoulos, 2009; Sood & Tellis, 2011) first invented and developed by current industry incumbents.

According to Yu & Hang (2010, p.437), there are two preconditions for a market disruption to occur: *performance overshoot* on the focal mainstream attributes of the existing product, and *asymmetric incentives* between existing healthy business and potential disruptive business. Performance overshoot proved very difficult to evaluate. The printer data and trajectory charts compared to expert perceptions of "good enough" layer thicknesses and build volumes for most uses (see Appendices G & H), do not indicate that entry-level industrials would have clearly "overshot" their users' needs at the time of the personal printers' emergence. In hindsight, the collected empirical data and selected performance attributes seem insufficient for such an evaluation. Nevertheless, industrials may have been too sophisticated or simply unsuitable for quick and rough "drafting" type of use near the end user, as indicated by the fact that even some of the most affluent organizations such as Ford Motor Company, GE and NASA have set up personal 3D printers for such purposes (see e.g. Make magazine, 2013 p.21; CSC, 2012). Ford Motor Company believes that these systems are good enough for its engineers to use in early concept design (Wohlers Associates, 2013a, 136). It should be noted that Perez et al (2013) and Roberson et al (2013) found significant performance differences between industrial printers. We could make the interpretation that the certain entry-level industrial printers may have overshot the needs of the very lowest tiers of the market (see Figure 4) but not the interviewed experts' needs.

Asymmetric incentives (or asymmetric motivation) seem to be more prevalent. The incumbents (e.g. 3DSystems, Stratasys, Objet, Z Corp) have been predominantly fairly large companies with at least a decade of experience in the industry (see e.g. Wohlers Associates, 2013a+b). The interviewees suggested that the incumbents evidently considered the personal printer market to be too small and yield too small margins, compared to their existing customers and printer models, and thus didn't enter until much later than the entrants. In contrast, the entrants have by far been very recent – most have entered the industry in 2009 or later – small garage enterprises or startups that probably find small markets and margins more attractive. Thus, the incumbents' and entrants' initial motivations to enter the emerging personal printer market have apparently been asymmetric, as the theory of disruptive innovations suggests.

Furthermore, as per Adner (2002), price trajectories (see Appendix F) can be used to interpret disruptive innovations through the concepts of *preference overlap* and *preference asymmetry*. The price gap between the lowest-priced industrial printers and typical personal printers has been and still is huge. Thus, due to purchase price and maintenance costs, industrial printers seem to have been completely out of consumers' reach. On the other hand, as we saw above, even the biggest companies have found use for personal printers. This suggests that there is high preference asymmetry in the 3D printer market: personal printers may be attractive for some professional users and consumers, whereas industrial printers seem to be only attractive for professionals. Also, both printer types can be used for similar types of jobs, suggesting there is a considerable preference overlap between buyer segments. By this model, the player that is attractive in both segments is considered to have the upper hand, and especially so if the segments overlap. In addition, Adner suggests that price has an explicit role in driving disruption. Both concepts seem to support personal 3D printers' disruptive characteristics.

Theory would suggest that the incumbents' sales would begin falling after the entry of the disruptive innovation, and they would escape the intensified price competition by abandoning their lowest market segments, retreating upmarket to higher-margin products and leaving the low end of the market for the entrants. The findings in this case don't support it. Unit sales of the biggest incumbents as well as the total sales of industrial machines have experienced significant growth throughout the existence of personal 3D printers. Also, instead of retreating upmarket, the leading incumbents have introduced lower-priced industrial models as well as made their forays in the personal 3D printer market by acquiring some of the personal printer entrants.

In contrast, theory suggests that disruptive entrants would begin to make inroads to higher segments over time. There a slightly rising trend in personal printers' prices (see Appendix F), which is due to the fact that after their initial product, many entrants have typically went on by introducing more sophisticated and more expensive models over time. During the Stratasys/Makerbot acquisition, Makerbot disclosed their intent to shift toward prosumer / professional users through product improvement and rising prices (Stratasys, 2013d). The emergence of the "prosumer" class of printers – often associated with printers of $2000 and up (see e.g. Make magazine, 2013) – may be one sign of a shift toward higher segments. A few entrants have also introduced models that are explicitly targeted for professional users (such as the Makerbot Replicator Z18), priced clearly above personal printers yet below incumbents' lowest-priced models.

In order to evaluate whether a product is becoming disruptive or not, we would have to agree how it is measured. As I pointed out in the literature review, there are several different approaches. Christensen (2006 p.50), Sood & Tellis (2011) and Markides (2006 p.21) seem to measure the degree or moment of disruption by performance offered meeting the demanded, performance level of new technology crossing the performance of old technology, technology-level market shares, firm-level market shares, or market capitalization. Gilbert (2003) employed sales revenues as an indication of disruption in the minicomputer/mainframe case. Schmidt & Druehl (2008) drew comparisons based on unit sales. I will address some of them here.

Evaluating personal printers' performance proved fairly difficult, since it cannot be attributed only to a few measures. Thus, defining performance demanded by the mainstream market is equally challenging. On the basis of my data on two performance attributes, personal printers have developed to meet the levels that the interviewed experts considered as "good enough" for most purposes, simulating performance demanded by the mainstream market. In addition, these attributes have developed over time to be on par with (and build volumes even exceeding those of) entry-level industrials.

More in-depth tests performed by Perez et al (2013) and Roberson et al (2013) suggested that recent prosumer-class printers may very competitive with entry-level industrials in overall performance. On the other hand, the interviewees generally deemed personal printers to be inferior to entry-level industrials. These findings do not necessarily contradict: interviewees' experiences may have been primarily of earlier, less advanced models and it is typical for disruptive products to be initially inferior in the primary performance attributes. Disruptive innovations do, nevertheless, advance over time in an incremental fashion. Interestingly, several interviewees did consider the fairly recent stereolithography-based Formlabs Form 1 (see Appendix D) to be very promising and a possible candidate for replacing industrial machines in a university lab (Chekurov). It has to be noted that Christensen (2000, 2006) does not expect that a disruptive innovation would ever reach or surpass the incumbents' products performance, nor does it need to.

As for the market shares, in 2007 a total of 5004 (66 personal + 4938 industrial) 3D printers and AM systems were sold worldwide. For 2014, sales of over 98 000 units (87 000 personal and 11 000 industrial are expected (see pages 86-87). As a result, personal printers' share of the market has grown to dwarf that of industrial printers, even though the latter have experienced significant growth as well. However, sales revenues of personal printers are still miniscule at a mere 6,5% of total market revenue for printers and systems (see page xx).

The unit sales seem to point to a significant total market expansion, and not a disruption of incumbents. How can this be interpreted? Perhaps the best explanations are offered by Christensen & Raynor's (2003) concept of new-market innovations and Gilbert's (2003) notion of market expansion. Fortunately, Christensen & Raynor (2003 p.49-50) developed a set of "Three Litmus Tests for Disruptive Innovations" that help to identify a disruptive innovation and to put it in the right category. I will address these tests here.

> *"Firstly, for an idea to become a* ***new-market disruption****, at least one and generally both of two questions must be answered affirmatively:*
>
> - *Is there a large population of people who historically have not had the money, equipment, or skill to do this thing for themselves, and as a result have gone without it altogether or have needed to pay someone with more expertise to do it for them*

- *To use the product or service, do customers need to go to an inconvenient, centralized location?"(Christensen & Raynor, 2003)*

I would answer both questions affirmatively. Comparing to the relatively small industrial printer sales, personal printers' unprecedented numbers (and even more optimistic sales forecasts) points to a huge population of buyers who must have previously been nonconsumers. Also the surge of the "personal fabrication" or "Maker Movement" phenomena proves that there has been a large amount of people "trying to get a job done", as Christensen & Raynor (2003 p.102) put it. Prior to the RepRap project, 3D printing had been largely unavailable for consumers. For enterprises, although there have been 3D printing service bureaus and in-house industrial printers (in centralized, shared locations) (see e.g. Beckert, 1998), the personal machines have made it possible to put one on every engineers' desk. Also the industry research firm Wohlers Associates (2011a) argued that while these machines do not produce parts at industry standard levels of quality, they provide access to an entirely new set of customers.

*"Secondly, **low-end disruption** is possible if two questions can be answered affirmatively:*

- *Are there customers at the low end of the market who would be happy to purchase a product with less (but good enough) performance if they could get it at a lower price?*
- *Can we create a business model that enables us to earn attractive profits at the discount prices required to win the business of these overserved customers at the low end?" (Christensen & Raynor, 2003)*

It is difficult to estimate to what extent existing entry-level industrial printer buyers' (low end of the market at the time) have been attracted by personal printers. The early RepRaps and their first derivatives may have been simply too far from acceptable performance to be attractive to any business users. Thus, they have not immediately encroached on the incumbents' sales, as low-end disruption would suggest. However, the prices of personal 3D printers have been exceptionally low compared to industrial printers. The entrant companies have typically been small startups, for the business models of which even small margins are attractive.

Thirdly, once an innovation has passed the new-market **or** low-end test, Christensen & Raynor (2003 p50) leave one more litmus test to answer affirmatively:

- *"Is the innovation disruptive to <u>all</u> of the significant incumbent firms in the industry? If it appears to be sustaining to one or more significant players in the industry, then the odds will be stacked in that firm's favor, and the entrant is unlikely to win."*

Prior to the RepRap project and its derivatives, no manufacturer was making printers below the $9900 mark. Also, personal printers were not improved versions of industrial printers, but rather architectural reconfigurations with (at least initially) less performance and functions. Hence, I would consider them disruptive to all incumbent manufacturers that offer plastic printers in the price classes of, say, $10,000-50,000.

