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Innovation and de facto standardization: The influence of dominant design on innovative performance, radical innovation, and process innovation

Alexander Brem [a,*], Petra A. Nylund [b], Gerd Schuster [c]

[a] The Mads Clausen Institute, University of Southern Denmark, Alsion 2, 6400 Sønderborg, Denmark
[b] Faculty of Business and Communication Studies, University of Vic, Sagrada Família 7, 08500 Vic, Spain
[c] School of Business and Economics, University of Erlangen-Nuremberg, Lange Gasse 20, 90403 Nuremberg, Germany

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ABSTRACT

Setting technology standards is the route to market growth and to potentially influencing the performance of a whole industry. When a market accepts a particular technology as one that defines the specifications for products in the entire industry, a dominant design is set. In this article, we investigate how the existence of a dominant design affects subsequent innovation in an industry. In particular, we study the influence on innovative performance, radical innovation, and process innovation. Analyzing longitudinal, cross-sectional patent data for more than 2.6 million patents filed from 1978 to 2013, we find support for our hypotheses that an industry's innovative performance and degree of radical innovation are negatively influenced by dominant design in that industry, and that process innovation is fostered by the occurrence of a dominant design. We discuss the findings in the light of the increasing speed of technological development and standardization. Additionally, results from a sensitivity analysis for different threshold values of dominant design call for adjusting a binary definition of dominant design with different threshold values depending on the effects under study.

1. Introduction and background

In the process of rapid technological change, superior technology plays an important role in the stimulation of product innovation and process innovation (Utterback and Abernathy, 1975; Tushman and Anderson, 1986). Surprisingly, many examples show that the development of a superior technology does not automatically lead to the establishment of a new standard (Viardot, 2005), e.g. as the evolution of standards can also be triggered by non-technological reasons (Arthur, 1990). The establishment of a new standard can be a major lever to reach dominant market share and survive on markets with rapid technological change (Suárez and Utterback, 1995). As an industry passes through the product life cycle, product variety tends to be reduced and the technology becomes standardized. Companies participate in a technology race, in which they want to dominate the choice of standards and consequently increase market share (Damsgaard and Lyytinen, 1998). A dominant design exists if the market accepts a particular product's design as the standard for the whole industry or product category (Abernathy and Utterback, 1978; Utterback, 1994). A dominant design is the turning point for an industry, e.g. the 1908 Ford model T became the dominant design in the automotive industry in the early 20th century (Fujimoto, 2014). To better understand this phenomenon, this article investigates how the existence of a dominant design affects subsequent innovation in an industry.

With the institutionalized standardization of dominant design, i.e., by industrial norms, there is large potential for policy makers to control innovation activities (Blind, 2013). However, only recently policy initiatives have occurred, e.g. the Lead Market Initiative (LMI) including a communication titled “Towards an increased contribution from standardization to innovation in Europe” (European Commission, 2008), which focuses on standardization as a crucial innovation policy instrument (Choi et al., 2011; Blind, 2013). The final report of the LMI centers on strategic actions for developing more consistent standardization to encourage the diffusion of innovative practices (European Commission, 2011).

Utterback and Abernathy (1975) and Murmann and Frenken (2006) have conceptualized standardization on the product level. They state that a dominant design exists in an industry when a majority of innovations are based on the same technological design (Murmann and Frenken, 2006). In the race to strive for best-in-field innovations, companies need to consider not only their

* Corresponding author.
E-mail addresses: brem@mci.sdu.dk (A. Brem), petra.nylund@uvic.cat (P.A. Nylund), gerd.schuster@fau.de (G. Schuster).

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own innovations, but also the best and most recent innovations and dominant designs which are publically available in their technological field (Narula, 2004). Although the interrelation of standards, standardization, or dominant designs and innovation seems to be a major contributor to a firm's competitiveness, the influence of standardization on innovation has been investigated to a limited extent only (e.g. Farrell and Saloner, 1985; Galvin and Rice, 2008; Blind, 2013; Blind and Mangelsdorf, 2013). Blind (2013) recently studied this relationship in a comprehensive discussion on the influence of standards and standardization for the whole innovation process. From his perspective, the influence of standardization on innovation has been largely under researched because of two reasons: primarily, due to the traditional perspective that standards will always negatively influence innovation, and additionally, due to the fact that policy initiatives therefore did not consider standards as an instrument to foster innovation activities and as a consequence did not foment research on the topic. Publications on the investigation of this relationship are continually increasing, but only a few have strived to extend empirical research on the relationship between standardization and innovation (e.g. Swann, 2000, 2010). Nevertheless, research profiling 528 papers retrieved from the database ISI Web of Science shows that the research topic is generating growing interest with yearly publications on standards and innovation which nearly tripled between 1995 and 2000 and more than doubled between 2000 and 2008 (Choi et al., 2011).

2. Theory and hypotheses

This article studies the influence of standardization and dominant design on innovation on the industry level. To better understand the concepts of dominant design and standardization, we start by defining the basic terms in the context of this article. We then examine the existing theory about the impact of dominant design on subsequent innovation and formulate related hypotheses.

2.1. Definition and distinction of dominant design and standardization

The definition of dominant design has evolved over time from a broad concept to a more specific phenomenon. Srinivasan et al. (2006) and Narayanan and Chen (2012) provide very useful overviews of various definitions of dominant design including the definitions by authors such as Abernathy and Utterback (1978), Anderson and Tushman (1990), and Christensen, et al. (1998), which we complement with the definition of Murmann and Frenken (2006). They state that a "dominant design exists in a technological class when the majority of designs have the same technologies for the high-pleiotropy core components" (Murmann and Frenken, 2006, p. 23). In the context of the marketplace, James Utterback defined dominant design as a design that "wins the allegiance of the marketplace […] that competitors and innovators must adhere to if they hope to command significant market following" (Utterback, 1994, p. 24). In other words, market forces may inevitably lead to acceptance of a product's design as the leading design in the industry or product category (Abernathy and Utterback, 1978; Utterback, 1994; Srinivasan et al., 2006). This phenomenon is also described as de facto standard or dominant design (Soh, 2010), which is the object of examination of this article.

