Exploring the coevolution of design and technology

Tim Schweisfurth, Frank Tietze, Cornelius Herstatt

Abstract

The importance of design for the success of product innovations has caught increasing attention of scholars lately (Rindova and Petkova, 2007, Verganti, 2008). Previous research is related to user-centered design (Brown, 2008, Veryzer and Borja de Mozota, 2005a), design contribution to NPD (Gemser and Leenders, 2001, Talke et al., 2009), or design-driven innovation (Dell'Era and Verganti, 2009, Verganti, 2009). Apart from few seminal contributions (Clark, 1985, Dell'Era and Verganti, 2007a, Walsh, 1996) research on product innovations has yet insufficiently investigated the relationship of functional (i.e. technology) and design dimensions (i.e. aesthetics, 'product language').

Drawing on the literature of dominant design (Abernathy and Utterback, 1978, Murmann and Frenken, 2006, Suárez and Utterback, 1995), technological evolution (Dosi, 1982, Iansiti and Khanna, 1995, Saviotti, 1996) and innovation in design (Borja de Mozota, 2003, Verganti, 2008) we suggest that product design innovations are related to technical innovation patterns and characteristics of technology trajectories. Hence, we explore the relationship of design and technological innovations throughout the evolution of product categories.

We argue that periods of incremental technical change trigger the cumulative development of design innovations, where both technology and design continue to develop along previously established trajectories. Contrarily, after periods of disruptive technical change that transform previously established product architectures into new industry standards, design innovation becomes increasingly important. Emerging dominant technological designs open opportunities for innovation in design and hence trigger periods where design features become essential for product diversification.

Our explorative study builds on two pairs of meso-level case studies. Both, the technical developments of loudspeakers (Borwick, 2001) and bicycles (Dowell, 2006, Dowell and Swaminathan, 2006) are characterized by incremental improvements where the products' architecture remained largely unchanged and thus product designs evolved along established paths. For instance, bicycles became stepwise equipped with increasingly complex suspension forks, gear systems and more efficient brakes but always maintained the 'original' product architecture. Similarly, the quality of loudspeakers has increased continuously while they became cheaper to manufacture due to stepwise enhanced membrane materials and constantly improved bandpass filters. On the contrary, technical developments of watches (Glasmeier, 1991) and cameras (Carranza, 2010, Chandy and Tellis, 2000) are characterized by major, disruptive technological changes altering the products' architecture that opened new design spaces for a variety of new product types. For instance, quartz watches allowed new designs due the replacement of mechanical clockworks. Also, the novel technical architecture of digital cameras enabled a range of new product designs (e.g. "ultra compact" or "prosumer" cameras).

For our analysis we employ US patent data from 1970 onwards, using utility patents as proxy for technological and design patents as proxy for design innovations. To validate our findings we deepen our analysis with expert interviews from each industry and archival data.

We contribute to previous research by deriving propositions on relationship of technology and design innovations. We propose that design innovation is stationary during eras of ferment, after technological discontinuities. Then, our findings suggest that the importance of design innovations increases strongly after the emergence of a dominant design, during the early stages of incremental change. In the later era of incremental change, we propose that incremental (cumulative) technology developments positively coevolve with continuous design developments.

1 Introduction

Within the field of research on product innovation, scholars have been mainly focusing on the application of technologies to provide new functions in products. This notion has changed increasingly with the last decade, where scholars started to point towards the significance of product appearance, shape and aesthetics as determinants for successful products (Bloch, 1995, Gemser and Leenders, 2001, Talke, Salomo, Wieringa and Lutz, 2009). These considerations towards the importance of industrial design support the view, that products generate value for users not only on the technological, functional level, but also on the level of product design, which can be regarded as the semantic dimension of products (Krippendorf, 1989, Verganti, 2009). We follow Verganti (2008, p. 440) in our notion of design, who points out that "design deals with the meanings that people give to products and with the messages and product languages that one can devise to convey that meaning". This definition does not only include the aesthetic, visual appearance of products, but also the symbolic and emotional implications of product design (Rindova and Petkova, 2007).[1]

There is growing evidence on the assertion that innovation may take place in technology (functions) and design (product language and meaning), and many authors have dismissed the view of design being a differentiator for industries in a late technological maturity state as onesided (Dell'Era et al., 2010, Hoegg and Alba, , Verganti, 2008), but plead for a continuous investment into design efforts throughout the whole product lifecycle (Gemser and Leenders, 2001). Yet, there exists few empirical evidence on the question, what dynamic relationships and cross-fertilization exist between technology and design throughout technology and industry lifecycle. We aim to shed light on this question and explore, how technological and design innovation relate and if there are patterns of coevolution between these two. We aim to contribute to the literature on innovation in industrial design and technological evolution - we establish an evolutionary view of industrial design, show how industrial design evolves contingent on the state of technology life cycle, and derive propositions about the coevolution of technology and design in different stages of the life cycle.

The remainder of this paper is organized as follows. In the next chapter we review the literature on evolution of technology, design, and the relationship between both. We identify a gap in the literature and present our research question. In the third section we explain the methods being employed. We then present our findings and condense them in form of propositions. We then discuss our outcome, derive managerial implications and conclude.

2 Literature Review

Technology evolution

As already emphasized by the notion of Kuhn (1962), where scientific progress is known to take a staged trajectory, technological development is commonly accepted to evolve along lifecycle (Brockhoff et al., 1991). There is consensus in the literature on the interpretation of S-shaped evolution of technological performance throughout lifecycle stages (Andersen, 1999). In the early lifecycle stage, fundamental scientific and technological problems are resolved that are associated with high R&D risk and technological uncertainty. For instance, emerging technologies are uncertain concerning their potential value and success (Dosi, 1982). With only a small number of pioneering firms willing to bear the high technological uncertainty, in such early stage, the number of patent applications is typically low, only slowly increasing but centered around a small number of firms. When the 'basic' technological and market uncertainties decay and a 'dominant design' has been established (Abernathy William and Clark, 1985), a broad range of market applications can be developed. A common prediction in the literature is that technological uncertainty decreases when a dominant design appears. Thus, in that stage, the R&D risk and technological uncertainty decreases while the number of patent applications increases which address predominantly small technical challenges resulting in incremental innovations. This argumentation was repeatedly supported by various scholars (e. g. Abernathy William and Clark, 1985, Dosi, 1982, Henderson and Clark, 1990, Tushman and Anderson, 1986, Utterback and Suarez, 1993). Hence, the developments along the life cycle stages can also be interpreted as a number of sequential incremental innovations building upon each other in a cumulative manner, hence for certain development paths or so called trajectories. Murmann and Frenken (2006: 944), referring to Sahal (1985), Dosi (1982)

[1] The plurivalent acceptation of "design" may lead to confusion. With innovation in design we mean innovation related to shape, meanings, product language or aesthetics, which is contrasted by innovation in technology, delivering new functionality. This risk of confusion is even more problematic when talking about dominant design and design spaces. In this paper dominant design relates to technology, whereas we use design space both in connection with technology and (industrial/product) design.

and Nelson and Winter (1982) highlighted that "most rapid improvements in technological history have typically taken place along well-defined technological trajectories".