Following these "litmus tests", personal 3D printers seem to match the general criteria for a new-market disruptive innovation. On the other hand, the dramatically lower unit prices and entrants' small sizes with apparent ability to survive on low margins also hint to a low-end disruption. In Christensen & Raynor's (2003, p.48) numerous examples, few innovations were purely new-market or low-end, but somewhere between (such as Canon photocopiers). Thus, personal 3D printers would in my opinion classify as a hybrid of these approaches, yet leaning more toward the new-market disruption. This would perhaps also help explain why incumbents didn't begin fleeing upmarket: while low-end disruptions motivate the incumbents to flee the attack, new-market disruptions induce incumbents to ignore the attackers (Christensen & Raynor 2003, 46). Moreover, one clear signal of new-market disruption is a high and increasing rate of growth in a new, emerging market. An explosive rate of growth in new market or new context of use is also a signal of nonconsumers. (Christensen et al 2004, 5, 8) This is definitely the case with personal printers, as one can conclude from Appendix C.

In addition, Gilbert's (2003) model of three phases of disruption (see page 46-47) particularly useful here, as it posits that a disruptive innovation starts off in a new market (outside the incumbents' markets) and eventually grows and expands the total market, while slowing the growth of the established business. Eventually, the disruptive innovation, having improved greatly over time, significantly reduces the size of the old market. Gilbert's notion of net industry growth and strong market expansion is also supported by Utterback & Acee (2005 p.16), Yu & Hang (2009) and Schmidt & Druehl (2008). Personal 3D printers' tremendous growth with the heavily expanding total market supports Gilbert's model. However, incumbents' growth is not slowing down. Christensen & Raynor (2003 p.111) argued that the growth in the new value network does not affect demand in the mainstream market for some time – in fact, incumbents sometimes even prosper for a time *because* of the disruption (italics by author). This seems to be the case in the 3D printer market and in line with Gilbert's (2003) findings of mainframes and disruptive minicomputers, both of which experienced rapid rates of growth in sales for quite a while.

Since most of the buyers seem to be nonconsumers, one could argue that Christensen (2000) notion that incumbents overshoot their customers' needs may be less relevant in a new-market disruption. Also the fact that incumbents' total sales seem to have gone mostly unaffected refers to a new-market disruption, since the theory suggests that there is a delay before it begins encroaching on the incumbents lower segments. In contrast, in a low-end disruption scenario, disruption of incumbents' segments would begin immediately. That said, data on manufacturers' unit sales for individual models is unavailable and it remains unclear what the ultimate effect on the entry-level printers' sales has been. One account is offered by Wohlers Associates (2013a, 124), who observed the Average Selling Prices (see page 86) of industrial printers to have risen during the last few years, explaining it partly due to good sales of high-end systems (including metal ones) but also to falling sales in the low-end:

> *"Another reason is that machines at the low end of the industrial systems segment ($10,000 to $30,000 units) are not selling as briskly due to the recent growth and popularity of the under- $5000 personal 3D printers."*

Disruptive innovations are often inferior in the primary performance attributes. Several of the interviewees for this thesis considered personal 3D printers to be weaker in printing reliability, overall printing quality, build quality of the machine itself, and ease-of-use. Then again, a new-market disruptive innovation brings a new value network and new performance attributes (see page 36). New-market disruptive innovations lack the raw functionality of existing products but bring new benefits such as convenience, customization or lower prices. The attribute bundle means the product will only find success if it takes root among new customers or in a new context of use. Christensen et al 2004 p.7

For personal 3D printers, my empirical findings suggest the following attributes set the personal printers apart from industrial printers:

- affordability/low-cost printing (low purchase price, low material cost, low maintenance cost)
- convenience (printing locally near the user even without computer; portability due to small size and light weight)
- customization (allows experimentation with parameters and materials)
- potential to function as a teaching tool (easy observability of printing process due to open physical structure).

Personal 3D printers seem to resemble the consecutive new-market disruptions of Xerox photocopiers and later Canon desktop ones in the sense that all three represented tradeoffs between convenience and output quality. According to Christensen & Raynor, 2003 p.65, Xerox's photocopier was been a new-market disruption relative to offset printing, since it enabled nonprinters to make copies in the convenience of their own workplace. Then again, Xerox's initial machines were so expensive and complicated that they were housed in corporate photocopy centers manned by technicians. (Ibid, p.65) In contrast, when Canon and Ricoh later introduced their countertop photocopiers, they were slow and produced poor-resolution copies, but they were so inexpensive and simple to use that people could afford to put one right around the corner from their office (Ibid, p.57).

In similar vein as the Xerox example, one could assume that personal 3D printer buyers may value convenience (ability to use the device locally) more than printing quality, and vice-versa for the industrial printer buyers. Such a negative correlation would be in line with the Schmidt & Druehl's (2008) fringe-market low-end encroachment pattern. Even though both diffusion patterns create new markets, the detached-market scenario doesn't really apply to personal 3D printers as it assumes an initially high price - and personal 3D printers have come at considerably *low* prices. Schmidt & Druehl (2008, p. 354) considered the desktop computer (PC) market to be a "fringe" segment relative to the midrange segment (apparently for minicomputers), because its preferences are closest to it. Following this analogy, personal 3D printers' buyers would be a fringe market relative to entry-level industrial printers' buyer segment.

As a result, Schmidt & Druehl (2008 p.364) argue that managers should look for settings where local end users are willing to trade quality for convenience. The authors observed several cases of low-end encroachment where the old high-quality product was used in a centralized location and a ''low-quality'' new product was targeted directly toward more local end users. Thus, in these situations preferences are negatively correlated. (Schmidt & Druehl, 2008 p.364) According to (Christensen et al, 2004 p.269), disruptive products or services are typically simpler to use than the incumbents' products. This may not be the case with personal 3D printers. However, their connectivity (many do not require a computer for printing), low weight, small size and low price do allow placing them closer to the users, thus contributing to their convenience. The fact that end users have been known to trade output quality for convenience, may help offset the perhaps lesser print quality.

5. Conclusions

Going back to the quote in the introduction, the expert's perception is actually easy to understand. Perhaps unknowingly, he actually captured the very essence of a disruptive innovation in that one sentence. Disruptive innovations do indeed typically start off as inferior to existing, incumbent products. Thus, demanding customers who are already consuming a potentially competing project will reject the innovation because of its performance limitations (Christensen et al 2004, p. 7). Then again, they don't need even need to be as good as incumbents' products.

Disruptive innovations, and personal 3D printers as an example, can be useful for people whose alternative is to have no machine at all – to nonconsumers. Target customers [nonconsumers] will compare the disruptive product to having nothing at all. As a result, Christensen & Raynor (2003) argue that they are delighted to buy it even though it may not be as good as other products available at high prices to current users with deeper expertise in the original value network. The performance hurdle required to delight such new-market customers is quite modest. (Christensen & Raynor, 2003 p.110-111)

Thus, returning to the research questions on page 8, the conclusion is affirmative: in the light of my empirical findings, personal 3D printers can be classified as a disruptive innovation. To be more specific, I would place them on a continuum between low-end and new-market disruptions. Mindboggling unit sales that dwarf incumbents' unit sales point to a large amount of nonconsumers as buyers. Also the fact that incumbents' overall sales have remained unaffected point to the fact that they have originated from a space outside the existing markets. Then again, drastically low unit prices and entrants' sizes and business models refer to a low-end disruption.

While similar in technological principles, personal 3D printers differ from the entry-level industrial printers in the sense that they shine in new attributes such as convenience, customization and affordability, which are often associated with disruptive innovations, along with low unit price and simplicity. In contrast, they have started off as inferior in e.g. output quality, as did inkjet printers and office photocopiers. While the printing quality of typical personal printers might still not be on par with pro-level printers and thus unsuitable for commercial purposes, there are a lot of other uses and buyers for whom it is "good enough". However, theory suggests that disruptive innovations are easier to use, yet also more expensive to use than incumbents' ones. Empirical findings didn't support either one those premises in this case.

As for the factors that have contributed to the birth of personal printers, I found incumbent companies' expired 3D printing patents, the RepRap printer project, open-source development work and the underlying Maker Movement/development communities as the most significant influences. Further development of the personal printers is still limited by certain patents that are still in force.

Finally, as the term "disruptive innovation" suggests, one would expect the industrial printers to become disrupted. This is where things get a little bit tricky. According to Christensen (2006), a disruptive innovation is a specific phenomenon and perhaps misleading as a term, as it does not necessarily lead to market disruption. Hence, he considered "Christensen Effect" to be more accurate. Theory suggests that disruption of an incumbent may take a considerable amount of time, especially in a new-market disruption scenario, or it might not happen at all in the sense that incumbents would ever be completely displaced. As a new-market disruptive innovation, personal 3D printers' sales have grown outside the incumbents' markets and therefore clear signals of encroachment on incumbents' unit sales or revenues are yet to be seen. In addition, major incumbents have resorted to acquisitions of entrants and launching their own personal models as a survival strategy. As a result, the major incumbents seem fairly well protected. However, once more 3D printing patents expire in the near future, personal printers are only going to improve.

The theory of disruptive innovations has caused confusion regarding the consequences for individual incumbents. As resulted with the advent of inkjet printers, steel minimills, minicomputers and personal computers, I would argue that the composition of 3D printers offered on the market has been disrupted permanently by the personal printers. I would expect the low-end of their industrial printer lines to face increased pressure from personal printers, as per the theoretical framework on page 55. Nevertheless, theory doesn't suggest that incumbents would necessarily become disrupted. These findings support the fact that besides the disruption of incumbents, the theory of disruptive innovations can also be about significant market expansion. As the theory has gained prominence, managers of established businesses have come to know better and reacted accordingly.

As an area of further research, I would address the role of acquisitions as incumbents' response strategy to disruptive innovations in more detail.