In this context, we emphasize that dominant design and standards are strongly related, but not identical concepts, even if prior research has used these terms synonymously (Katz and Shapiro, 1986; Anderson and Tushman, 1990; Besen and Farrell, 1994; Schilling, 1998). Following the remarks of Srinivasan et al. (2006), we define standards as the inevitable requirement for technical specifications of products resulting from the interdependence among several components (Srinivasan et al., 2006) – standards are mainly implemented in industrial norms. From this perspective three aspects differentiate standards from dominant designs: Firstly, standards have the functional purpose to connect different components of a product or service, independently of its manufacturer/service provider or its market acceptance, whereas market acceptance is a central prerequisite of a dominant design (Srinivasan et al., 2006). Secondly, dominant designs emerge from competition in the product life cycle after a long process of problem solving (Gawer and Cusumano, 2014), e.g. in the home video market when Blu-Ray won the competition against HD-DVD, whereas standards emerge from the previous competition of dominant designs (Shapiro and Varian, 1999) or, in other words, from the progressive nature of the product life cycle in which an industry is forced to standardize core components (Gawer and Cusumano, 2014). Thirdly, standards can comprise many dominant designs, e.g. in the mobile phone market with the subscriber identity models SIM, Mini-SIM, and Micro-SIM. Hence, if a market accepts particular technology standards defining the specifications for products in the entire industry, a dominant design is set.

2.2. The influence of dominant design on innovative performance

The emergence of a dominant design in an industry is an important event, which directly affects the technology life cycle and indirectly affects the strategies and performance of firms in that industry (Srinivasan et al., 2006). The traditional perception of the interrelationship of standardization and innovation is that standardization hinders innovative performance (Blind, 2013). A common definition of innovative performance has been frequently discussed in innovation management research (Pakes and Griliches, 1980; Ahuja and Katila, 2001; Cockburn et al., 2010). In this article we define innovative performance in the context of an output factor as the cumulated results of innovative activities in an industry or product category. Nevertheless, standardization is also found to promote innovation if certain framework conditions are considered (Blind, 2013). Standards can explain technological specifics and therefore diffuse state of the art solutions (Swann, 2000). The firm that has brought up a dominant design shapes future generations of products, resulting in what Srinivasan et al. (2006) call an "architectural franchise" – a type of monopoly power which might lock out competition for a while and consequently increase innovative and firm performance (Schilling, 1998). Blind (2013) recently provided empirical evidence that standardization can promote innovation. By means of dominant design, innovation activities are positively influenced by avoiding a "lock-in into old technologies" (Blind, 2013, p. 9), by an increase of the efficiency of the supply chain through economies of scale and the reduction of product variety, which allows emerging technologies and industries to faster reach critical mass. On the other hand, dominant design can negatively influence innovation by the creation of monopoly power, the increase of competitors' costs, market concentration and a subsequent reduction in product choice, as well as a potentially premature selection of technologies (Swann, 2000). These negative effects are especially pronounced when a dominant design is protected by strong intellectual property rights (Woo et al., 2015).

Empirical evidence on the relationship between dominant design and a firm's individual innovative performance is given by Soh (2010). If a company aims to bring up or strengthen a dominant design, the tight collaboration with partners helps to accomplish this task. Soh (2010) finds that firms with high proximity to other firms in industry alliances, an extensive information flow

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between firms in the collaboration network, and the strategic intent to open up the innovation process and share knowledge with partners, achieve better innovative performance. Swann and Lambert (2010) support this conclusion as they find respondents in the Community Innovation Survey being more successful in innovation activities when they perceive standards as an instrument to receive information instead of perceiving standards as an obstacle to innovation. On the macro level, Swann (2010) also argues that the perception of standards as a framework or infrastructure condition combines both positive and negative impacts, because any type of infrastructure generates opportunities for its users but also limits the user options. Consequently, a crucial question is whether dominant design and subsequent standardization generally constrains or enables innovation.

Previous findings contribute contradictory results on both the firm and industry level. While recent studies find that an individual firm's innovative performance is generally fostered by an existing dominant design in an industry (Swann, 2000; Soh, 2010), others find that the time lag after the occurrence of a dominant design plays a crucial role (Blind, 2013), while Suarez and Utterback (1995) on the other hand clearly indicate that a negative relationship might exist. Specifically, they find that those companies, which enter a market after the occurrence of a dominant design, fail more often than those companies, which entered the market in the pre-dominant design phase. As a consequence, less innovative activities will be conducted as fewer players remain on the market. The overall innovative performance in an industry is therefore negatively influenced by dominant design (Swann, 2010; Blind, 2013), resulting in the success of a few and the separation of many. The self-regulating nature of the patent citation mechanism leads to a concentration of selected technologies with the potential to breakthrough, mostly coming from pre-dominant design entrants (Suarez and Utterback, 1995). This concentration reduces the variety of technologies, overall resulting in a lower innovative performance in that industry. To shed light on the contradictory findings about the relationship between dominant design and innovative performance, we therefore hypothesize:

Hypothesis 1. The existence of a dominant design in an industry will be negatively related to the level of innovative performance in that industry.