Modern models of innovation thus acknowledge that innovation can be a cumulative process that builds upon previous discoveries (Gallini and Scotchmer, 2002) generating a continuum of improvements on some pioneer inventions (Aghion et al., 2001, Budd et al., 1993, Harris and Vickers, 1987, Knott and Posen, 2005, Merges and Nelson, 1990, Murray and O'Mahony, 2007, Scotchmer, 1991). For instance Rothwell (1994, p. 26) proposed an innovation process that "industrial innovation can be depicted as a process of know-how accumulation or learning process, involving elements of internal and external learning."

Murray and O'Mahony (2007) pointed out that the framework of cumulative innovation is particularly well suited, but not limited to knowledge-intensive fields with a distributed 'locus of innovation' such as software, biotechnology and creative industries (Powell et al., 1996). Recent evidence (Fleming, 2001, Garud and Karnøe, 2003, Katila and Ahuja, 2002) proves that innovations are, more often than not, cumulative to the extent they incorporate prior knowledge from multiple sources. Particular in the current evolution of high technologies almost all technical progress builds on a foundation provided by earlier innovators (Scotchmer, 1991).

While the discussion about path dependent, incremental innovations following trajectories was ongoing not the least until the late 1970s, innovation management literature has also focused on of disruptive innovation and discontinuous technologies (Anderson and Tushman, 1990, Christensen, 1997, Tushman and Rosenkopf, 1992). Disruptive innovations are understood as those which lead to a major divergence from established trajectories, also sometimes referred to as path-breaking innovations (Christensen et al., 2010). The emphasis on cumulative innovation may, at first glance, seem in contrast to the interpretation of the disruptive nature of innovation (Christensen, 1997) and radical innovations' contributions to progress. However, an innovation that accumulates disparate technologies from various sources may be as disruptive as an innovation that builds on a narrow stream of prior technologies and vice versa. Anderson and Tushman (1990) and Tushman and Anderson (1986) extend this view and propose a cyclical model of technological change, in which disruptive and incremental changes in technology alternate (see Figure 1).

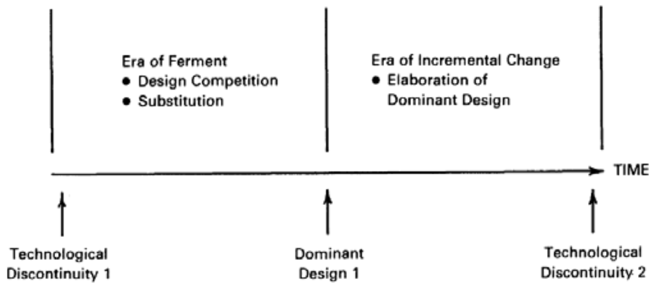

Figure 1: The technological cycle (Anderson and Tushman, 1990)

In this view, technological trajectories are disrupted by discontinuities, which are a singular, major advances in technology, impacting on product or processes within one industry. This disruption is followed by an "era of ferment", in which different variants of the new technology are proposed by firms, that compete with each other. This phase of variation ends with a dominant design, which becomes the prototypical, standard architecture of a product category (Abernathy and Utterback, 1978, Anderson and Tushman, 1990). With the emergence of a dominant design, technology enters an era of incremental change and technological progress takes little steps only until a new technological discontinuity hits the industry.

Design evolution

Whereas the evolution of technologies has been studies rather intense, findings on the evolution of design are still scarce. The notion that designs, like technologies, follow certain paths has been brought forward by Dell'Era and Verganti (2007b). They suggest that the evolution in design is coupled to the evolution of socio-cultural models, when it is incremental in nature (Verganti, 2008). Approaches like user-centered design help firms to elicit unmet and latent user needs and adapt existing design to these (Veryzer and Borja de Mozota, 2005b). These continuous innovations in meaning build on the original design and align it to socio-cultural developments. Like technologies, innovations in design travel certain trajectories of meaning. These findings are supported by psychological research, which suggests, that people prefer changes in design, that were not too far from existing prototypical design in an existing category (Hekkert et al., 2003), and thus are easier to make sense of when they build on known industrial designs. Mere exposure effects enforce this (Zajonc, 1968), as people tend to prefer those design, to which they have been exposed to before (Carbon et al., 2006). Dell'Era and Verganti (2007a) corroborate the evolutionary notion of design when they show that design innovation on industry level can also be assigned to early movers and imitators. Whereas the former proactively introduce innovation in product language, the latter tend to focus on certain product designs, which are emerging from markets. Yet the evolution of design does not seem to be as deterministic as technological evolution towards higher performance, but may also occur in recursive cycles, where certain designs come back after certain time and go through multiple life cycles (Cappetta et al., 2006, Christiansen et al.).

Cappetta et al. (2006) extend the idea of evolution of design on industry level, as they show that innovation in aesthetics and style also follows certain paradigms, where eras of ferment and eras of incremental innovation alternate. At end of eras of ferment, most companies converge on one style or design and only innovate in concordance with that design. This convergence in style leads to archetypical design, which is a concept analogous to the dominant design in technological development (Verganti, 2008). As counterpart to the continuous evolution of design described here, Verganti (2008) proposes the concept of radical innovation in design. Here, innovation in meanings is not derived from actual user need, but rather disrupts the socio-cultural regimes and environment in which users are located.

Concerning the interplay of technology and design, Verganti’s differentiation between innovation in function (technologies) and product language or meaning (design) and the respective degree of innovativeness (radical/incremental) was one of the first concepts to describe this relationship (Verganti, 2008). Verganti (2007a, p. 584) present three different scenarios: incremental innovation in design and radical innovation in technology, the opposite situation, and the case where “there is a strong interaction between the linguistic and technological dimensions that underlines reciprocal influences”. This argument relates to the notion, that technological developments can trigger new opportunities in design, and suggest that the evolution of design may be more dependent on the technological possibilities than the other way around. To explain, how the interplay between technology and design innovation creates user value (Rindova and Petkova, 2007) draw on cognitive theory. In order to resolve incongruities, which are caused by technological discontinuity in users’ mental frames, design should continue to be similar to the substituted product category. In case of incremental technological innovation, more advanced designs may differentiate themselves from existing products and trigger positive feelings (Hekkert, Snelders and Wieringen, 2003, Rindova and Petkova, 2007).

Despite these conceptual considerations towards the coevolution of design and technology on industry level, there hardly exists any empirical research in this field. Talke, Salomo, Wieringa and Lutz (2009) is a seminal exception, where the authors show how both design and technical newness contribute to product innovativeness. Interestingly, they find that design newness has a more sustainable effect on car sales than the effect of technology, which becomes relevant later in the lifecycle and lasts shorter. In terms of combined effects of design and technology they found no significant, but positive results.

In summary, there is a rather large body of literature available on technological evolution, which stands in contrast to little research on the evolution of design and even less empirical results with regard to the interplay of technology and design in industries. With our study we aim to contribute to addressing this gap and show, how innovation in design and innovation in technology are interrelated. Hence, our main research question reads: What are the patterns of technology and design coevolution in industries during different phases of technological change?