6. References

PUBLICATIONS

Adner, R. (2002). "When Are Technologies Disruptive? A Demand-Based View of the Emergence of Competition". *Strategic Management Journal,* no. 23, pp. 667-668.

Carayannopoulos, S. (2009). "How Technology-Based New Firms Leverage Newness and Smallness to Commercialize Disruptive Technologies". *Entrepreneurship Theory and Practice,* March 2009, pp. 419-438.

Chandy, R. K. & Tellis, G. J. (2000) "The Incumbent's Curse? Incumbency, Size, and Radial Product Innovation". *Journal of Marketing*, vol. 64 (July 2000, pp. 1-17.

Christensen, Clayton M. (2000). *"Innovator's Dilemma: when new technologies cause great firms to fail".* Second Edition. Harvard Business School Press, Boston, Massachusetts, U.S.A.

Christensen, Clayton M. & Raynor, Michael E. (2003). *"Innovator's Solution: creating and sustaining successful growth"*, Harvard Business School Press, Boston, Massachusetts, U.S.A.

Christensen, Clayton M; Anthony, Scott D. & Roth, Erik A. (2004). *"Seeing What's Next: using the theories of innovation to predict industry change",* Harvard Business School Press, Boston, Massachusetts, U.S.A.

Christensen, C. (2006). "The Ongoing Process of Building a Theory of Disruption", *Journal of Production Innovation Management*, 2006, no. 23, pp.39-55.

Danneels, E. (2004). "Disruptive Technology Reconsidered: A Critique and Research Agenda", *Journal of Product Innovation Management,* no. 21, pp. 246-258.

Danneels, E. (2006). "From the Guest Editor: Dialogue on the Effects of Disruptive Technology on Firms and Industries". *Journal of Product Innovation Management,* no. 23, pp. 2-4.

Dubois, A. & Gadde, L-E. (2002). "Systematic combining: an abductive approach to case research", *Journal of Business Research,* vol.55, pp. 553-560.

Eisenhardt, K. M. (1989). "Building Theories from Case Study Research", *The Academy of Management Review,* vol. 14, no. 4, pp. 532-550.

Eriksson, Päivi & Kovalainen, Anne (2008). *"Qualitative Methods in Business Research"*, SAGE Publications, London, United Kingdom.

Euchner, J. (2011). "Managing Disruption: An Interview with Clayton Christensen". *Research-Technology Management,* January-February 2011, pp. 11-17.

Gilbert, C. (2003). "The Disruption Opportunity". *MIT Sloan Management Review,* Summer 2003, pp. 27-32.

Gilbert, C.G. (2005). “Unbundling The Structure of Inertia: Resource versus Routine Rigidity”, *Academy of Management Journal*, vol. 48, no. 5, pp. 741-763.

Govindarajan, V. & Kopalle, P.K. (2006). ”The Usefulness of Measuring Disruptiveness of Innovations Ex Post in Making Ex Ante Predictions”. *Journal of Product Innovation Management,* 2006, no. 23, pp. 12-18.

Markides, C. (2006). “Disruptive Innovation: In Need of Better Theory”. *Journal of Product Innovation Management,* no. 23, pp. 19-25.

Schmidt, G. M. & Druehl, C. T. (2008). ”When Is a Disruptive Innovation Disruptive?”, *The Journal of Product Innovation Management,* no. 25, pp. 347-369.

Smith, P.G. (2005). “Book reviews”. *The Journal of Product Innovation Management*, no. 22, pp.213-220.

Sood, A. & Tellis, G.E. (2011). “Demystifying Disruption: A New Model for Understanding and Predicting Disruptive Technologies”. *Marketing Science,* vol. 30, no. 2, March-April 2011, pp.339-354.

Stake, Robert E. (2005). Qualitative Case Studies. In “The SAGE Handbook of Qualitative Research”. 3rd ed. SAGE Publications, Thousand Oaks, California, U.S.A. pp. 443-466.

Tellis, G. J. (2006). “Disruptive Technology or Visionary Leadership”. *Journal of Product Innovation Management,* no. 23, pp. 34-38.

Utterback, J. M. & Acee, H. J. (2005). “Disruptive Technologies: An Expanded View”. *International Journal of Innovation Management,* vol. 9, no. 1, pp.1-17.

Yin, Robert K. (2009). “Case Study Research: Design and Methods”. 4th edition. *SAGE Publications, Inc.,* Thousand Oaks, California, U.S.A.

Yu, D. & Hang, C.C. (2009). “A Reflective Review of Disruptive Innovation Theory”. *International Journal of Management Reviews,* vol. 12, pp. 435-452.

SECONDARY SOURCES

Anderson, Chris (2012). “*Makers: the new industrial revolution”*, Crown Publishing Group, New York, U.S.A.

Ashley, S. (1995). “Rapid prototyping is coming of age”, *Mechanical Engineering*, vol. 117, no. 7, pp. 62-68.

Ashley, S. (1996). “A new dimension for office printers”, *Mechanical Engineering*, vol. 118, no. 3, pp. 112-115.

Beckert, B. A. (1998). “Concept Modelers: a Testbed for Quick Prototypes”, Computer-Aided Engineering, April 1998, vol. 17, no. 4, pp. 46-54.

Computer Sciences Corporation (CSC), (2012). Srinivasan, V. & Bassan, J. *“CSC Leading Edge Forum: 3D Printing and the Future of Manufacturing”,* Computer Sciences Corporation, Falls Church, Virginia, U.S.A.

de Bruijn, E. (2010). *“On the viability of the Open Source Development model for the design of physical objects. Lessons learned from the RepRap project”,* Master’s Thesis, University of Tilburg, The Netherlands, 08.11.2010.

de Jong, J. P. J. & de Bruijn, E. (2013). ”Innovation Lessons from 3D-Printing”, *MIT Sloan Management Review,* Winter 2013, vol. 54, no. 2, pp. 43-52.

Gartner, (2013d). Basiliere, P., Burt, M., Raina, A., Halpern, M; Plummer, D. C. & Shah, Z. *“Predicts 2014: 3D Printing at the Inflection Point”*. Gartner, Inc., Stamford, Connecticut, U.S.A.

“Genisys Xs”, (1999). *Computer-Aided ENGINEERING*, June 1999, pp. 25.

Gershenfeld, Neil (2005). “*Fab: the coming revolution on your desktop – from personal computers to personal fabrication”*, Basic Books, New York, U.S.A.

Gershenfeld, N. (2012). “How to Make Almost Anything, The Digital Fabrication Revolution”, *Foreign Affairs,* vol. 91, no. 6, pp. 42-57.

Huxley, M. & Weisberg, S. (2002). “Desktop rapid prototyping cuts costs and improves designs”, *CADalyst*, vol. 19, no. 8, pp. 26-35.

Jones, R., Haufe, P., Sells, E., Iravani, P., Olliver, V., Palmer, C. & Bowyer, A. (2011), ”RepRap – the replicating rapid prototyper”, *Robotica*, vol. 29, pp. 177-191. (An earlier unpublished version was first used with this thesis).

MAKE magazine (2013). *“MAKE: Ultimate Guide to 3D Printing 2014 (Special Issue)”,* Maker Media Inc., Sebastopol, California, U.S.A.

Malone, E. & Lipson, H. (2007). “Fab@Home: the personal desktop fabricator kit”, *Rapid Prototyping Journal*, vol. 13, no. 4, pp. 245–255.

Pearce, J.M., Blair, M. C., Laciak, K.J., Andrews, R., Nosrat, A. & Zelenika-Zovko, I. (2010). “3-D Printing of Open Source Appropriate Technologies for Self-Directed Sustainable Development”, *Journal of Sustainable Development,* vol. 3, no. 4, pp. 17-29.

Perez, M. A., Ramos, J., Espalin, D., Hossain, M. S. & Wicker, R. B. (2013). “Ranking model for 3D printers”, *Proceedings of the 2013 Solid Freeform Fabrication Symposium.* University of Texas at El Paso, W. M. Keck Center for 3D Innovation. Pp. 1048-1065.

Plastics Technology (1996) “`Office modelers' for rapid prototyping”, vol. 42, no. 5, pp. 60-62.

Potter, Caren D. (1997) “Concept modelers: The latest trend in rapid prototyping”, *Computer Graphics World*, vol. 20, no. 12, pp. 45-49.

Roberson, D.A., Espalin, D. & Wicker, R.B. (2013). “3D printer selection: A decision-making evaluation and ranking model”, *Virtual and Physical Prototyping*, vol. 8, no. 3, pp. 201-212.

T.A. Grimm & Associates (2010). *“3D Printer Benchmark: North American Edition”*. T.A. Grimm & Associates, Inc. Edgewood, Kentucky, U.S.A.

The Economist (2012). “Special report: Manufacturing and innovation, a third industrial revolution.” 21.4.2012

Wohlers Associates, (2001). “*Wohlers Report 2001: Rapid Prototyping and Tooling State of the Industry Annual Worldwide Progress Report”*, Wohlers Associates, Inc, Fort Collins, Colorado, U.S.A.

Wohlers Associates, (2002). “*Wohlers Report 2002: Rapid Prototyping and Tooling State of the Industry Annual Worldwide Progress Report”*, Wohlers Associates, Inc, Fort Collins, Colorado, U.S.A.

Wohlers Associates, (2005). “*Wohlers Report 2005: Rapid Prototyping, Tooling and Manufacturing State of the Industry Annual Worldwide Progress Report”*, Wohlers Associates, Inc, Fort Collins, Colorado, U.S.A.

Wohlers Associates, (2006). “*Wohlers Report 2006: Rapid Prototyping and Manufacturing State of the Industry Annual Worldwide Progress Report”*, Wohlers Associates, Inc, Fort Collins, Colorado, U.S.A.