2.3. The influence of dominant design on the type of innovation

Standardization is considered to be a critical factor in the constructive stages of the microeconomic innovation process and the subsequent macroeconomic development (Swann, 2000, 2010). Standardization helps to build focus in the innovation process by variety reduction (Tassey, 2000), and it helps to reach critical mass in a market as it serves as foundation for technical advancements (Krechmer, 1996). The variety of technologies decreases and a phenomenon takes place in which the consumption of other consumers as an indicator for quality, bandwagon effects, or the fact that information on a product is frequently available if many other consumers use the product (ceteris paribus) help to explain why radical innovations are sometimes delayed or completely locked-in if standards are set (Arthur, 1989; Katz and Shapiro, 1992). Radical innovation thus tends to imply the absence of dominant design (Oerlemans et al., 2013). Similarly to innovative performance, a widely accepted definition of radical innovation is missing (Green et al., 1995; Katila, 2000). Katila (2000) separates previous attempts to define radical innovation into four perspectives: organizationally, industry-, user-, and technologically radical. In the context of this article, we define radical innovation as technologically new and significant innovation (as

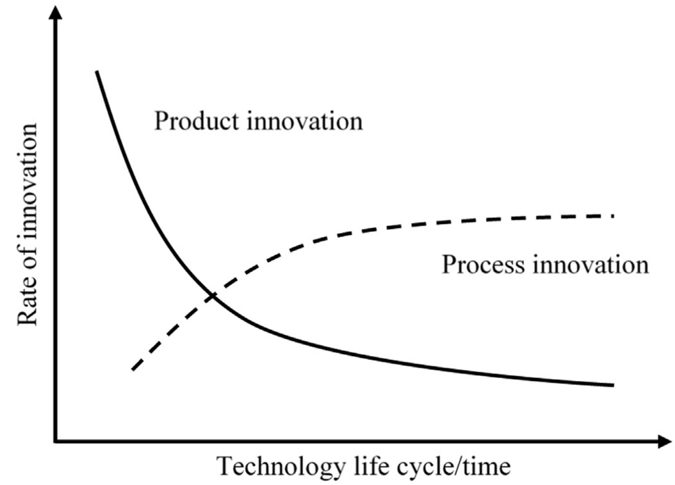

Fig. 1. Innovation and stage of development (adapted from Utterback and Abernathy (1975)).

counterpart to incremental innovation). Another dimension related to the type of innovation is the source: are innovations driven by technologies (technology-push) or by the markets (market-pull)? Such a formulation neglects the fact that impulses for innovations mainly come from the area of regulation, i.e. based on political decisions, changes in laws, or by new standards. Hence, regulatory-push might be considered as an additional dimension (Brem and Voigt, 2009).

Research on technology management additionally shows that industry dynamics change significantly after a dominant design emerges (Anderson and Tushman, 1990; Rosenkopf and Tushman, 1994; Baum et al., 1995). “Competition moves from product innovation to process innovation” (Dodgson et al., 2013, p. 149), efficiency of product development increases and the number of competitors decreases (Utterback and Abernathy, 1975; Suarez and Utterback, 1995). In the context of this article, we refer to the model of process development by Utterback and Abernathy (1975) and define process innovation as the cumulative improvements to the entire (production) process, which is applied to create a product or service. The first articles on dominant design by Abernathy and Utterback (i.e. Utterback and Abernathy, 1975; Abernathy and Utterback, 1978; Abernathy, 1976) have cumulated to the development of a model describing that many product innovations occur in the initial stage of an industry or product category, while the advent of dominant design initiates the shift to process innovation (Akiike, 2013) (Fig. 1).

Nevertheless, we also need to mention that the findings of a recent study by Frenz and Lambert (2012) challenge the interpretation of the results of previous studies (e.g. the studies of Abernathy (1976) and Swann and Lambert, 2010). In factor analyses of variables taken from the UK Innovation Survey from 2002 to 2008, Frenz and Lambert (2012) find that the use of standards only slightly correlates with other modes of innovation, especially with process modernizing. Digging deeper into the causal explanations of these contradictory findings, the evolution of radical products indicates that these types of products face limited market acceptance and high uncertainty resulting in the need for large development efforts and the production of numerous product variants (Utterback, 1994; Sørensen and Stuart, 2000; Srinivasan et al., 2006). The sequential development of various technologies over several years consequently increases time to market and decelerates the emergence of dominant designs. Due to incumbent inertia and the increase of competitors’ costs, the existence of an established dominant design is expected to lower the probability

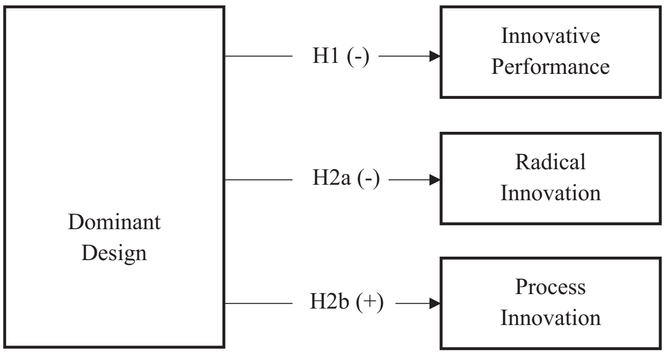

Fig. 2. Path diagram of hypothesized effects.

of the emergence of another subsequent dominant design or any radical improvements to the existing product (Srinivasan et al., 2006). Therefore, we postulate:

Hypothesis 2a. The existence of a dominant design in an industry will be negatively related to the degree of radical innovation in that industry.

Hypothesis 2b. The existence of a dominant design in an industry will be positively related to the degree of process innovation in that industry.

Fig. 2 summarizes the hypothesized relationships.

3. Data and method

To test the hypotheses derived above, we use longitudinal patent data covering all patenting industries from the OECD Citations database, January 2014 edition. The data set lists data on patent and non-patent literature citations for 2,625,490 patents in 627 patent classes. It includes patent applications filed at the European Patent Office (EPO) from 1978 to 2013, and hence constitutes 20,894 patent class years. The cross-sectional data allows us to test our hypotheses across a great span of industries and the longitudinal aspect of the data set permits us to control for differences between industries. We prefer this European data to similar data from the United States Patent and Trademark Office (USPTO) since EPO patents are considered better indicators of innovative performance (Belderbos et al., 2014; Jaffe and Lerner, 2004). The advantage of EPO patents is due to the higher cost of patenting as calculated by Van Pottelsberghe de la Potterie and François (2009), the lower work-load of patent examiners, and lower patent-granting rates of EPO as compared to USPTO by Quillen and Webster (2001). EPO patent reviewers are able to spend more time on each review and, therefore, are able to more carefully examine if a patent application is worth a patent.