3 Methods

In order to investigate the research question we apply a comparative case study approach. As the research on design trajectories and their relationship to technological evolution is still in its infancy, this approach seems feasible and justifiable (Edmondson and McManus, 2007) and has been used by other scholars how explore similar phenomena (Schmoch, 2007). We compile four exploratory case studies from different industries. As our intention is to shed light on the question, how design trajectories behave in the wake of different phases of technological change, we chose to employ polar cases, where we expected the phenomena in focus to be clearly observable: both the technical developments of loudspeakers (Borwick, 2001) and bicycles (Dowell, 2006, Dowell and Swaminathan, 2006) are commonly agreed to be characterized by incremental improvements where the products' architecture remained largely unchanged and thus product designs evolved along established paths. On the contrary, technical developments of watches (Glasmeier, 1991) and cameras (Carranza, 2010, Chandy and Tellis, 2000) are commonly agreed to be characterized by major, disruptive technological changes altering the products' architecture that opened new design spaces for a variety of new product types.

Throughout this study we apply a sequential, two step research approach. In a first step, longitudinal patent data is compiled to illustrate technological developments (through utility patents) and design evolution (through design patents). In a second step, the findings are validated with complementary data obtained through expert interviews, which whom we discussed the plotted images of the technology and design development curves. The use of different sources of information also increases the validity of our findings by data triangulation (Denzin, 1989, Jick, 1979).

We use longitudinal US patent application data as proxy for industrial evolution. To proxy technology developments on industry level we used utility patents (Debackere et al., 2002, Schmookler, 1966). This procedure has been often used in research, but has been also critized for a number of reasons (Agarwal, 1998, Debackere, Verbeek, Luwel and Zimmermann, 2002). It has been argued that in different technology fields, industries and firms may differ in their patenting behaviors and cannot be compared directly. Also, not every patented invention leads to an innovation, which is introduced into markets, and not every marketed innovation is protected by a patent. Furthermore, it remains difficult to relate technologies directly to industries in which they are used. Yet various researchers point out that patents can – despite of the shortcomings - be regarded as valid indicators for technological change, as they are closely related to R&D output and are systematically available (Debackere, Verbeek, Luwel and Zimmermann, 2002).

Following the same logic we use design patents as proxy for innovation in design: design patents are IP rights that relate to ornamental appearance or form (Rademaker, 2000). They grant the right to its assignee to prevent "others from making, using, or selling the invention" (35 USC) and run 14 years. The requirements for patenting designs are novelty, originality, and ornamentality (35 USC 171). Unlike most other countries US law imposes similar standards on the application of design patents as on utility patents; as a consequence novelty examinations are also carried out for design patents in the USA. Due to the novel character of design patents and its focus on shape, form, and aesthetics we propose that – similar to the use of technological patents as proxy for technological activity – US design patents can be seen as proxy for innovative design activity of firms or industries.

One challenge that occurred during our study was that no direct concordance exists between utility and design patent classes. Yet we had to ensure, that both type of patents belong to the same type of product category or industry. We solved this problem by employing the USPT Classification Index, in which products and technologies are listed with their corresponding classes (both design and utility classification). We then filtered the patents using the index and excluded classes, which were obviously not fitting our industries. We then defined keywords for the industries we focused (title or abstract) and narrowed these down by the patent classes we extracted from the USPTC Index (keywords and classes are provided in Table 2 in the appendix). With both utility and design patents we searched for patents that were granted, but used the application date as measure for innovative activity in order to rule out the pendency (McGahan and Silverman, 2001). We used the USPTO database searching granted patents from 1970 until 2009. A summary of our dataset is depicted in Table 1.

	Utility patents	Design patents
Watch industry	2,518	2,961
Camera industry	11,008	1,849
Loudspeaker industry	4,192	2,054
Bicycle industry	6,518	1,352

Table 1: Summary of patent dataset

Our second data source is interviews with industry experts in the respective field. We conducted two such interviews per industry. These interviews had mainly the function to validate the correctness of conclusions, which we drew from the patent analysis. We confronted our interviewees with the patent analyses results. They helped us to align the data with respective historic events and technological or societal change. We also drew on them to clarify technical question we had.

Furthermore, we complemented the data with archival data in order to match patent evolution and historic events. We conducted a publication analysis and took scientific papers on the evolution and history of the respective industries into account. We also employed desk research and used magazines and online data (communities, fansites, etc.) from the respective industries. As all of our cases are consumer good settings in which users inform themselves about products, in all cases an array of archival data was available.

4 Findings

In this section we first provide a short historic summary of each industry with respect to changes in technology and design and link this historic analysis with the patent data. We then derive three propositions about the coevolution of technology and design, which built on the findings grounded in our cases. We align our patterns to Anderson and Tushman's (1990) model of technical change discussed above, who suggest a technology cycle of eras of ferment and eras of incremental change (see Figure 1).

Technological discontinuities and era of ferment

In the first half of the 20th century watches remained the technologically similar but experienced changes due to cultural and fashion trends. Before the beginning of the 20th century, mainly pocket watches were worn. During the course of WWI soldiers and pilots experienced wristwatches to be more convenient during battle and as a consequence wristwatches diffused to all parts of the society.[1]

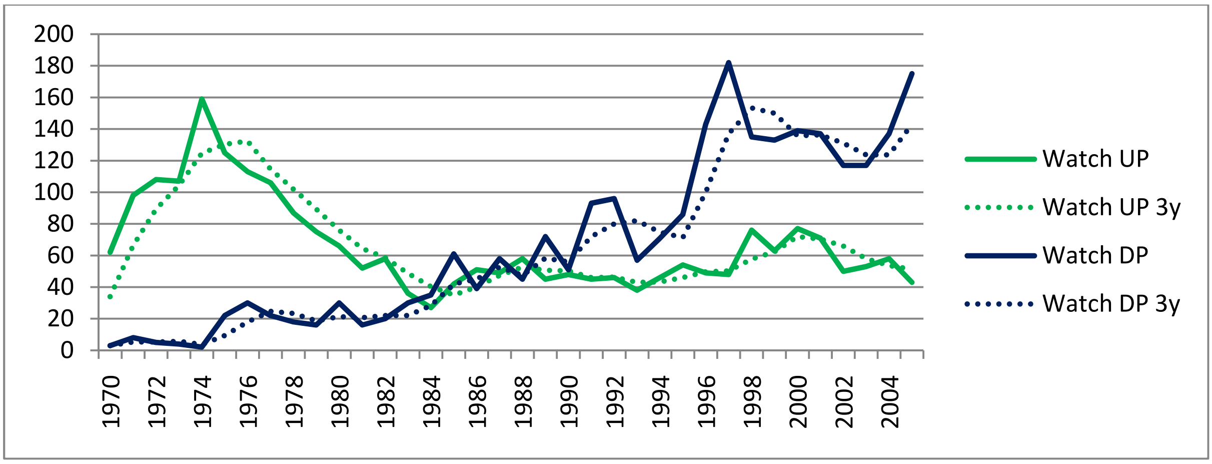

Figure 2: Evolution of technology (utility patents) and design (design patents) in the watch industry

Technologically, the main events of the history of the watchmaking industry in the 20th century are characterized by innovation in the field of electronics. Until the 1950, watches relied on mechanical functioning principals and were built of tiny metal parts. The accuracy of watches was largely dependant on the craftsmanship of the watchmaker, who had to carefully process the parts and assemble them

[1] This case draws heavily on the interviews conducted (industry experts), scientific publications (e.g. Glasmeier, 1991, Glasmeier, 1994, Numagami, 1996, Stephens and Dennis, 2000) and archival data

afterwards. In general all watches work on a similar principle and consist of a power supply, a part that oscillates regularly and a system to count and display those regular amplitudes.