Wohlers Associates, (2011a). “*Wohlers Report 2011, Additive Manufacturing and 3D printing State of the Industry. Annual Worldwide Progress Report”*, Wohlers Associates, Inc, Fort Collins, Colorado, U.S.A.

Wohlers Associates, (2011b). *“History of Additive Manufacturing”*. Wohlers Associates, Inc, Fort Collins, Colorado, U.S.A.

Wohlers Associates, (2013a). “*Wohlers Report 2013, Additive Manufacturing and 3D printing State of the Industry”*. Annual Worldwide Progress Report”, Wohlers Associates, Inc, Fort Collins, Colorado, U.S.A.

Wohlers Associates, (2013b). “*History of Additive Manufacturing”*. Wohlers Associates, Inc, Fort Collins, Colorado, U.S.A.

ONLINE RESOURCES

Christensen, C. (2014). Clayton Christensen Responds to *New Yorker* Takedown of “Disruptive Innovation”. http://tinyurl.com/ovpg558, viewed on 20.7.2014.

D'Aveni, Richard. (2013). 3-D Printing Will Change the World. http://hbr.org/2013/03/3-d-printing-will-change-the-world/ viewed on 12.7.2014.

Fabbaloo.com, (2011). http://tinyurl.com/mh9fddh, viewed on 25.5.2014.

Formlabs, (2013). http://formlabs.com/blogs/blog, viewed on 10.01.2014.

Formlabs, (2014). www.formlabs.com, viewed on 10.1.2014.

Gans, J. (2014). The easy target that is the Theory of Disruptive Innovation. http://tinyurl.com/oqlzcs9, viewed on 20.7.2014

Gartner, (2013a). Press Release 2.10.2013. Available at http://tinyurl.com/lr2n8kt

Gartner, (2013b). Press Release 26.3.2013. Available at http://tinyurl.com/btkgftv

Gartner, (2013c). Press Release 19.8.2013. Available at http://tinyurl.com/mnpvhms

Gartner, (2014). 14.2.2014. Basiliere, P. (2014). Gartner, Inc. Available at http://tinyurl.com/mghjvjx

Google Patents, (2014). http://tinyurl.com/o3kyoby, viewed on 10.1.2014

Indiegogo, (2014). www.indiegogo.com, viewed on 6.6.2014.

Juniper Research Ltd, (2014). Press Release 22.4.2014, available at http://tinyurl.com/pjuck9v

Kickstarter, (2014). www.kickstarter.com, viewed on 16.7.2014.

Leapfrog B.V. (2014). http://tinyurl.com/oenfulb, viewed on 20.7.2014.

Lepore, J. (2014). The Disruption Machine. http://tinyurl.com/k44x95x, viewed on 20.7.2014.

Makerbot, (2014). www.makerbot.com, viewed on 10.1.2014.

Open-source Hardware Association (2013). www.oshwa.org, viewed on 31.12.2013

Patentbuddy, (2014a). http://www.patentbuddy.com/Patent/5121329, viewed on 10.1.2014.

Patentbuddy, (2014b). http://www.patentbuddy.com/Patent/6722872, viewed on 10.1.2014.

Patentbuddy, (2014c). http://www.patentbuddy.com/Patent/4575330, viewed on 10.1.2014

Pettis, B. (2012). Makerbot blog entry 24.9.2012, available at http://tinyurl.com/8jqzup7

RepRap, (2009). http://www.youtube.com/watch?v=iMhG4fWQnlE, viewed on 10.1.2014.

RepRap (2010). Blog entry 31.8.2010. http://blog.reprap.org/2010_08_01_archive.html viewed on 27.12.2013.

RepRap, (2014a). http://reprap.org/wiki/Mendel, viewed on 10.1.2014.

RepRap, (2014b). RepRap Family Tree. http://tinyurl.com/llnn5uf, viewed on 10.1.2014.

Stratasys Inc., (2013b) Press Release 19.06.2013. http://tinyurl.com/ma6wu5n

Stratasys Inc., (2013c) Financial Results, Q3, 7.11.2013. Available at http://tinyurl.com/pdxwmvn, viewed on 6.6.2014.

Stratasys Inc., (2013d) Stratasys-Makerbot merger, investor conference call, 20.6.2013. Slideshow available at http://tinyurl.com/kmku3b8, viewed on 6.6.2014.

Stratasys, Inc., (2014). Annual Report, March 3, 2014. Available at http://tinyurl.com/oxvvbho, viewed on 14.7.2014

3ders.org, (2014). http://www.3ders.org/pricecompare/?o=Price%20per%20kg. Viewed on 20.7.2014.

3DSystems, Inc. (2012) Press Release 09.01.2012. Available at http://tinyurl.com/ol8nqu6, viewed on 6.6.2014.

3DSystems, Inc. (2014). Annual Report, Available at http://tinyurl.com/pdxnep6, viewed on 15.7.2014.

Ultimaker, (2014a). www.ultimaker.com, viewed on 10.1.2014.

Ultimaker, (2014b). http://tinyurl.com/pxarhnm, viewed on 6.6.2014.

INTERVIEWS

Chekurov, Sergei. February 27th, 2014 in Espoo, Finland.

Mohite, Ashish. November 19th, 2013 in Espoo, Finland.

Mäkelä, Ismo. February 5th, 2014 in Espoo, Finland.

Partanen, Jouni (1). December 12th, 2013 in Espoo, Finland.

Partanen, Jouni (2). February 3rd, 2014 in Espoo, Finland.

Piili, Heidi. November 18th, 2013, via Skype.

Tuomi, Jukka. January 7th, 2014 in Espoo, Finland.

Väistö, Tapio. November 14th, 2013 in Espoo, Finland.

APPENDIX A. **Definitions.**

Additive Manufacturing (AM): a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies such as milling, drilling and grinding (ASTM Standard F2792-12a). The fabrication process occurs through the deposition of a material using a print head, nozzle, or another printer technology (Wohlers Associates, 2014).

Fused Deposition Modeling (FDM): a 3D printing technology whereby parts are built layer-by-layer by heating thermoplastic material to a semi-liquid state and extruding it [through a nozzle] according to computer-controlled paths. Trademark of Stratasys, Inc. (ASTM Standard F2792-12a; Stratasys, 2014) Sometimes also referred to as Fused Filament Fabrication (FFF); commonplace technology in personal 3D printers. The first FDM systems were introduced by Stratasys in 1991 (Wohlers Associates, 2013 p.55).

Industrial or professional 3D printer: A machine used for additive manufacturing that costs over 5000 USD, as defined by Wohlers Associates (2013).

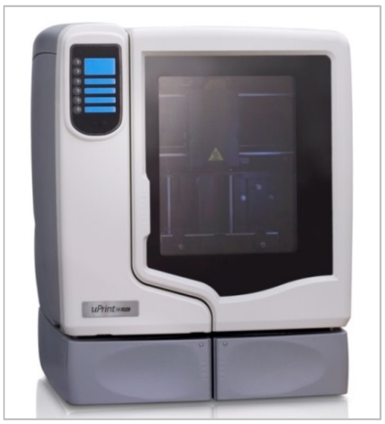
Personal 3D printer: A machine used for 3D printing that costs less than 5000 USD, as defined by the industry research firm Wohlers Associates (2013). Often employs FDM-type of technology and is often at least partially open-source.

Stereolithography (SLA): a 3D printing technology whereby parts are built layer by layer by hardening liquid resin with a laser beam. Originally patented by 3DSystems, Inc. See ASTM Standard F2792-12a.

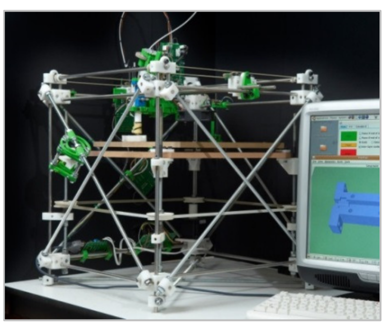
3D Printing: term is often used synonymously with Additive Manufacturing; in particular associated with machines that are low end in price and/or overall capability. (ASTM Standard F2792-12a)

APPENDIX B. Typical 3D printer models, past and present.

Z Corp Z402 was one of the first machines to be called a "3D printer" to distinguish it from previous industrial AM systems. These smaller units were suitable for office use and were thus also known as "office concept modelers" or "desktop rapid prototypers". They were significantly more affordable than the AM systems, costing around 55.000-60.000 USD in ca. 1997. In practice, companies often used them in centralized locations such as laboratories to reach a large amount of in-house users. (Beckert, 1998) However, they often replaced service bureaus' offerings, (Ibid, 1998) which were even more centralized. Other similar devices were the Stratasys Genisys and 3DSystems Actua2100. Photo courtesy of Pennsylvania State University.



Stratasys uPrint is the quintessential, contemporary entry-level industrial 3D printer. Brought to the market in early 2009 for a price of $14.900, the uPrint employed FDM-technology, weighed 76 kg, and measured 76x66x66 centimeters in external diameters. Annual maintenance costs were quoted at $1950 (Wohlers Associates, 2011). Stratasys later introduced a more affordable Mojo 3D printer for just under $10.000. Both models were still available in June 2014. Photo courtesy of Stratasys, Inc.



RepRap Darwin was the first iteration of the RepRap open-source 3D printer. The first unit was built in May, 2007. The structure was designed so that the printer could print most of its own parts, and any parts that the RepRap machine could not make for itself had to be cheaply and widely available. (Jones et al, 2011). The first generation machine could print 48% of its own parts, ignoring fasteners such as nuts, bolts and washers. The Darwin weighed 14 kg and had 60x52x65 cm as its external measures. (Ibid, 2011) Photo courtesy of reprap.org.