Patents have been found to be a relevant indicator of innovation (Griliches, 1990; Jaffe et al., 1993; Joshi and Nerkar, 2011), and patent counts correlate highly with alternative measures of innovation such as R&D inputs, patent citations, and new product announcements (Hagedoorn and Cloodt, 2003).

For our study we assume that citation and consequently application of existing technological inventions lead to a certain level of standardization and therefore to dominant designs. The way an intellectual property system is built leads to a self-regulating functionality in which weak and old concepts are eliminated and strong and new concepts are promoted. This is why we measure dominant design through citations by patent applicants and patent reviewers as described in detail in the section below.

3.1. Measures

3.1.1. Dependent variables

We define dependent variables, one for each of our three hypotheses, and thus obtain the dependent variables *innovative performance*, *radical innovation*, and *process innovation. Innovative performance* is measured as the patenting frequency of each patent class, calculated as the number of patent applications in a given year (Ahuja and Katila, 2001; Hall and Ziedonis, 2001; Keil et al., 2008; Stuart, 2000). Since dominant design is a phenomenon related to technological classes, all the dependent variables are measured for each patent class. *Radical innovation* is measured as the average number of forward citations for a patent class in a given year. This measure is indicative of the value of a patent (Cloodt et al., 2006; Sorenson et al., 2006; Wang et al., 2012). This measure includes both examiner and applicant citations, and is already present in the data set for each patent. *Process innovation* is measured as the share of patent applications in a given patent class and year that has International Patent Classifications (IPCs) with *processes* as the category of subject matter. The distinction is made at the eight-digit level of the IPC codes. There are four IPC categories of subject matter: *processes, products, apparatus* or *materials*. We are thus able to measure the degree of process innovation across patent classes.

3.1.2. Independent variable

Dominant design is measured binarily as whether a dominant design exists in a certain patent class during a certain year. A dominant design exists in a patent class year if the percentage of patents that cite the same patent is above a threshold value of 50 percent. This value is used as it represents a majority of citations, i.e. a design is dominant if a majority of other innovations in a patent class includes the same design. We omit 444 patent class years with a dominant design that is cited to 100 percent, since these patent class years all have an innovative performance of less than three patents.

3.1.3. Control variables

We control for several characteristics of the dominant design including the *age*, *time lag*, and *scope* which are expected to moderate the hypothesized relationships. The *age* of the dominant design is measured as the number of years that a design has been dominant. Hence, it measures how long an innovation maintains its status as a dominant design before new innovations become predominantly based on other technologies. The *time lag* is measured as the number of years since the patent of the dominant design was first published. It thus measures the time it takes for an innovation to become a dominant design. The *scope* is measured as the number of distinct four-digit IPC classes of the dominant design (Lerner, 1994), and is hence the breadth of patent classes in which an innovation is expected to be relevant.

We control for heterogeneity among patent classes e.g. the differences between complex and discrete industries (Grimpe and Hussinger, 2014) or service and manufacturing industries (Hipp and Grupp, 2005), by running the regressions with patent-class effects. Patent classes are measured as four-digit IPC technology codes (Trajtenberg, 1990; Cloodt et al., 2006; Singh, 2008; Katila and Ahuja, 2002; Guellec and van Pottelsberghe de la Potterie (2001); Fleming, 2001; Silverman, 1999; Wang et al., 2013). In addition, we control for heterogeneity of continents by only using data of European patents. Through this geographical restriction of the data, we control for the possibility of different industry developments in different parts of the world, and also for the differences in patenting procedures.

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3.2. Estimation method

The data includes 35 years of observations, which means the estimation method needs to take into account time-variant effects. The method also needs to consider the variations among patent classes, controlling for fixed patent class effects. We therefore use a regression method particularly suitable for long panels, i.e. cross-sectional time-series feasible generalized square (FGLS) regressions with panel-specific first-order autoregressive (AR(1)) autocorrelation (Cameron and Trivedi, 2005). The autoregressive correlations ensure that the dependent variable is also a function of its own previous values for each patent class. Since the error structure is specified for each patent class, the specified model is a panel regression model that takes into account the heterogeneity among patent classes. The chosen method thus avoids time-variant and cross-sectional endogeneity issues (Baltagi, 2008).

The model for the fixed-effects regressions can be expressed as:

$$Y_{it} = \alpha + X_{it}^{1} * \beta_1 + \cdots + X_{it}^{k} * \beta_k + u_{it}$$

$$u_{it} = \rho^* u_{it-1} + \eta_{it}; \eta \text{ is } iid\left(0,\ \sigma_\eta^2\right)$$

X_{it} is a vector of the independent and control variables and u_{it} is a fixed effect for the ith patent class.

4. Results

The mean values, standard deviations, and correlations among the variables used in the analyses are presented in Table 1. Because of high correlations between the dependent and control variables, we examine other statistics that may indicate multicollinearity. The Variance Inflation Factors (VIFs) are under 3.4, and the tolerance over 0.30, so there is little need for concern about multicollinearity (Kutner et al., 2004).

To illustrate patent application behavior, Fig. 3 shows patent application frequencies of all existing patent classes per year. While we see a pretty steady increase of patent applications with minor recessions in the years 1994 and 2009, we can also see that patent class years with a dominant design (marked with bold dots) are all found below 10 patent applications per year, whereas patent class years with no dominant design have up to 12,535 patent applications per year and a mean of 244 patent applications.