The replacement of the mechanical working principle through electronics can be considered a disruptive technological change in watchmaking. The first of three major technological innovations that paved this avenue is the invention of the electrical watch. In this watch the spring coil and many parts of the escapement were replaced by an electric, battery-driven motor. These inventions demarcated a new boundary of miniaturization of electric motors and battery, but the accuracy of these watches was not much higher and did not deliver more benefits to the users than the mechanical watch. These first attempts to integrate electronic working principles into the watch were carried out jointly by the watchmaker companies Elgin Watch (USA) and Lip (France). The second major invention towards electronic watches was the electromechanical tuning fork watch and can be regarded as the Swiss answer to the Elgin-Lip innovation. It was invented by a Swiss engineer on behalf of Max Hetzel (Bulova Accutron). In this watch type two inductor coils are powered by a battery and stimulate the oscillation of a tuning fork. These oscillations are transferred to an index wheel which turns the gear train. Due to its high frequency the tuning fork watch is approximately ten times more accurate than good mechanical watches. The third and most radical innovation is the invention of the quartz watch that completes the transformation from mechanics to electronics. However, it hardly can be traced back to a single firm or inventor, as many firms experimented with quartz technology – the first company to bring a quartz watch to market was Seiko in 1969. Quartz watches rely on the fact that quartz crystals oscillate at a very high rate when being exposed to electric current. These vibrations are counted and transferred to a display by electronic circuits. A major benefit of the quartz watch is its accuracy as opposed to mechanical watches. Combined with new developments in the production of quartz crystals and circuits in the early 1970s these watches were also cheaper than their mechanical counterparts. Aside from providing higher accuracy and more functions at a lower price, quartz technology allowed the use of different display types, which opened many possibilities to alteration of the exterior appearance of watches: in addition to displaying the time with analog hands, LCD and LED technology enabled new possibilities in design. Also, miniaturization of batteries and the quartz workings opened new degrees of freedom in design.

The advent of the quartz technology altered the watchmaking industry in a severe way. Many of the traditional watchmakers were driven out of the market as they could not compete with the low prices of quartz watches, and could not embark on the new technology either. Price competition even increased as large electronic companied entered the market, drawing on their existing expertise in circuit design and semiconductors.

The advent of the quartz technology in the 1970 can be regarded as technological discontinuity for the watch industry. As we can observe in Figure 2, a steep increase in technological innovation starts at this point, peaks in the middle and decreases towards the end. This technological variety can be regarded as the era of ferment, where different versions of functioning principles and display types competed. During this time period design innovations stay more or less at the same level.

A similar development pattern can be observed in the camera industry, which also underwent a radical technology change. Until the end of the 20th century the photography industry was based on chemical, analog printing technologies. From the 1980s onwards, the industry however went through a disruptive change when the basic principle of photography made a transition towards digital technology.[1]

In a first period from the mid 1980s to the early 1990s most of the established players in the photography industry made a number of basic technological developments that laid the foundation for the industry's transition. For instance, Polaroid developed sophisticated technical capabilities in a number of areas related to digital imaging by the end of 1989. Whereas the percentage of the firm's patents related to electronics between 1976 and 1980 was only 6 percent, between 1986 and 1990 that had increased to 28 percent. Polaroid participated in initial developments of the digital sensor. Polaroid's sensors were for instance able to produce a resolution of 1.9 million pixels when the majority of the competition had sensors that generated only 480,000 pixels. Polaroid was well positioned by 1989 to develop digital

[1] This case draws heavily on the interviews conducted (professional photographer, industry expert), scientific publications (e.g. Benner, 2010, Benner and Tripsas, 2010, Gavetti, 2005, Morozov and Morris, 2009, Tripsas and Gavetti, 2000) and archival data

cameras. Also, Eastman Kodak was an early leader in high end sensor technology. The first digital camera was developed inside Kodak in 1982. However, despite employing the engineer who invented the first digital camera (patented in 1978) and holding more than 1,000 digital-imaging patents, Kodak did not introduce a digital camera to consumers until 2001. The digital cameras introduced in the mid-1980’s were mainly studio and professional cameras that resembled scanners, and were produced and sold primarily by graphic arts firms that did not enter consumer digital photography later on.

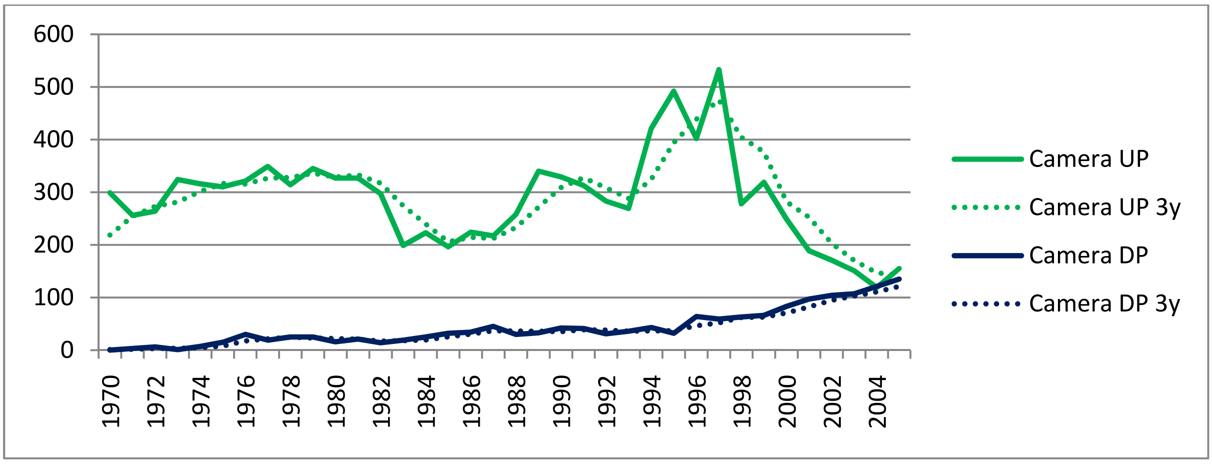

Figure 3: Evolution of technology (utility patents) and design (design patents) in the camera industry

In the early 1990s, different firms started to offer digital mass-market cameras to consumers. The first consumer digital camera was available in the US in 1991. It was a non-color grayscale camera with 90,240 pixel that could store 32 images in internal memory. In 1994, Eastman Kodak introduced the “Quicktech” camera jointly developed with Apple. In 1995 Nikon introduced the first digital SLS camera (E2) with the senor being developed by Fuji. In 1997, the Coolpix series was introduced by Nikon after which sales of digital cameras started to raise and the technology started to develop rapidly. By 1996, there were over 40 firms on the market selling digital cameras.