Ultimaker 2 is a typical example of a modern personal 3D printer. It was developed by Ultimaker B.V. of Geldermalsen, Holland and introduced in September 2013. Like the above Stratasys and the RepRap, the Ultimaker is based on FDM technology. Also like the RepRap, the Ultimaker is completely open-source and its blueprints and software are freely available. Like many in its class, the Ultimaker offers stand-alone printing with a memory card reader and option for WiFi printing. External diameters measure at 36x34x39 centimeters. Price ex VAT is 1895,00 € ($ 2750). (Ultimaker, 2014) Photo courtesy of Ultimaker B.V.

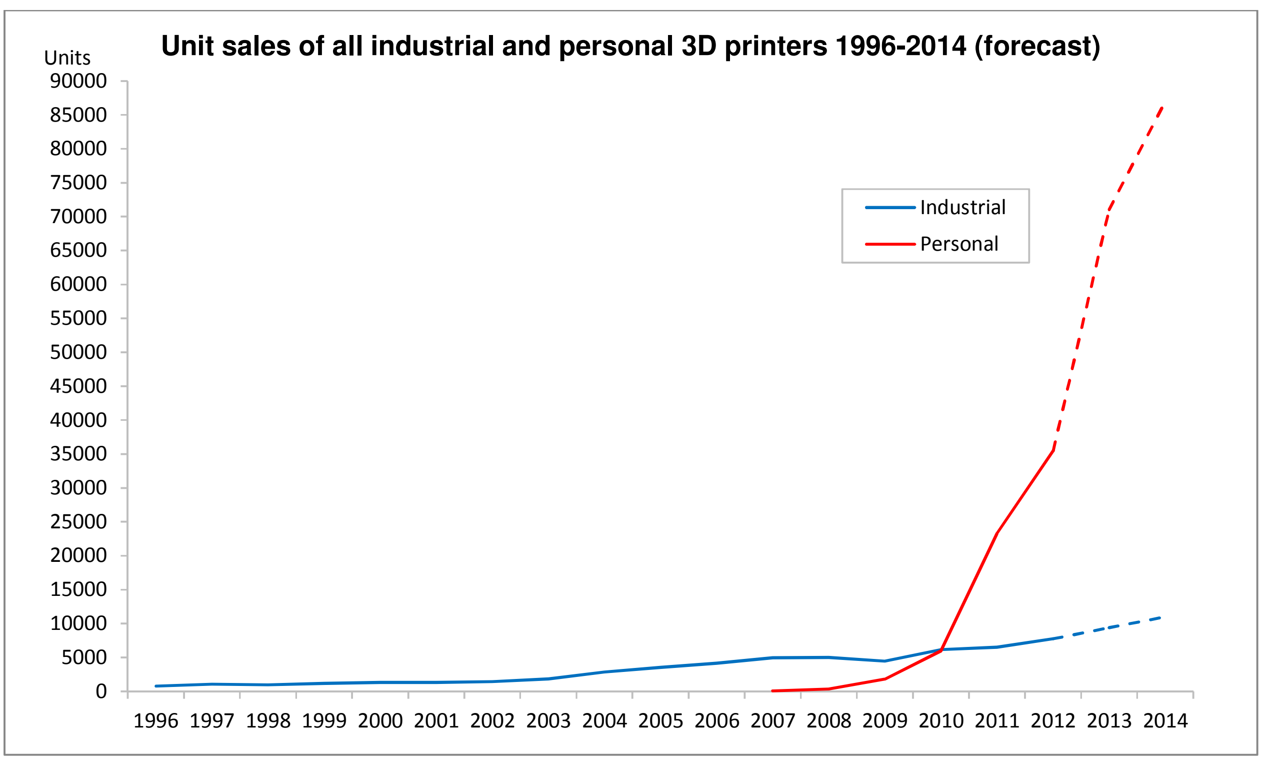
APPENDIX C. **Unit sales of all 3D printers 1996-2013 (forecast).**

Year	Unit sales of 3D printers Personal $200-5000	All industrial $5001-1,5M
1996		792
1997		1043
1998		968
1999		1184
2000		1309
2001		1301
2002		1470
2003		1871
2004		2854
2005		3526
2006		4151
2007	66	4938
2008	355	5007
2009	1816	4486
2010	5978	6164
2011	23265	6513
2012	35508	7771
2013	71016 (a	N/A
2014	87000(b	11000(c

Source: Wohlers Associates (2013a)

a) Stratasys (2013d) has estimated unit sales to double from year 2012 to 2013. b) my own estimate based on data from Gartner (2013a) and Wohlers Associates (2013a).

c) Wohlers Associates' (2013a) forecast



APPENDIX D. Personal 3D printer data table (5/2007 – 1/2014)

LOW-END 3D PRINTERS						
Manufacturer	Model	Price, USD	Introduced	Layer thickness, µm	Print area, mm	Build volume, cm3
MAKERBOT[7]	Replicator Mini	1375	Jan 2014	200	100x100x125	1250
	Replicator 5th gen	2899	Jan 2014	100	252x199x150	7522
	Replicator 2X	2399[4]	Dec 2013			
	Replicator 2X	2799	Jan 2013	100	250x150x160	6000
	Replicator 2	2199	Sep 2012	100	284x152x155	6691
	Replicator	1750	Jan 2012	200	225x145x150	4894
	Thing-o-matic (KIT)	1225	Sep 2010	300[1]	100x100x100	1000
	Cupcake CNC (KIT)	750	Apr 2009	373[1]	100x100x130	1300
3DSYSTEMS	CubePro	2799	Jan 2014	70	275x265x240	17490
	Cube III	999	Jan 2014	70	152x152x152	3512
	CubeX	2499	Jan 2013	125	275x265x240	17490
	Cube II	1299	Jan 2013	200	140x140x140	2744
	Cube	1299	Jan 2012	250	140x140x140	2744
ULTIMAKER	2	2750[2]	Sep 2013	20	225x225x205	10378
	Original (KIT)	1700[2]	Mar 2010	20	210x210x205	9041
BITS FROM BYTES[6]	3DTouch	3900	Sep 2011	125	275x275x210	15881
	BfB 3000 plus	3900	May 2011	125	275x275x210	15881
	BfB 3000	3300	Apr 2010	100	320x300x200	19200
	Rapman 3.1	1300	Apr 2009	125	270x205x210	11624
REPRAP	Huxley	386[3]	Aug 2010	100	140x140x110	2156
	Mendel	483 (350 €)[3]	Oct 2009	100	200x200x140	5600
	Darwin	690 (500 €)[3]	May 2007	300	200x150x100	3000
FORMLABS	Form1	3299	Oct 2012	25	125x125x165	2578
SOLIDOODLE	4th gen	999	Nov 2013	100	203x203x203	8365
	3rd gen	799	Nov 2012	100	203x203x203	8365
	2nd gen	499	Apr 2012	300	152x152x152	3512
	1st gen	699	Sep 2011	300	102x102x102	1061
LEAPFROG	CREATR	1613(1250 €)[2]	Apr 2012	50	230x270x200	12420
DMFC[5]	Up! Plus 2	1649	May 2013	150	140x140x135	2646
	Up! Mini	899	May 2012	200	120x120x120	1728
	Up!	2690	Jul 2010	200	140x140x135	2646
PRINTRBOT	Simple	449	May 2013	100	100x100x100	1000
	Printrbot LC	799	Nov 2012	100	152x152x152	3512
	PLUS	999	Dec 2011	100	203x203x203	8365
	original, 1st gen.	750	Dec 2011	100	127x127x127	2048
DEEZMAKER	Bukobot 8 v2 (KIT)	1299	May-2013	50	200x200x200	8000
ALEPH OBJECTS	Lulzbot Taz 3	1995	Jan-2014	75	298x275x250	20488
ROBO3D	Robo 3D ABS+PLA	699	Feb-2013	100	254x254x203	13097

[1]estimates, [2]excluding local VAT, [3]build material costs, [4]price change, [5]Delta Micro Factory Corp, [6]acquired by 3DSystems, [7]acquired by Stratasys