Taking a look at innovative performance in different patent classes, especially in those with prominent dominant designs, Fig. 4 graphs innovative performance of the four patent classes riding equipment, train tracks, threads, and automated musical instruments, which all have over seven years of dominant design. Confirmatory of the observation above, we see that the years with dominant designs have remarkably lower performance, which leads to the assumption that dominant design remarkably influences innovative activity. There seems to be a negative relationship between dominant design and innovation performance, i.e. performance can decrease because there is a dominant design or inversely it may be harder for a dominant design to exist in industries with high innovative performance.

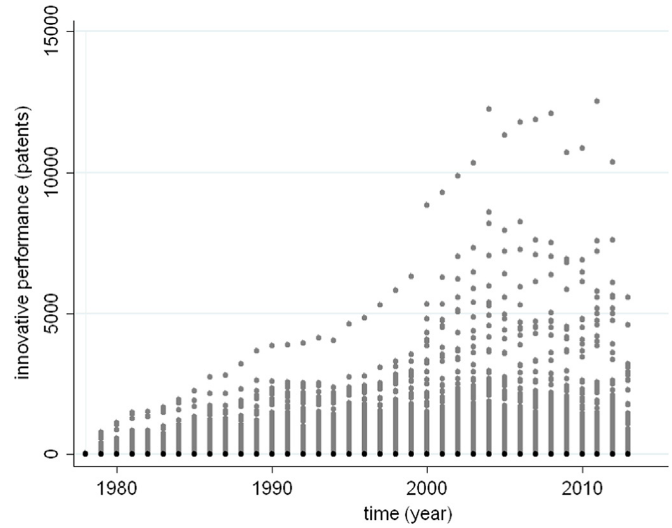

Fig. 3. Innovative performance of all patent classes over the years.

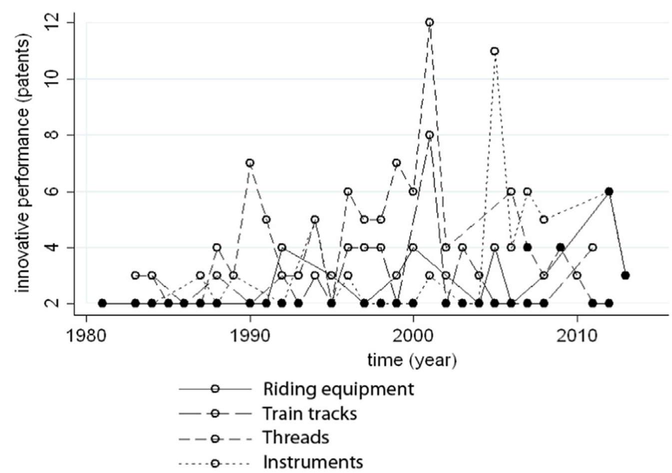

Fig. 4. Innovative performance of four patent classes that have over seven years of dominant design; observations with a dominant design marked with filled circles, observations without a dominant design marked with hollow circles.

The results of the regression analysis are reported in Table 2. Model 1 is the regression of the independent and control variables on innovative performance. Model 2 is the regression on radical innovation, and model 3 is the regression on process innovation.

In model 1, we thus test our first hypothesis about the relationship between the *dominant design* and *innovative performance*. The relationship is significant and negative, which supports

Table 1
Descriptive statistics and correlations.

	Mean	S.D.	1	2	3	4	5	6
1. Dominant design	0.018	0.134						
2. Innovative performance	239.376	603.406	−0.054[a]					
3. Radical innovation	2.342	1.671	−0.001	−0.009				
4. Process innovation	0.013	0.079	0.061[a]	0.008	0.008			
5. Age	0.000	0.015	0.113[a]	−0.006	−0.003	−0.003		
6. Time lag	0.299	3.277	0.666[a]	−0.036[a]	−0.031[a]	0.030[a]	0.017[a]	
7. Scope	0.075	0.712	0.770[a]	−0.041[a]	0.027[a]	0.057[a]	0.059[a]	0.502[a]

n=20,894.

[a] Correlations significant on the 5% level.

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Table 2
Regression results.

	Innovative performance Model 1	**Radical innovation** Model 2	**Process innovation** Model 3
Dominant design	−128.254[a]	−0.133	0.022[a]
Age	14.406[a]	−0.011	0.000
Time lag	1.531[a]	−0.015[a]	−0.000[b]
Scope	9.558[a]	0.134[a]	0.002[a]
Constant	124.875[a]	2.158[a]	0.028[a]
Diagnostics			
Log likelihood	−127,866	−28,370	−28,540
Wald χ^2 (df)	671[a]	154[a]	74[a]

[a] Estimates significant on the 5% level.
[b] Estimates significant on the 10% level.

our Hypothesis 1. The control variables *age*, *time lag*, and *scope* have smaller positive effects on innovative performance.

In model 2, we test the second hypothesis that there is a negative relationship between *dominant design* and *radical innovation*. The relationship is not significant when we control for heterogeneity between patent classes. The results hence do not support our Hypothesis 2a. The effect of the control variable *scope* is positive, whereas the effect of *time lag* is negative. Innovation in a patent class thus does not become more radical when a design is based on an older patent, at least not when the threshold for dominant designs is set at fifty percent.

In model 3, we test the third hypothesis relative to the relation between *dominant design* and *process innovation*. This relationship is positive, as expected in our Hypothesis 2b. The lower explanatory power of this model compared to our other models is due to the absence of process innovation in many patent classes. Still, the coefficient of *dominant design*, the constant, and the Wald χ^2 of the model are significant, so the relationship does hold for those patent classes that have process innovation.