It however took until 1999 that a first camera incorporated all elements of a dominant design although individual features were introduced earlier. Until 2002 non-SLR cameras already coalesced on the dominant design but just in 2004 the dominant design was solidified with over 50% of new models incorporating all of its elements.

Since the mid 2000s the application portfolio of digital cameras broadened beyond traditional photography cameras. After 2002, the first mobile phone cameras were introduced in the US. In 2006, Nokia offered a mobile phone model with an integrated three-mega pixel camera. In January 2006, Kodak announced a 10-year partnership with Motorola to develop mobile camera phones with Kodak sensors. By 2009, nearly 70% of mobile phones contained cameras with multi-mega pixel resolutions.

By the end of 2003, digital cameras began to outsell film cameras for the first time in the United States. In the early years of the new century, camera manufacturers also stopped production of analog cameras. For instance, Nikon stopped making most of its traditional film cameras in early 2006. The industry transformation was so huge that even some traditional firms had to exit the industry not having successfully managed the transformation to the new digital paradigm. For instance, in 2006, Konica Minolta announced their withdrawal from the photography industry despite having been the third-largest producer of traditional photo film. Other traditional camera companies, such as Canon, thrived in the new digital world.

In 2006, signs indicated that the digital camera market was maturing. After growing almost 670% from 2000-2005, unit sales of digital cameras slowed down to an increase of only 26% in 2009. Canon became the world leader in digital cameras with an almost 19% share in 2006. In 2007, Nikon, Sony and Panasonic dominated the market for low-cost digital SLRs. In 2008, Kodak's announced that it has successfully transformed into a digital photography firm after immense strategic attempts initiated in 2003.

To summarize, from the early 1990s to the end of the 2000s the photography industry underwent a radical change through the technology disruption from an analog trajectory towards digital cameras. The disruptive change towards digital photography proved challenging for various 'traditional' camera makers. Some firms like Nikon and Eastman Kodak have survived the transition, but only with considerable investments. For instance, Estman Kodak had invested $4 billion' into digital research and related technologies since the early 1990's. However, other firms like Polaroid and Konica Minolta had to exit the industry.

Like in the watch industry, we can observe a disruption in the camera industry in the beginning of the 1990s. Here the era of ferment lasted 10 years as well, and ended with the emergence of the dominant digital camera design 1999. Here we also observe a strong technological cycle, but a rather unchanged activity in design patents. We formalize these observations in Proposition 1:

> *In the era of ferment, innovation in design is stationary, whereas technology has one boom cycle.*

Era of incremental change

The emergence of a dominant design marks the start of the era of incremental technological change. In the case of the watch industry technological innovation stayed at a similar level in the first years of such phase. However, we observe that design innovations start to grow coincidentally with the emergence of a dominant design with respect to the functioning principles itself (quartz), but also in terms of new possibilities to display time (LCD displays defeat LED technology) around 1980. At that time, technological innovations retreated into the background, but the new design possibilities still influenced the industry. In terms of mechanical watches many companies disappeared and industry changed structurally - one example is the establishment of clusters or consortia like in Switzerland, where one major supplier for clockworks emerged, who delivered to the whole industry. In concequence, various firms started to focus on design aspects to differentiate themselves from competitors. One reason for this development was, that the firms, that were still using mechanical clockworks had to create customer value in a different way than accuracy, hence decided to focus on new design. On the other hand the quartz technology opened new possibilities and industrial design spaces for firms, as watches could be built smaller and more versatile. One company that profited from these developments was Swatch, whose selling proposition was very much focused on different designs. We observe the growing importance of design in contrast to technological innovation in the early years after the emergence of a dominant design in the watch industry from 1980 until 1997. Thus we formalize Proposition 2:

> *In the first period of the era of incremental change, innovation in design starts to grow, whereas innovation in technology remains stationary.*

In the following we turn to industries, in which we observe various incremental changes instead of radical, disruptive changes leading to major industry transformations. We focus on the loudspeaker (see Figure 4) and the bicycle industry (see Figure 5).

The birth of the speaker industry coincided with the establishment of the phone: Werner von Siemens developed a moving coil transducer, which was then adapted by Alexander Bell and Johann Reis in their telephones in the late 19th century. In the early 1900s, loudspeakers were mainly used for speech reinforcement, as the bandwidth was limited and music needed a broader spectrum of frequencies.[1]

In 1925, the first electrodynamic speaker was developed by Edward Kellog and Chester Rice to overcome the drawbacks of existing loudspeakers. The inventors managed now to reproduce lower frequencies as their speaker was based on the principle of electromagnetics. This leap in technology allowed the reinforcement of a larger spectrum of frequencies and more powerful amplification. Following these developments helped to bring loudspeaker technology into peoples' homes for listening to music. The engineering design of the Kellog-Rice direct-radiator loudspeaker can be regarded as the ancestor of speakers still today. There are some different functioning principles (like electrostatic, ribbon, and

[1] This case draws heavily on the interviews conducted (CEO loudspeaker company, industry expert), scientific publications (e.g. Augspurger, 1985, Blesser and Pilkington, 2000, Eargle and Gander, 2004, Gander, 1998) and archival data

plasma speakers), but the technology of most speakers can be traced back to the 1925 invention by Kellog and Rice. Even if most disciplines of the audio industry experienced severe technological changes (especially with respect to different sound storing media), the development of speakers evolved rather predictable. Developments came not only from technology, but were also driven by applications and developments in adjacent fields.

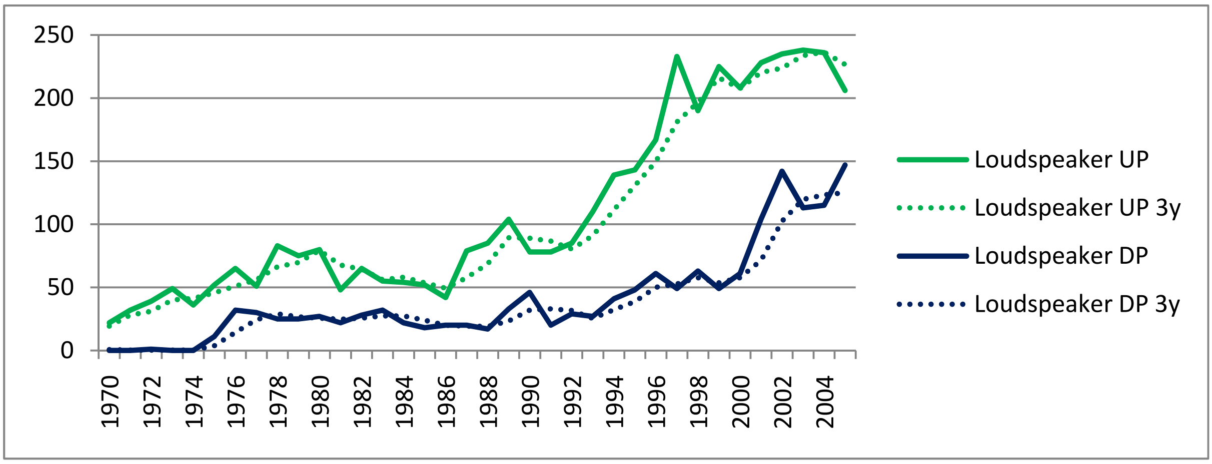

Figure 4: Evolution of technology (utility patents) and design (design patents) in the loudspeaker industry

In the 30s and 40s movie theaters and home speaker drove the development. This required optimization of loudspeakers in connection with quality and also exterior shape which was made possible the work of Albert N. Thiele and Richard N. Small, who explored the dynamics of the speaker itself and the enclosure. This resulting trend of developing loudspeakers focusing on small studios and homes lasted until the seventies.