APPENDIX D (cont'd). **Data sources.**

Model	Data source			
Replicator Mini	makerbot.com, 2014			
Replicator 5th gen	makerbot.com, 2014			
Replicator 2X	makerbot.com, 2013			
Replicator 2X	makerbot.com, 2014	Makerbot blog 9.1.2013	Perez et al (2013)	
Replicator 2	Makerbot Press Release 19.9.2012			
Replicator	Roberson et al (2013)	Wohlers History 2013	http://www.thingiverse.com/thing:18813	
Thing-o-matic (KIT)	Makerbot blog entry 25.9.2010	http://tinyurl.com/or9wyx5		
Cupcake CNC (KIT)	http://archive.is/x1zEp	Wohlers Report 2011	Wohlers History 2013	
CubePro	3DSystems Press Release 6.1.2014	3DSystems Press Release 20.5.2014		
Cube III	3DSystems Press Release 6.1.2014	3DSystems Press Release 20.5.2014		
CubeX	3DSystems Press Release 7.1.2013			
Cube II	cubify.com 2014	User manual		
Cube	3DSystems Press Release 9.1.2012	http://tinyurl.com/ndxsvv4		
2	Ultimaker blog entry 18.9.2013	ultimaker.com 2014		
Original (KIT)	ultimaker.com 2014	Wohlers Report 2013	http://tinyurl.com/3zwovjo	
3DTouch	3DSystems Press Release 26.9.2011	Wohlers History 2013	Roberson et al (2013)	addlab.aalto.fi
BfB 3000 plus	3DSystems Press Release 23.5.2011			
BfB 3000	3DSystems BFB3000 brochure	Wohlers Report 2011	http://tinyurl.com/ogv9g5t	
Rapman 3.1	Wohlers History 2013	Wohlers Report 2011	3DSystems RapMan brochure	addlab.aalto.fi
Huxley	www.reprappro.com/faqs/#accuracy	reprap.org 2014	Reprap blog entry 31.8.2010	
Mendel	www.reprappro.com/faqs/#accuracy	Jones et al (2011)	RepRap blog entry 13.10.2009	
Darwin	Jones et al (2011)	Pearce et al (2010)		
Form1	Wohlers Report 2013	Formlabs, 2014	http://tinyurl.com/mjb9s5e	
4th gen	Solidoodle blog entry 22.11.2013	solidoodle.com (2014)		
3rd gen	Solidoodle blog entry 16.11.2012	solidoodle.com (2014)	Wohlers Report 2013	
2nd gen	Solidoodle blog entry 19.4.2012	solidoodle.com (2014)	http://tinyurl.com/7z7lslk	Wohlers 2013*
1st gen	Wohlers History 2013	solidoodle.com (2014)	http://tinyurl.com/ou6xmzu	
CREATR	Leapfrog Creatr tech sheet (2014)	Wohlers Report 2013	leapfrog.com 2014	
Up! Plus 2	pp3dp.com (2014)	http://tinyurl.com/a28qruo		
Up! Mini	Wohlers Report 2013	pp3dp.com 2014		
Up!	Wohlers Report 2011			
Simple	printrbot.com 2014	http://tinyurl.com/ondakx8		
Printrbot LC	printrbot.com 2014	Wohlers Report 2013	http://tinyurl.com/os5najl	
PLUS	printrbot.com 2014	Wohlers Report 2013		
original, 1st gen.	kickstarter.com, 2012			
Bukobot 8 v2 (KIT)	Bukobot.com, 2014			
Lulzbot Taz 3	lulzbot.com, 2014	Aleph Objects Press Release 08.01.2014		
Robo 3D ABS+PLA	http://tinyurl.com/mglxswr	Wohlers Report 2013		

[1]Wohlers Associates 2013a, 2013b

APPENDIX E. **Entry-level, professional-grade "desktop" 3D printers 3/1996 – 12/2013**

Manufacturer	Model	Introduced	Price, USD	Price from	Layer thickness, µm	Print area, mm	Build volume, cm^3
STRATASYS	Mojo		9500	May-2013			
	Mojo	May 2012	9900	May-2012	178	127x127x127	2048
	uPrint SE	Nov 2011	13900	Nov-2011	254	203x152x152	4690
	uPrint	Jan 2009	14900	Jan-2009	254	203x152x152	4690
	Dimension BST 768	Apr 2006	18900	Apr-2006	254	203x203x305	12569
	Dimension (BST)		19900	Jan-2006			
	Dimension (BST)	Feb 2004	24900	Feb-2004	250	203x203x305	12569
	Dimension	Feb 2002	29900	Feb-2002	250	203x203x305	12569
	Genisys Xs	Apr 1999	45000	Apr-1999	330	203x203x305	12569
	Genisys		55000	Dec-1997			
	Genisys	Mar 1996	55500	Mar-1996	356	203x203x203	8365
3DSYSTEMS	ProJet 1200[4]	Dec 2013	4900	Dec-2013	30	43x27x180	209
	ProJet1000	Nov 2011	10900	Nov-2011	102	171x203x178	6179
	Projet1500	Sep 2011	14500	Sep-2011	102	171x228x203	7915
	V-Flash FTI-230	May 2011	9900	May-2011	102	228x171x203	7915
	V-Flash	Sep 2007	9900	Apr-2008	102	178x229x203	8275
	Invision LD		14900	Mar-2006			
	InVision LD[1]	Apr 2005	22900	Apr-2005	150	160x210x135	4536
	InVision	Oct 2003	39900	Oct-2003	38	298x185x203	11191
	Thermojet	Mar 1999	49995	Mar-1999	40	250x190x200	9500
	Actua2100		65000	Dec-1997			
	Actua2100	May 1996	60000	May-1996	38	254x203x203	10467
Z CORPORATION[5]	Zprinter 150	Jul 2010	14900	Jul-2010	100	236x185x127	5545
	Zprinter 310 plus		19900	Jan-2006			
	Zprinter 310 plus	Oct 2005	25900	Oct-2005	89	203x254x203	10467
	Zprinter 310		26000	Aug-2004			
	Zprinter 310	Feb 2003	29900	Feb-2003	89	203x254x203	10467
	Z400		35500	May-2002			
	Z400	May 2001	49000	May-2001	76[3]	203x254x203	10467
	Z402	Dec 1997	59000	Dec-1997	89	203x254x203	10467
OBJET[2]	Objet24	Dec 2010	19900	Dec-2010	28	240x200x150	7200
	Alaris30		24900	Sep-2010			
	Alaris30	Oct-2008	40000	Oct-2008	28	294x196x150	8644
	Eden250	Jan-2006	60000	May-2006	16	250x250x200	12500
	Quadra	Mar 2000	69000	Mar-2000	20	270x300x200	16200
SOLIDO[6]	SD300 Pro	Dec 2009	9950	Feb-2010	168	160x210x135	4536
	SD300	May 2005	28000[7]	May-2005	165	160x210x135	4536
ASIGA	Freeform Pico[4]	Nov-2011	6990	Nov-2011	1	30x40x76	91,2
ENVISIONTEC	Perfactory Micro[4]	May-2012	14999	May-2012	25	40x30x100	120

[1]same as Solidimension SD300 (Wohlers Associates, 2006, 83), [2]Objet merged with Stratasys in April 2012 (Wohlers Associates, 2013b), [3]some sources quote 89 microns, [4]Very limited build volumes, mostly for dental and jewelry use, [5]Z Corporation was acquired by 3DSystems in November 2011, [6] aka Solidimension, no longer in operation, [7]22 000 €, estimate in USD 28 000.

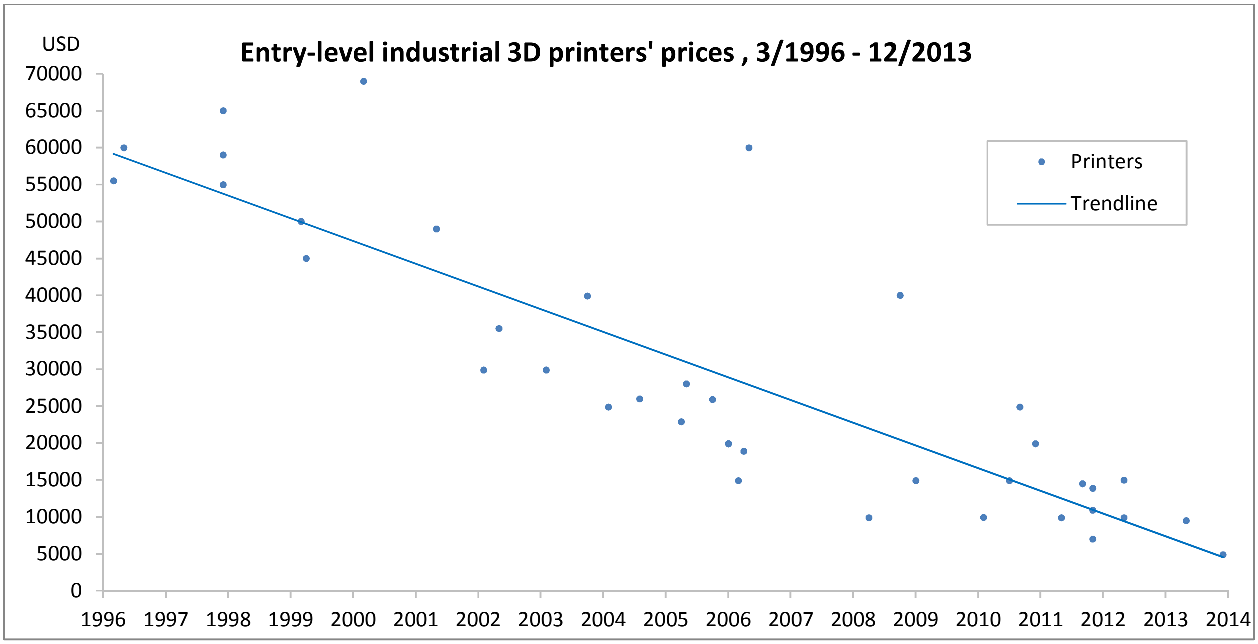
APPENDIX E (cont'd). Data sources.