Since existing theory is not altogether conclusive regarding the threshold value for dominant design, we conduct a sensitivity analysis of our results for different threshold values. The results of the sensitivity analysis are reported in Table 3. For model 1, in which we test the relation between dominant design and innovative performance, the results are robust for threshold values of dominant design between 0.05 and 50 percent. For model 2, our results regarding the relation between dominant design and radical innovation hold for threshold values of 15 to 37 percent. Thus, although Hypothesis 2a is not supported for a 50-percent threshold, it is supported for lower threshold values and thus for more generous definitions of dominant design. For model 3, the results on dominant design and process innovation are significant for threshold values between 2 and 50 percent.

The results regarding innovative performance and process

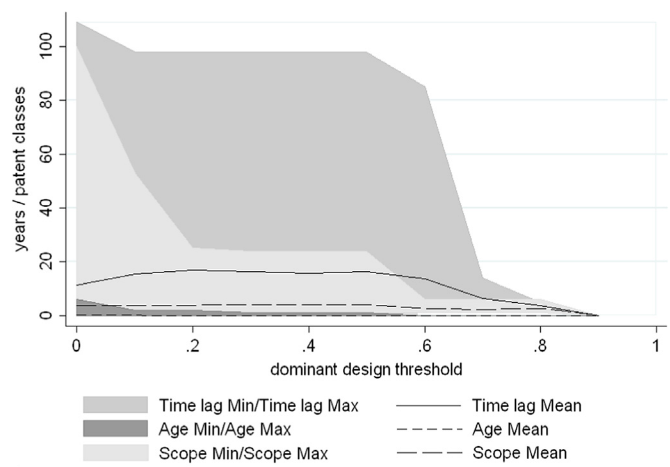

Fig. 5. The control variables as functions of the threshold value for dominant design.

innovation are thus very robust for lower threshold values but do not hold for higher threshold values. This warrants a closer look at the tail of the distribution. The percentage of patents that cite one same patent is above 50 percent for only 21 of the patent class years, which is why we get little significance for higher threshold values.

In our data set, both *time lag* and *scope* look exponentially distributed for those values that have a dominant design. Patent classes with long *time lag* (i.e. over fifty years) include train tracks, threads, riding equipment, and instruments, had many observations of dominant design, as well as other train related patent classes. Patent classes with large *scope* (i.e. over ten) include e.g. those related to train tracks, threads, headwear, footwear, and cosmic radiation energy. *Age* is never over one, i.e. there is never

Table 3
Sensitivity analysis of the threshold value of dominant design.

	Innovative performance		**Radical innovation**		**Process innovation**	
	Lower limit (0.05%)	Upper limit (50%)	Lower limit (15%)	Upper limit (37%)	Lower limit (2%)	Upper limit (50%)
Dominant design	−1116.52[a]	−63.943[a]	−0.086[a]	−0.168[a]	0.004[a]	0.023[a]
Age	18.680[a]	35.485	−0.010	−0.011	−0.000	−0.029
Time lag	−0.180[a]	0.761[a]	−0.008[a]	−0.014[a]	0.000	−0.000[b]
Scope	1.144[a]	4.622[a]	0.062[a]	0.136[a]	0.001[a]	0.002[a]
Constant	1263.719[a]	59.923[a]	2.145[a]	2.156[a]	0.027[a]	0.028[a]
Diagnostics						
Log likelihood	−130,003	−127,382	−28,401	−28,370	28,547	28,540
Wald χ^2 (df)	523[a]	100[a]	158[a]	155[a]	39[a]	75[a]

[a] Estimates significant on the 5% level.
[b] Estimates significant on the 10% level.

more than two consecutive years of a dominant design if the threshold value for *dominant design* is fifty percent.

Fig. 5 shows the means and range of *age*, *time lag*, and *scope* for different threshold values. The *time lag*, which measures the time it takes for an innovation to become a dominant design, is more resistant to higher threshold values. The mean is less than 20 years, usually around 18 years. This is quite a long period of time, especially considering that the minimum and maximum *time lag* range is quite big. The *time lag* is quite stable between the 15 and 55 percent threshold values, and then goes down to almost zero. The *scope*, i.e. the technological span of dominant designs, is comparably narrow, whereby its range is stable between the 20 and 55 percent thresholds, and then goes down below ten patent classes with a higher threshold value. Finally, the *age*, which measures how long an innovation maintains its status as a dominant design, has a very narrow range with a maximum of six years for very small threshold values. This maximum is reduced to two years for a threshold value of ten percent and is then further reduced to one year.

5. Discussion

5.1. Interrelationship of dominant design, innovative performance, product innovation, and process innovation

Our results indicate that innovative performance in a technological class is negatively influenced by dominant design in that class. In other words, there is a negative relationship between dominant design and the degree of innovation, i.e. innovative performance decreases because there is a dominant design in place. This supports the observation in Fig. 4, which indicates that classes which have a dominant design for more than seven years, have a very low patenting frequency. As Blind (2013) argues, dominant designs can have positive effects (e.g. increase of efficiency, helping to reach a critical mass for production), as well as negative effects (e.g. market concentration or the premature selection of technologies). Even though we use a patent-based measure for the dominant design, the existence of a dominant design is strongly influenced by market acceptance of the technology. For this, the case of HD-DVD vs. Blu-Ray may serve as a recent example, where not the best available technology won the battle for dominance, but the one with the more competitive design and stronger ties with strategic partners (Soh, 2010). However, although innovative performance decreases with the event of a dominant design, this behavior is cyclical as dominant designs emerge and disappear: In industries with dominant design there is still innovative activity, but the type of innovation changes temporarily. While overall innovation performance is negatively affected by dominant design, process innovation is positively influenced by the occurrence of a dominant design in a technological class. With this result, we can empirically support the basic assumption of Utterback and Abernathy (1975) that the rate of innovation changes over time from product to process innovation. Process innovation increases while the total innovation performance decreases when there is a dominant design. Across all classes, however, process innovation remains a minor share of total innovation, so that the intersection of product and process innovation shown in Fig. 1 is never reached. Still, it may be possible that the intersection will be reached in certain industries, so that process innovation becomes more frequent than product innovation. As prior literature suggests, the increase in process innovation may lead to a higher level of efficiency and a decrease in the number of competitors (Utterback and Abernathy, 1975; Suarez and Utterback, 1995).