In the ten years following 1970 some efforts were undertaken in the loudspeaker industry to optimize the sound of speakers using scientific methods, by focusing on the reflections inside the cabinet and measuring the performance of loudspeakers, which also offered new implications for the industrial design of speakers. Advances in circuit design led to more sophisticated development of electronic crossover and bandpass filters, which optimized the channeling of higher frequencies to the tweeter and lower frequencies to the woofer. This scientific and measurement boom is reflected in the patent increase during the seventies.

In the latter half of the 20th century, development of loudspeakers was especially driven by development in ICT. On the demand side, the shift from analogue technology to digital technology was especially coupled to the recording medium. CD and latter DVDs displaced cassette and records as sound carriers and posed higher challenges to speakers with respect to sound quality.

On the supply side, the computerization enabled a much more sophisticated, computerized approach to loudspeaker (engineering) design: The usage of finite elements methods, simulations and other computer aided design methods led to new circuit designs, which furthered the avenues of development laid out in the seventies. Another force which added to the increase in new designs came from the introduction of new materials in the speaker itself, where cones where shapes of titan, beryllium, or aluminum. These innovations, in turn, opened new possibilities and triggered industrial design activities, which is represented in a increase of both technology and design activities with the beginning of the internet age in the nineties.

Similar to the development pattern observed for loudspeakers, a similar coevolution can also be observed in the bike industry, which was also affected by incremental technological change.[1]

Since the invention of the "running machine" by Baron von Drais in Germany in 1817 the bicycle technology and design was further developed, mainly continuously. Through several development stages the "running machine" evolved and around the beginning of the 20th century, the bike architecture and

[1] This case draws heavily on the interviews conducted (CEO biking company, industry expert), scientific publications (e.g. Dowell, 2006, Dowell and Swaminathan, 2006, Lüthje et al., 2005, Pinch and Bijker, 1984) and archival data

design started to appear essentially similar to today's appearance - the dominant design emerged in the form of the pneumatic safety bicycle at the end of the 19th century.

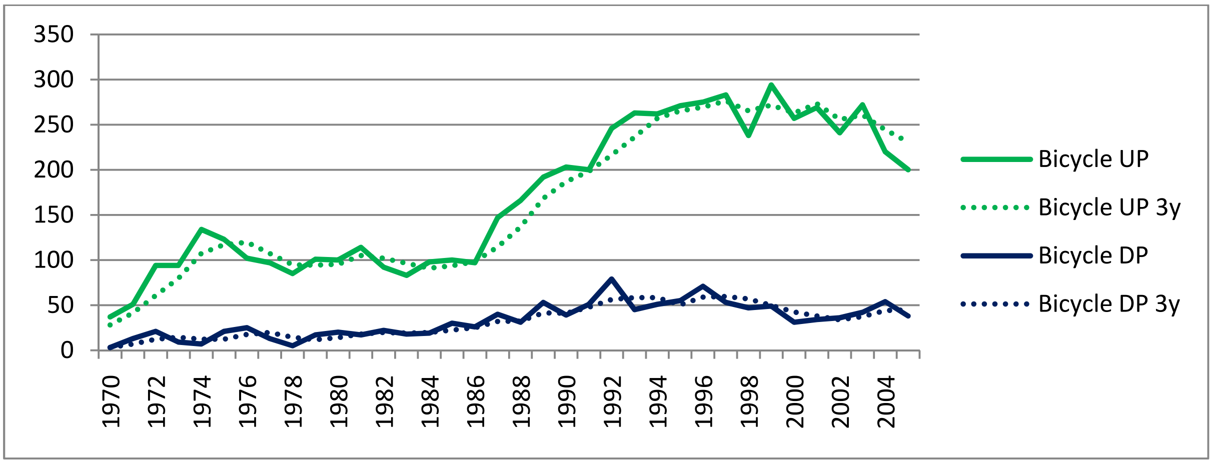

Figure 5: Evolution of technology (utility patents) and design (design patents) in the bicycle industry

Following essential developments of the bicycle in the 19th century, the subsequent technological developments in the 20th century "were confined to "tweaking" of details, rather than overall redesign of the machine as a whole" (van der Plas and Baird, 2010: 16). In the second half of the 20th century however several incremental innovation "waves" appeared particularly related to the introduction of the mountain bike. These developments are well reflected in the development of annual patent applications as depicted in Figure 5. During these technical developments the basic architectural design of the bike did not change dramatically but was rather adjusted as innovations took place along the components and subsystems.

In 1973, the mountain bike was invented in Mount Tamalpais in Marin County, California, USA. While the early version of the mountain bike was based on a tradition bike type used in the 1930s (the "Schwinn Cruiser"), the first mountain bike with a similar architecture as known today was produced by Joe Breeze in 1977. The first mass production mountain bike was marketed under the name "Stumpjumper" manufactured by the company Specialized, first produced in 1981. In the following years the mountain bike segment developed from a user driven niche market to a mass market, in which it was fully integrated by the mid-1980s(Lüthje, Herstatt and Hippel, 2005)(Lüthje, Herstatt and Hippel, 2005)(Lüthje, Herstatt and Hippel, 2005)(Lüthje, Herstatt and Hippel, 2005). Today, most of the early mountain bike manufacturers who emerged around the early user groups have vanished. The increased number of annual patent applications depicted in Figure 5 appears associated mainly with technological development of the mountain bike and subsequently triggered developments primarily associated with five component sets.

According to (van der Plas and Baird, 2010) "perhaps the most important innovation during this time has been the introduction, and perfection, of gearing systems." In 1982 the Japanese component manufacturer Shimano introduced the first full gearing system dedicated to mountain bikes ("Deore"). after initial applications in the late 1970s Shimano also turned out to become by far the largest patent applicant in the US accounting for 18.37% of all applications in our dataset, with aggressive incremental development activities focused on various bicycle components, particularly gear shifts and brakes. In the 1980s also new firms emerged manufacturing gearing components such as SRAM who introduced the Grip Shift (or twist shift) gear-change method and technology to the mountain bike market in 1988.