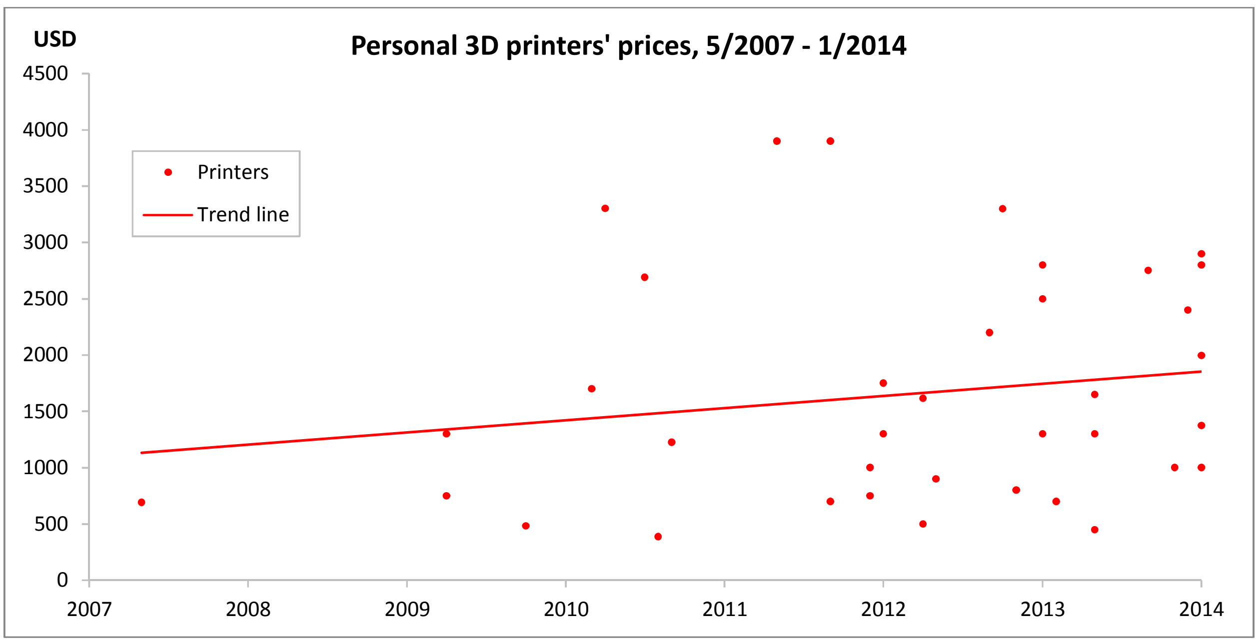
Model	Data sources			
Mojo	Wohlers Report 2013			
Mojo	Stratasys Press Release 08.05.2012	http://tinyurl.com/mqppsem	Wohlers History 2013	Stratasys, 2014
uPrint SE	Stratasys Press Release 17.11.2011			
uPrint	Stratasys Press Release 26.01.2009	uPrint User's Manual	http://tinyurl.com/m5awo7u	Wohlers History 2013
Dimension BST 768	Stratasys Product Brochure	Dimension BST 768 User's Manual	Stratasys Annual Report 2007	
Dimension (BST)	http://tinyurl.com/mbw98mq			
Dimension (BST)	Stratasys Annual Report 2005			
Dimension	Huxley & Weisberg (2002)	Wohlers Report 2002		
Genisys Xs	Computer Aided Engineering, June 1999	http://tinyurl.com/n8naukg	Stratasys Annual Report 2000	http://tinyurl.com/m3v9jdy
Genisys	Potter (1997)			
Genisys	Kochan (1997) Assembly Automation	Potter (1997)	Stratasys Annual Report 1997	Ashley (1996)
ProJet 1200	3DSystems Press Release 04.12.2013			
ProJet1000	3DSystems Press Release 29.11.2011	3Dsystems.com, 2014		
Projet1500	3DSystems Press Release 26.09.2011	3Dsystems.com, 2014		
V-Flash FTI-230	Wohlers Report 2011			
V-Flash	3DSystems Press Release 25.09.2007	3DSystems Press Release 20.10.08	Wohlers History 2013	http://tinyurl.com/lthlmtn
Invision LD	3DSystem's Press Release 01.03.2006			
InVision LD	3DSystems Press Release on 06.04.2005	Invision LD Brochure 12.10.2005	Wohlers History 2013 (Solido)	
InVision	3DSystems Press Release 08.10.2003	http://tinyurl.com/mbw98mq	Huxley & Weisberg (2002)	
Thermojet	3DSystems Press Release 10.3.1999	Huxley & Weisberg (2002)	Wohlers Report 2001	Wohlers History 2013
Actua2100	Potter (1997)			
Actua2100	Potter (1997)	Plastics Technology, May 1996		

APPENDIX E (cont'd). **Data sources.**

Zprinter 150	Z Corp Press Release 21.7.2010	http://tinyurl.com/2df8vfd	Wohlers Report 2011	
Zprinter 310 plus	Wohlers History 2013			
Zprinter 310 plus	ZCorp Press Release 17.10.2005	http://tinyurl.com/cc88or	Wohlers History 2013	
Zprinter 310	http://tinyurl.com/mbw98mq			
Zprinter 310	Wohlers History 2013	http://tinyurl.com/lfj35le	http://tinyurl.com/mvyy87s	
Z400	Huxley & Weisberg (2002)	Wohlers Report 2002		
Z400	Huxley & Weisberg (2002)	Wohlers Report 2001		
Z402	Beckert (1998)	http://tinyurl.com/pq4qzgp	Potter (1997)	
Objet24	Wohlers Report 2011			
Alaris30	Wohlers History 2013			
Alaris30	Wohlers History 2013	Alaris30 sales brochure	http://tinyurl.com/qbzxfk8	
Eden250	Wohlers Report 2006			
Quadra	Objet Press Release 29.11.2000	Wohlers Report 2011	Wohlers History 2013	
SD300 Pro	Wohlers History 2013	http://tinyurl.com/m3p52re	Roberson et al (2013)	http://tinyurl.com/mjkvsrf
SD300	Wohlers Report 2006	Wohlers Report 2005		
Freeform Pico	Wohlers Report 2013	http://tinyurl.com/kpkzfjd	http://tinyurl.com/kqjh763	
Perfactory Micro	Wohlers Report 2013	http://tinyurl.com/kqx8l9e		

APPENDIX F. **Price trajectories of 3D printers.**



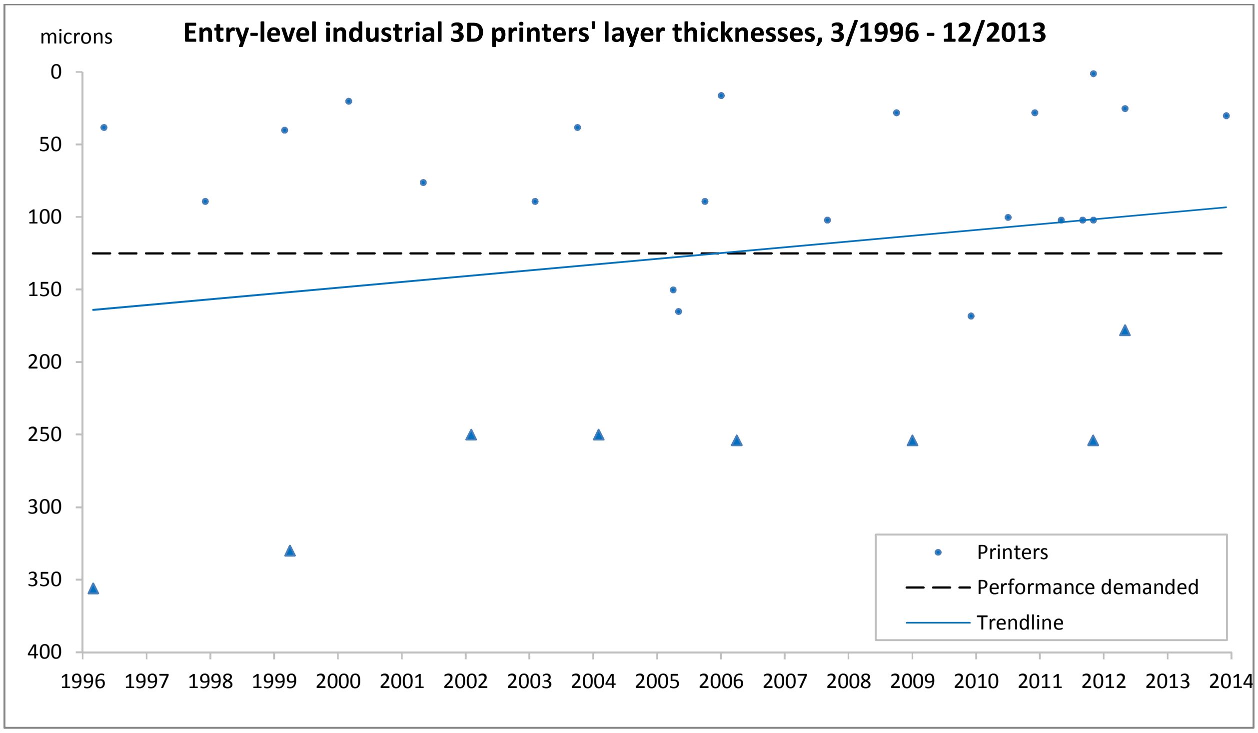


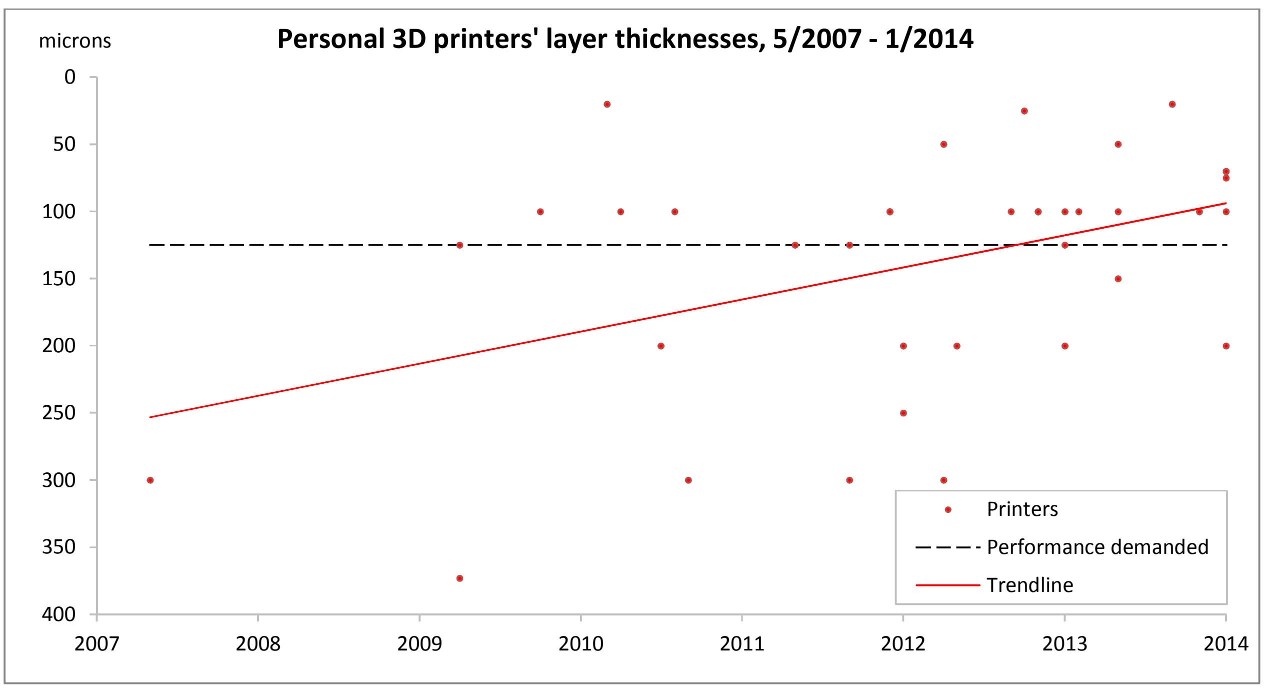
Notes:

Graph data from Appendices C and E. The same printer model may be included more than once, if it was subject to a price decrease. This occurred primarily in the industrial printers. Thus, the total number of observations does not equal the amount of printer models. The prices of personal printers have changed mostly in connection with newer product generations.