Regarding process innovation, Scherer (1984) initially used patent data to distinguish process R&D and product R&D, later also applied by Cohen and Klepper (1996). To date, there is however no published research that uses patent data for measuring process innovation, even though there is earlier research on measuring process innovation with data from surveys such as the Community Innovation Survey (e.g. Brouwer and Kleinknecht, 1999; Jensen and Webster, 2009; Dachs and Peters 2014).

5.2. Dynamics of dominant designs

Defining the specifications for an entire product category as a de facto standard is the ultimate goal of a dominant design (Abernathy and Utterback, 1978; Utterback, 1994; Soh, 2010). The majority of follow-up innovations will be based on the same technological design, which is supposed to bring the company that has introduced the technology a competitive advantage. However, if a dominant design exists in a product category, the question which remains unanswered is at which threshold value a de facto standard becomes a dominant design.

Results from the sensitivity analysis for different threshold values of dominant design are very robust for lower threshold values but do not hold for higher threshold values. Hence, this offers interesting insights for defining a threshold value range, which does not yet exist. For innovative performance, the lower limit is 0.05 percent, and the upper limit is 50 percent. For process innovation, the lower limit is a slightly higher 2 percent, whereas the upper limit is similarly 50 percent. The percentage of patents that cite one same patent is above 50 percent for only 21 of the patent class years. Hence, the significance for higher threshold values is low. The reduced range of significant threshold values for process innovations support our choice of 50 percent as a threshold value. It appears that more relationships can be discovered by defining dominant design as existing in an industry or technological class if the percentage of innovations that include the same design is above a threshold value of 50 percent. For radical innovation, the lower limit is 15 percent and the upper limit is 37 percent, and Hypothesis 2a is thus only supported for threshold values between 15 and 37 percent. This shows that a 50 percent threshold value may not always be adequate, but that the threshold value of dominant design should be adapted to the model as a whole.

The control variables used in our analysis show very interesting insights into the dynamics of dominant designs (see Fig. 5 for reference). The most surprising fact is that dominant designs are established for maximum six years, measured across all industries, with an average below one year. An explanation for that might be the fact that the innovative performance has increased a lot since the 1980s, not only in Europe, but worldwide, so that it is more

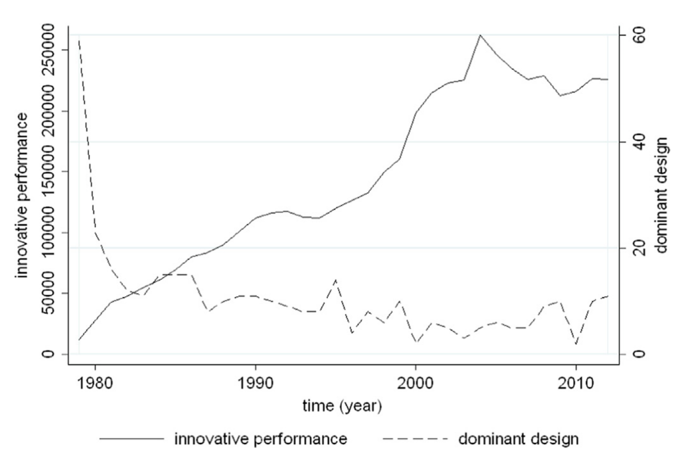

Fig. 6. Innovative performance and dominant design over time.

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difficult to set and defend a dominant design. Fig. 6 shows that whereas innovative performance has increased over the years, the number of industries with a dominant design has gone down, especially during the 1980s. Moreover, this might be explained by the fact that the technological developments over the last 30 years are so dynamic that it has become very difficult to set a dominant design. This is because designs on the verge of becoming dominant are often "leapfrogged" by another technology. Our results might differ if we looked at another time frame, analyzing the dynamics before the period between 1978 and 2013. In a data set spanning from 1888 to 1982, Anderson and Tushman (1990) also find support for the assumption that dominant design is followed by a period of incremental innovation. As we have discussed, Hypothesis 2a about the influence of dominant design on radical innovation may have found stronger support in the past, which perhaps is an explanation for only finding support for this hypothesis when relaxing the conditions for the threshold value of dominant design.

We find that a higher rate of technological development which leads to less lasting dominant designs is supported by the fact that the industries with the most years of dominant design are all classical industries, e.g. riding equipment, train tracks, threads, and automated musical instruments.

In addition, we find that the scope of a dominant design is usually quite narrow, and that there is a quite long time lag of 15–20 years after the first publication of the dominant design. This might be explained by the fact that technological evolutions do not occur overnight. We can expect time lags to be shortened by the evolution of the Internet, where data on new innovations is more readily available.

6. Implications

6.1. Theoretical implications

We have explained how the effects of dominant design on the industry level differ from previous findings regarding the effects on the firm level. Against this background, we conducted a quantitative analysis of patent data to empirically ascertain how an industry's innovative performance is influenced by a dominant design, and how this affects the type of innovation within the industry. With this approach, this is the first study analyzing the influence of dominant designs across many different industries. Moreover, this is the first analysis measuring different threshold values of dominant designs. Other papers so far examine one or a few industries with known dominant designs, so no threshold is necessary or meaningful. With our analysis of the threshold values of dominant design we facilitate the identification and prediction of dominant designs. For this, our research included all industries to identify dominant design thresholds. As our paper is based on a large-scale database, we hope to contribute to the understanding of the evolution of dominant design and its consequences on a broad basis.