Another innovation wave of incremental innovations started related to the material choice for the bicycle frame. In 1975 the first carbon-tubed, metal lugged frame appeared, the "Exxon Graftek". In 1976 the first aluminum frame bike was introduced by "Kettler" in Germany. After initial failures to reap the benefits from aluminum frames in contrast to softer steal frames, the technology was further developed and successfully introduced by Look, Trek and others. The experiments with new frame materials continued in the following years. In 1986, in the USA Kestrel introduced a non-lugged, carbon fiber frame and Trek

launched a first lugged carbon frame. In the following years, aluminum frames increasingly substituted steel frames in the mountain bike mass market while carbon frames still remain to be preferably used in the high-end market segment.
When the frames were increasingly manufactured from aluminum and carbon, because of more favorable weight and torsion properties, new problems emerged. The highly stiff and lightweight frames were too stiff to be effectively used in downhill racing. Not the least, as reaction to this problem, suspension forks were developed. Although suspension forks were known for bikes already since the introduction of the "Niederrad" introduced at the late 19th, early the 20th century, in 1989 suspension forks were developed in parallel by Paul Turner (Rock Shox, North Carolina, USA) and Doug Bradbury (Manitou). While early suspension forks were developed for the front wheel, with the introduction of full suspension bikes as early as in 1991, the design changed to some extent. The invention of suspension forks, which became subsequently popular in the mass market, gave birth to new firms such as Rock Shox throughout the 1990s. After initial experiments with full suspension bikes in 1988 manufacturers introduced the first models at the Eurobike fair in 1991. From these years on, full suspension became a trend throughout the 1990s and early 2000s.
Meanwhile, in 1984, another innovation had been introduced by the French company LOOK, originally a ski equipment manufacturer. LOOK introduced the clip-less pedal applying downhill snow skiing binding or cleat technology to bicycle pedals. Also Shimano started to develop pedal systems. Whereas LOOK cleats were large and protrude from the sole of the shoe, Shimano cleats were small and could be fitted in a recess in the sole, making it possible for walking. In the following years, various other manufacturers started to produce own designs of clipless pedal systems, most notably Crank Brothers, BeBop, Coombe, Speedplay, and Time.
Another series of incremental innovations emerged with respect to brakes, after the company Magura introduced the first hydraulic caliper brake system in 1987, and Shimano followed with an introduction of integrated brake/gear levers. In 1994, the USA division of Sachs (SRAM) introduced the first mass-produced hydraulic disc brake system. While still most inexpensive department store-style mountain bikes often use regular V-brakes, most higher-end mountain bikes produced since the mid-2000s use disc brakes.
Comparing the evolution of the biking and the loudspeaker industry, we observe strong similarities. In the loudspeaker industry, we find that technology and design coevolve among the same paths, yet at a different level. Technology has not changed in a discontinuous way since the emergence of the dominant design in the 1920s. We observe a similar continuous coevolution in the biking industry, where the dominant design emerged at the end of the 19th century already, and innovation mainly took place on component level, both in technology and aesthetics. Taking these considerations into account, we can derive proposition (3):

> *In the second phase of the era of incremental change, technology and design coevolute on parallel trajectories.*

5 Discussion

Based on patent data complemented with expert interviews and archival data, our findings suggest that the coevolution of technology and design on industry level is dependent on the respective state of technological evolution. In the following paragraphs we discuss our findings and explain how they are aligned with existing research.

Era of ferment: technological change and stationary design

Our first proposition suggests, that in one industry during the era of ferment, technological activities boom, whereas the innovation in design stays at a stationary level. This can be partly explained with the focus of all corporate actors on technology development, as the preceding technological discontinuity triggers a technological competition for the dominant design within the industry - this includes both the new entrants and incumbents. New entrants enter the industry attempting to use their technological competence to establish a dominant design, like electronic firms in the case of the watch and the camera industry. These companies have technological competences, which needs to adapted to a new context and added to the technological activity in the industry. Yet, they do not have knowledge about users' preferences within the new industry and neglect the adaptation of their products and technologies to socio-cultural needs and existing usage schemes (designs). However, innovation in design is also not being pursued by incumbents, who have established knowledge with respect to socio-cultural evolutions in their customer field. In the era of ferment, these companies try to improve their technological efficiency, in order to keep it capable of competing with the breakthrough technology, which threatens to substitute their own one.

The stagnation of innovation in design during radical technological change can also be explained by focusing on users' and corporate cognition (Rindova and Petkova, 2007). People are accustomed to products from a certain product category in terms of technology and design. Over time, mindsets and frames emerge that make sense of products and the functionalities and semantics they stand for. Any innovation poses a challenge for these established frames and calls for a new interpretation and sense-making (Kaplan and Tripsas, 2008, Weick, 1995). Times of radical technological change pose a severe challenge to these framing processes.

As discontinuous technologies offer new functionalities and possibilities, users need to build new knowledge and frames to understand these changes (Veryzer, 2005). Former schemes employed to make sense of technology cannot be employed any longer, and incongruities within these schemes result in strong (negative) feelings towards product relying on a new technology (Rindova and Petkova, 2007). One mean to resolve these incongruities is to keep the industrial design similar to known products from a category, even if the underlying functioning principles and technologies change drastically (Moreau et al., 2001). That way, users rather have to extend than change their interpretation schemes. Even if the new technology outperform the previously existing one, users of that technology can get accustomed to new functionalities easier, and cognitive frames and schemes for that technology are adapted and build. Yet these processes are rather cognitively challenging and sophisticated, so that exposing users to radical technologies and changing the product design, language and meanings at the same time, may overburden users. As soon as the cognitive framing and sense making of technology has proceeded, users are ready for innovation in design and the resulting incongruities in product semantics (see the phase of stationary technology and rising design).

Next to the users, corporate actors are also affected cognitively by radical technology change. Incumbents that are on a certain technology trajectory are overthrown by the advent of a technological discontinuity. Hence, they keep on designing products how they used to, both in connection to technology and industrial design. New entrants who possess sufficient knowledge about the new technology are also involved in cognitive transitions as they need to adapt their preexisting assumptions on the delivered user benefit, as the technology interpretation process is in progress (Orlikowski, 1992) and user preferences are ambiguous (Kaplan and Tripsas, 2008). Due to these challenges most of the attention and cognitive resources of corporate actors will be rather allocated to technology than on industrial design.

Era of incremental change: stationary technology, catching up of design and coevolution of design and technology

After the emergence of a dominant design commonly an era of incremental change follows. We propose to distinguish two different phases. In the first phase, technology development activity stays at a low level, whereas importance of design innovation grows. In the second phase, technology and design innovations coevolve along parallel trajectories.

The first phenomenon can be explained theoretically by two mechanisms. On the one hand, new radical technology may open up new design spaces with regard to industrial design (Baldwin and Clark, 2000). Whereas the exploration of the technological design space comes to a closure with the emergence of a dominant design (Baldwin et al., 2006, Pinch and Bijker, 1984), a new technological functioning principle triggers new opportunities with respect to innovation in meaning. For instance, in the case of watches, the quartz technologies enabled many new opportunities with regard to form and shape of watches, as many parts that needed to be embodied in the watch became redundant. This new design space with respect to meaning needs to be explored by firms, who in turn increase their investment in innovation in design. The growing importance of design in relation to technology may be enforced by the emergence of a dominant design. Those firms, who rely on the technology embodied in the dominant design need to invest in design to help users switching to a new cognitive frame, which is inclined with the newly emerged dominant design, and helps them to make sense of it. Companies, that have lost the technology race, and are still stuck with the old technology, also increasingly invest in design, as the technology embodied in their products cannot compete with the discontinuous functioning principle. Thus, they fully have to focus on innovation in meaning to deliver value to users by satisfying needs related socio-cultural shifts. Additionally, innovation in product form may evoke perceptions of high functional performance with users (Hoegg and Alba, 2011).