APPENDIX F (cont'd). Price trajectory chart.

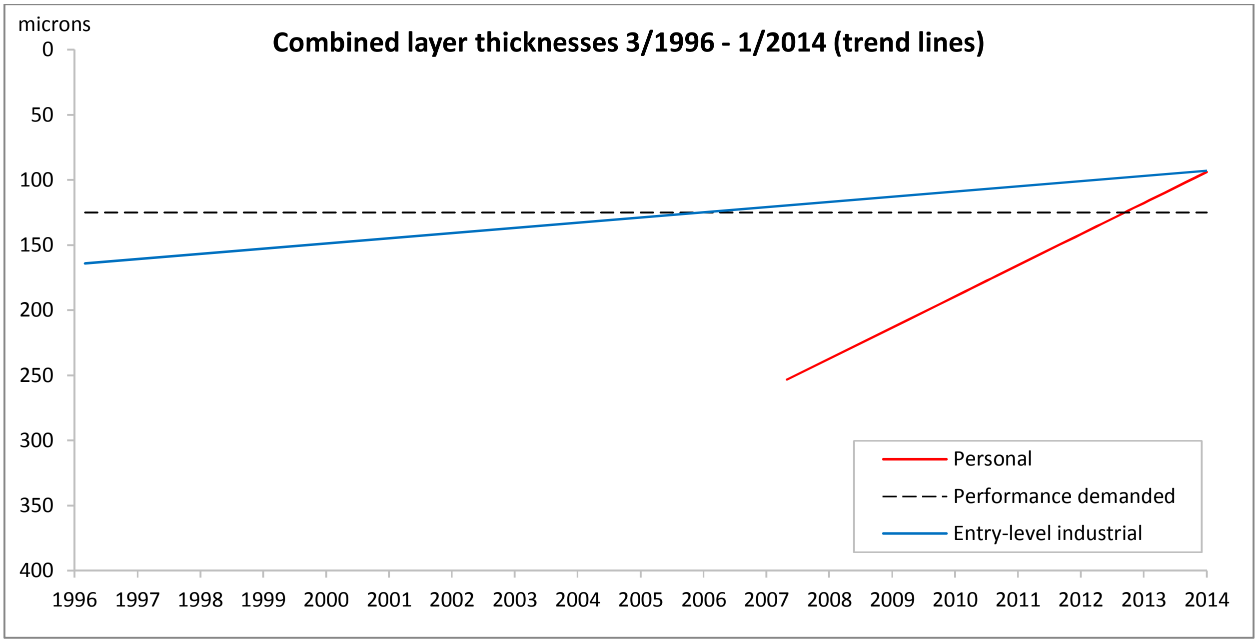
APPENDIX G. **Performance trajectories (layer thicknesses).**



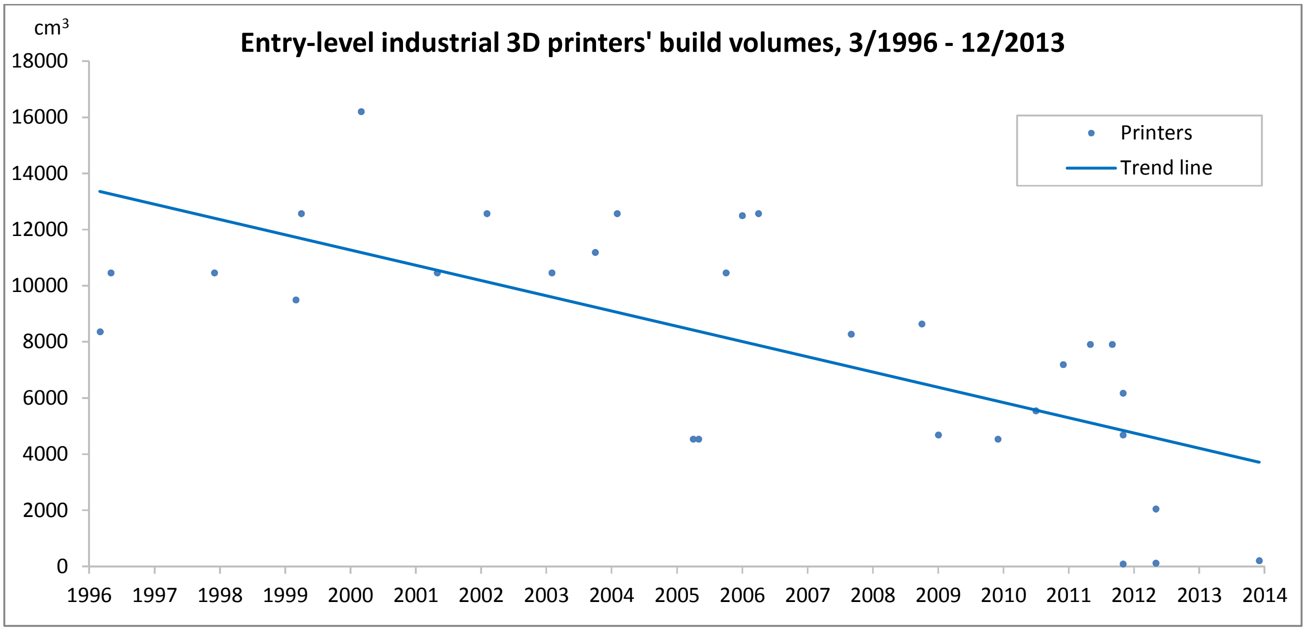


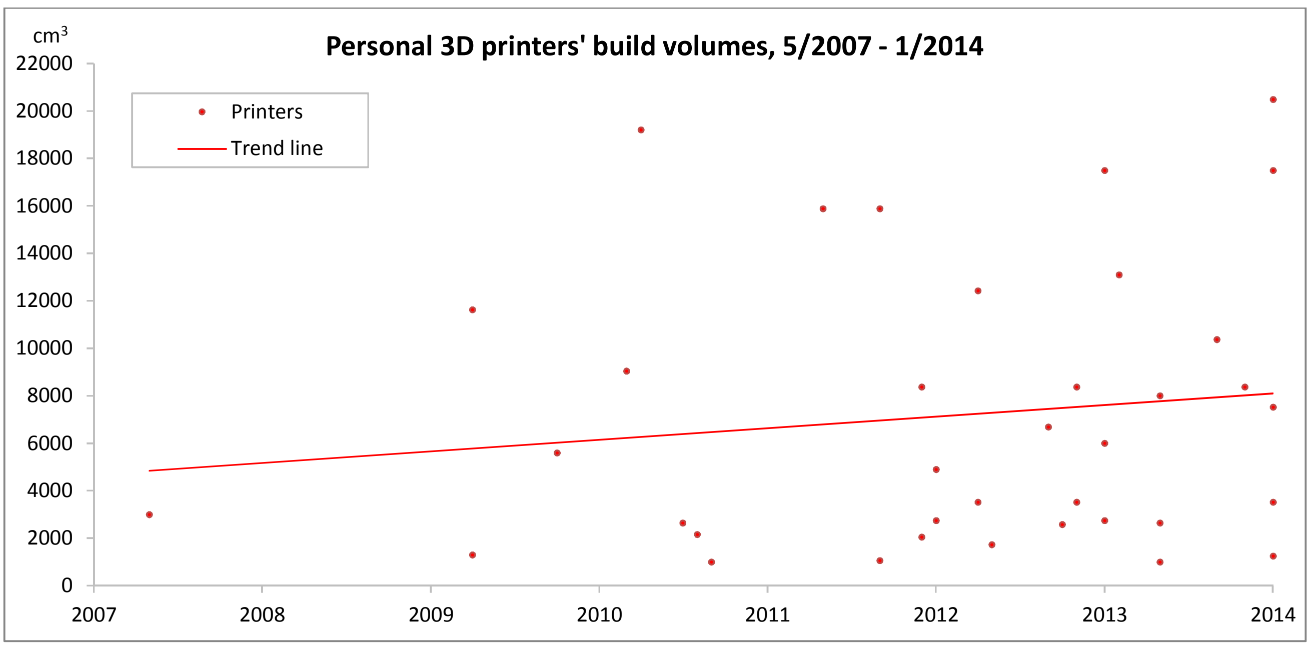
▲ FDM-printers by Stratasys

APPENDIX G (cont'd). Performance trajectory chart (build volume)



APPENDIX H. Performance trajectories (build volumes).





APPENDIX H (cont'd). **Performance trajectory chart (build volume)**