With our research, we extend the understanding of dominant design in different industries. We find support for the basic assumption of the Abernathy-Utterback model (Utterback and Abernathy, 1975) that product innovations occur in the initial stage of an industry or product category, while the advent of dominant design initiates the shift to process innovation (Akiike, 2013). Additionally, we show that this is not only valid for one specific industry, but in general across many industries. Through the discussion of threshold values, we give concrete suggestions for further research on how to define a threshold value in order to identify emergent dominant designs. With that, we propose that a dominant design is a continuum within a range that depends on the data and variables analyzed. Our analysis of this range validates a binary definition of dominant design with a threshold value of fifty percent of innovations that include the dominant design for the study of the impact of dominant design on innovative performance and process innovation. However, the analysis shows that the threshold value is an important factor when studying the impact of dominant design and that this value may need to be adjusted according to the objective of study.

Our novel measure of process innovation (measured by the share of patent applications in a given patent class and year that has an IPC with processes as the category of subject matter) allows for further generalization across industries. Moreover, with our analysis of the control variables time lag, scope and age, we can foster the understanding of the influencing factor for the evolution of dominant designs.

6.2. Managerial implications

The evolution of dominant designs, initially studied by Utterback and Abernathy (1975), has important implications for the fate of firms entering or shaping an industry. As our discussion shows, dominant designs do not emerge overnight. On average, it takes 15–20 years until a dominant design emerges from an innovation, hence, companies should monitor these developments. As patent and other innovation data are now available on the Internet, innovation monitoring is manageable not only for multinational companies, but also for small and medium sized companies. Since the duration of dominant design is only a few years, on average even below one year, managers should be aware that dominant designs change more rapidly and occur less frequently than they used to do. This increased dynamism can be seen in many industries, one example being the electric car industry. The absence of a dominant design for batteries and charging systems is a salient obstacle for the evolution of this industry. Even if a standard is developed, which might have the potential to become a dominant design, the next technology is already developing towards a subsequent standard. Hence we can no longer rely on long periods of dominant design.

For policy makers the negative influence of dominant design on an industry's overall innovative performance needs to be observed and might be also controlled in certain rigorous conditions (e.g. monopoly or duopoly building through dominant design). Industry associations for standardization might be even more important in future to encourage the evolution of an industry by creating agreements on dominant designs. With a dominant design in place, process innovations can evolve to make production more efficient and, hence, cheaper. Without sufficient standardization, a principal benefit of technological development in general and intellectual property protection specifically will be lost.

7. Limitations and future research

Uncovering paths for future research, we need to mention the main limitations of this study. As shown in the discussion above, one major restriction is the selection of the time frame we have used for the analysis. The study has focused on data between 1978 and 2013. Hence, we do not account for earlier developments. This offers an interesting starting point for further research: has technological evolution dramatically changed in the last 36 years, which would additionally confirm the effects in this study? How would the effects change if a longer period was considered? Based on our results, we can assume that the evolutionary pattern has changed. As we used patent applications from the European Patent Office, additional insights might come from using data from other patent offices, such as the United

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States Patent and Trademark Office (USPTO) or the State Intellectual Property Office of China (SIPO).

Additionally, the operationalization of process innovation using patent data permits a cross-sectional and longitudinal analysis and may exclude certain other types of process innovation. As process innovation as well as innovation in general is not always patented due to cost factors or due to the use other forms of IP protection such as secrecy, which may be more suitable in some cases (Horstman et al., 1985), the effects of dominant design on process innovation may be even stronger than our data suggests. The question of whether a technology should be patented has been frequently discussed in literature (e.g. Rivette and Kline, 2000; Somaya, 2012).

Additionally, patents only measure one part of innovation output. Future research might complement patent data with other measures of innovation such as new product counts, R&D expenditure, and trademarks (Katila, 2000). Furthermore, to analyze dominant designs from a different angle, consumers could be involved in a qualitative or quantitative setup to analyze which dominant designs they perceive as established. This might give additional insights independently from the sheer quantitative analysis of patent classes from which dominant designs are emerging. In this context, other measures might be included as well, for instance individual market shares as indicators of success.

Another interesting aspect for further research might be a deeper analysis of different industries in order to find out where the different dynamics of dominant designs come from. For instance, we find that some industries have quite a few dominant designs, while others do not have a single one for many years. Industries where innovation is a planned process tend to reach a dominant design sooner (Jeong and Yoon, 2015). This confirms previous findings that patent and citation-tendencies may strongly differ across industries. Therefore, patent data is considered to best capture differences in innovative performance within the same industry, but may fail to entirely capture innovative performance across industries (Katila, 2000). Hence, the question arises if these industries do not have any dominant designs at all, or if they just do not patent. Standards regarding basic components may not be patented if they have no direct commercial value, but a dominant design of a basic component may still have an impact on the subsequent innovation in an industry. Very basic components may also be patented, but not cited when the standard is so dominant that its inclusion becomes obvious. This may be a reason why few industries have technologies with more than fifty percent dominance: New innovations may stop citing an innovation when it becomes very dominant and, thus, can be taken for granted.

Not patenting is another notable trend, which can be found in companies in different industries. As patents are associated with high costs and public availability, firms consider alternative options as well. Such options can be trading on virtual markets or the use of external innovation networks, which are both part of a strategic management of intellectual property (Horn and Brem, 2013). One approach is therefore not to claim any IP rights, but to be fast on the market as a technology pioneer. In this case, the challenge is to very quickly implement the next generation of the technology, as it is not possible to prohibit competitors from using the same technology. While caution must be taken when interpreting our results for industries with little patenting activity e.g. service industries (Blind et al., 2003), this offers another interesting research angle and requires shedding light on the phenomenon of how dominant designs may emerge without having IP protection.

In conclusion, the findings of this article provide strong evidence for the impact of dominant design on subsequent innovation. On one hand, this supports the inclusion of dominant design as a central concept for managing innovation in multinational companies. On the other hand, it emphasizes the need for policy initiatives such as the Lead Market Initiative of the European Commission to foster dominant designs and thereby support the growth of an industry.

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