The second phase is the coevolution of technology and design during the interplay of design and technology in the era of incremental change. This phase starts, when the new, pure industrial design possibilities of the technology have been exhausted and the design space of industrial design has been mined out. Innovation switches back to development of functions based on incremental change of technology. These micro-innovations of technology often take place at a lower hierarchical level than the functional principal itself (Clark, 1985), and in turn open space for small innovations in meaning. For instance, in the biking industry, functional innovations were mainly occurring at component level in the late era of incremental change, which triggered new design on that level as well.

Cognitively speaking, rather than switching mental frames, both corporate actors and user can extend their interpretation schemes with respect to technology and design. In most cases firms will try to adapt their design incrementally as well. This can be traced to cognitive characteristics of users. Advances in technology need to be communicated to user, so that they realize, use and understand the benefits of a new technology. Innovation in design then follows technological change to deliver meanings of technology to the users. Additionally new design may raise user attention and stimulate positive emotions towards technological innovations (Rafaeli and Vilnai-Yavetz, 2004). However, users tend to like those designs best, that are not too advanced. Similar to technology, radical deviance from known, prototypical aesthetics may result in incongruities with users' aesthetic preferences (Carbon, Hutzler and Minge, 2006, Rindova and Petkova, 2007). These considerations add to the explanation of why designs coevolve with technological incremental change.

6 Implications for management and conclusion

The managerial implications that can be derived from this study built on the notion that industrial design and innovation in meaning should be regarded as a strategic, additional layer of innovation in addition to traditional technological innovation. Technological and design innovations can exist independently from each other, but also be related and interwoven as in the cases presented in this paper. Especially the view, that design only plays a role in mature industries as a late differentiator should be abandoned. Rather, we propose that design should be managed contingent on the technological phase of a certain industry. Our findings can give guidance with respect to the question, at which point in time resources should be allocated to technology or design development. Especially in the phase of ferment, firms are mainly involved in technological innovation and design plays an inferior role. However, we propose, that this role changes as soon as a dominant design emerges. Thus managers have to prepare for this change from technology to design innovation early in time in order to take a leading position in the following era of ferment. Yet, after the emergence of a dominant design, design becomes increasingly important, as innovations in meaning have to catch up with the new opportunities, which have been furthered by the foregoing technological disruption. Here, managers need to mine out the opened up design spaces and focus on those industrial designs, which communicate the value of the newly established technology to the users.

As soon as the industrial design space is mined out, and innovation switches to incremental technological change again, incremental advances in technology need to be communicated to the users by innovations in product language in meaning.

The interplay of technology and design may help managers to innovate at a constant level and reach customer attention by continuously penetrating the market with new product introductions. When the technological situation is either uncertain, or a dominant design has established, managers can use innovation in design to keep the customers' attention up and differentiate from competitors. Vice versa, when most competitors focus on design innovation, new introduction of technology may help to compete in saturated markets.

In order to keep track of the innovation cycles in meanings firms should, like with technology, install strategic tools to track and monitor the evolution of industrial design in their respective industry. Design patents seem to be a suitable data source for assessing innovation and industrial change with regard to industrial design activity. Especially, the combination with utility patents can be a feasible means to track the coevolution of design and technology. These foresight mechanisms help to carve out design trajectories and locate the industry's position within design and (technology) life cycles. Especially in our case, where technology and design evolution are interrelated, this information can be used to support strategic decision making, e.g. in respect to resource allocation to either technology or design development.

To conclude, we suggest that innovation in design, like technology, follows certain trajectories. We present early evidence that the evolution of technology and design are not independent on industry level, but show specific pattern contingent on the phase of the technology life cycle. This deepens the notion that design should be regarded as important and strategic factor in the management of innovation.

Future research may focus on the question, how exactly technology and design stimulate each other on micro level, i. e. within certain firms or projects, and how firms manage trade-offs between investing in design or technology.

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8 Appendix

Industry	Keywords	US Classification	Search Syntax
Watches Technology	Watch	metal working horology chain, staple, and horseshoe making jewelry package and article carriers horology: time measuring systems or devices brushing, scrubbing, and general cleaning geometrical instruments illumination supports measuring and testing tools compound tools special receptacle or package	(TTL/watch OR ABST/watch) AND (CCL/29 OR CCL/968 OR CCL/59 OR CCL/63 OR CCL/224 OR CCL/368 OR CCL/15 OR CCL/33 OR CCL/362 OR CCL/248 OR CCL/73 OR CCL/81 OR CCL/7 0R CCL/206)
Watches Design	Watch	measuring, testing, or signalling instruments jewelry, symbolic insignia, and ornaments	(TTL/watch OR ABST/watch) AND (CCL/D10 OR CCL/D11)
Cameras Technology	Camera	photography optics: measuring and testing	(TTL/camera OR ABST/camera) NOT (video OR surveillance) AND (CCL/396 OR CCL/356)
Cameras Design	Camera	Photography and optical equipment	(TTL/camera OR ABST/camera) NOT (video OR surveillance) AND (CCL/D16)
Loudspeakers Technology	Loudspeaker Speaker	electrical audio signal processing systems and devices	(TTL/loudspeaker OR ABST/loudspeaker OR TTL/speaker OR ABST/speaker) AND CCL/381
Loudspeakers Design	Loudspeaker Speaker	recording, communication, or information retrieval equipment	(TTL/loudspeaker OR ABST/loudspeaker OR TTL/speaker OR ABST/speaker) AND CCL/D14
Bicycle Technology	Bicycle Bike	signals and indicators brakes clutches and power-stop control tent, canopy, umbrella, or cane supports: racks land vehicles package and article carriers metal working chairs and seats land vehicles: wheels and axles electrical generator or motor structure electric lamp and discharge devices: systems electricity: single generator systems communications: electrical optical: systems and elements illumination bearings exercise devices locks machine element or mechanism	(TTL/bicycle OR TTL/bike OR ABST/bicycle OR ABST/bike) AND (CCL/116 OR CCL/188 CCL/192 OR CCL/135 OR CCL/211 OR CCL/280 OR CCL/224 OR CCL/29 OR CCL/297 OR CCL/301 OR CCL/310 OR CCL/315 OR CCL/322 OR CCL/340 OR CCL/359 OR CCL/362 OR CCL/384 OR CCL/482 OR CCL/70 OR CCL/74)
Bicycle Design	Bicycle Bike	tools and hardware transportation	(TTL/bicycle OR TTL/bike OR ABST/bicycle OR ABST/bike) AND (CCL/D08 OR CCL/D12)

Table 2: Search strategy of patents employed in study (all are granted U.S. Patents, from 1970 till 2009)